Cerdanya basin characterisation using H/V and F-K seismic noise methods

Author: Rubén Soussé Villa
Advisor: Juanjo Ledo, Pilar Queralt
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.*

Abstract: Seismic noise methods are nowadays widely used in geophysics being easy and non-invasive techniques to characterise the subsoil. In the present study I use F-K and H/V methods to process data collected on the Cerdanya Basin during 2012 by ICGC. The main objective has been to determine the thickness of the basin sedimentary materials in two different locations: Ger, above the mountain, and an aerodrome, down the valley. H/V method uses single geophones to record triaxial seismic noise vibrations. The data processing is able to find the resonant frequency of the soil, which is a good indicator of the sedimentary material thickness but does not provide a numerical value. On the other hand, F-K method goes further and uses arrays of registering stations to acquire data. The processing and inversion of this seismic noise gives the Rayleigh waves propagation velocity for each subsoil layer, giving way to a good characterisation of the material that conforms them. This characterisation allows us to estimate the rocky basement depth, which finally becomes in 360 meters for the aerodrome and 100 meters for Ger. The final processing method performed has been to combine the results from the two previous methods to achieve a second thickness numerical measure, which approaches to the previous results obtained.

I. INTRODUCTION

Characterisation of the subsoil is a basic study nowadays for geological sciences, as well as to improve the knowledge about the seismic behaviour of any region or to explore possible underground reservoirs. Currently, the techniques that offer this kind of studies have mixed geological and physical contents, making use of physics' knowledge to achieve geological purposes.

In the present work, we use two of these techniques, H/V and F-K, to reproduce the study that *Institut Cartogràfic i Geològic de Catalunya* (ICGC) performed on the Cerdanya Basin [3]. These two methods provide a high reliability in subsoil layers characterisation and are usually combined with magnetotelluric techniques. As passive methods, they use only the environmental seismic noise, without the requirement of producing a controlled signal.

Data obtained by two arrays of geophones in two different points of the basin is analysed in this work to calculate the fundamental frequency of the soil and the rocky basement depth: H/V provides the soil main resonant frequency at every station, while F-K uses arrays of stations to calculate the dispersion curve of noise waves. The inversion of this curve will give us their layered propagation velocity.

All the computation required to process the data will be done with Geopsy, Max2curve and Dinver software.

II. THEORY

A. Seismic noise

The seismic noise is defined as ground movement because of non-seismic causes. This expects to difference noise from micro-seism. In seismic methods, usually noise is classified for frequencies as follows [2]:

- Low (< 0.3-0.5Hz): caused for distant sea waves.
- Medium (0.3-0.5Hz to1Hz): close sea waves.
- High (> 1Hz): human activity caused, as cars, machinery, etc.

Noise is considered to be principally superficial seismic waves of the soil, so they are described as Rayleigh and Love waves. Rayleigh waves compose its vertical component while both waves, Love and Rayleigh, composes the horizontal ones.

The propagation velocity of these waves varies depending on the ground density and strength, for example from sedimentary to rocky materials. Typically, these velocities are classified as follows:

Soil	Velocity (m/s)
Compact rock	> 1500
Rock	760 - 1500
Compact soil/soft rock	360 - 760
Soil	180 - 360
Soft soil	< 180

TABLE I: General classification of propagation velocities for different materials [2].

Rayleigh waves suffer dispersion, so they separate because of the different propagation velocity of the various frequencies of the wave fronts. Meanwhile, internal waves are not dispersive. These are classified in S (perpendicular to propagation vibration) and P (parallel to propagation vibration).

B. H/V Theory

H/V, also called Nakamura, is an experimental technique that consists in calculating the quotient of horizontal and vertical noise amplitude: the transference function of the sedimentary layers can be defined as the ratio between noise incidence on surface and on the rock basement, in frequency domain, so the ratio of spectral amplitudes. This transference function is also the amplification of waves from inner rock to surface, because of basin's geometry. Referring to the supposition of II.A where noise is mainly superficial, we can consider that all the noise travelling from the rock basement to surface is vertical, so we can approximate this function as the ratio of horizontal noise (surface noise) and vertical noise (noise from the rock), leading us to expression (1).

$$\frac{H}{V} = \frac{(S_x + S_y)/2}{S_z} \tag{1}$$

* Electronic address:`tfgac@ub.edu`

Where S_x and S_y are the horizontal seismic signals and S_z is the vertical one [2].

Doing this, we can obtain the amplification vs. frequency spectrum. It will lead us to determine the resonant frequency (or fundamental frequency) of the soil, which is the lowest frequency where amplification is produced –and usually the most important one. The resonant frequency value is directly related with the sedimentary layers thickness: a deep rocky basement will cause a low resonant frequency, while measuring directly on the rock the fundamental frequency will tend to infinite [5].

The direct relation between the fundamental frequency and the subsoil thickness (*H*) comes from the expression:

$$f_{fon} = \frac{\bar{V}_s}{4H} \quad (2)$$

Where *H* is in meter, f_{fon} in Hz and $\bar{V}_s$ is the average S wave velocity [1] [3]. This value can be numerically related with Rayleigh average velocity ($\bar{V}_R$) by $0.87 < \bar{V}_R/\bar{V}_S < 0.96$ [6], where we used $\bar{V}_R \approx 0.92\bar{V}_S$, and $\bar{V}_R$ is obtained with F-K arrays method.

With this method, only a 3 components geophone is required. It's a clear advantage in front of other methods requiring more instrumentation, while the fundamental frequency obtained can be used to determine the sedimentary materials thickness through the velocity found by the arrays.

C. F-K Theory

F-K is the short name for Frequency vs. Wavenumber (K), and this method is used to find the direction of the noise wave fronts and its propagation velocity in surface. To achieve this, the method uses seismic arrays of geophones, that will let is to correlate the different signals of each instrument. Finally, we will acquire the frequency of each wave front registered by each geophone and its velocity, all at the same time, so we will have a spectrum frequency vs. velocity of the noise wave fronts that have been propagated in the soil layers under our seismic array.

As we said, we will consider the noise as successive wave fronts that travel along the subsoil, with an angular frequency ω and a wave number $\vec{k}$: $y(\vec{x},t) = A\exp(i(\omega t \pm \vec{k}\vec{x})$. If we define the slowness as $\vec{u} = \vec{k}/\omega$, we can rewrite the last equation as:

$$y(\vec{x},t) = A\exp(i\omega(t \pm \vec{u}\vec{x})) \quad (3)$$

Where *A* is its amplitude, *t* the time and *x* the distance travelled.

The term $\vec{u}$ will be the slowness, with the same direction as the wave propagation and perpendicular to the wave front plane. Despite this, our array will only measure the horizontal component of the slowness ($\vec{u}_h$). As the wave plane has an angle φ with the vertical of the surface and an angle θ with the north (our reference), the real slowness ($\vec{u}$) and the measured one ($\vec{u}_h$) can be defined:

$$\vec{u} = \frac{1}{v_0}(\sin\varphi\sin\theta, \sin\varphi\cos\theta, \cos\varphi) \quad (4)$$

$$|\vec{u}_h| = |\vec{u}|\sin(\varphi) \quad (5)$$

Where v_0 is the waves velocity.

Supposing then that the wave plane will cross the array, the time it takes for the wave to travel form the origin to the station *i* will be $t_i = t_0 + \vec{r}_i\vec{u}_h$. In a certain moment, we can define the amplitude of a signal *s(t)* measured in an instrument as it follows:

$$y_i(t_0) = s(t_0 - \vec{r}_i\vec{u}_h) + n_i(t_0)$$

Where y_i is the amplitude in the station *i* and $n_i(t)$ is the noise.

After the wave has travelled during a time $\vec{r}_i\vec{u}_h$ the signal observed in the geophone will be: $y_i(t_i) = s(t_0) + n_i(t_0 + \vec{r}_i\vec{u}_h)$. So, if we have different instruments separated a distance r_i between them, the signal will be the same at all of them. Then if we add all the registers:

$$b(t_i) = \frac{1}{N}\sum_{i=1}^{N} y_i(t_i) = s(t) + \frac{1}{N}\sum_{i=1}^{N} n_i(t_0 + \vec{r}_i\vec{u}_h) \quad (5)$$

In order to study the noise in the frequency domain, it is useful to use the Parseval's theorem (6):

$$\int_{-\infty}^{\infty} b^2(t)dt = \int_{-\infty}^{\infty} |B(\omega)|^2\, d\omega \quad (6)$$

Where $B(\omega)$ refers to the Fourier transform of *b(t)*.

In order to create a model for the array response to a signal, we consider a seismic wave with a slowness of $\vec{u}_{h0}$, travelling from the centre of the array and reaching station *i* in the instant t_0. As we have seen, the registration in this station would be $y_i(t_0) = s(t_0 - \vec{r}_i\vec{u}_0)$. Now, if we compare it with the real observed noise wave front (with slowness $\vec{u}_h$ as said), the shift between signals would be: $y_i(t) = y_i(t + \vec{r}_i(\vec{u}_h - \vec{u}_{h0}))$

Defining the equation (5) as the beam energy (*E(ω)*) [4], we can call its slowness dependent part as the *array response* (7):

$$A(\vec{u}_h - \vec{u}_{h0}, \omega) = \left|\frac{1}{N}\sum_{i=1}^{N} \exp(j\omega\vec{r}_i(\vec{u}_h - \vec{u}_{h0})\right| \quad (7)$$

So, the beam energy in terms of *A*:

$$E(\omega) = \int_{-\infty}^{\infty} |Y_i(\omega)|^2\, |A(\vec{u}_h,\omega)|^2 d\omega$$

Where $Y_i(\omega)$ is the Fourier transform of $y_i(t_i)$ from (5) [4].

The response of the array (*A*) forms specific patterns depending on the configuration of the array (fig. 1.a and 1.b). The maximums disposition depends on slowness and frequency of waves that crossed the array, which causes displacements of the maximums (fig. 1.c). From these shifts, the software estimates numerically the slowness, azimuth (direction) and frequencies of noise wave fronts. Finally, the waves frequency versus its calculated slowness will be represented in the dispersion curve (fig.4).

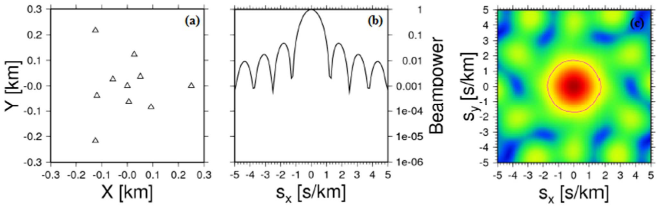


FIG. 1: (a) An array configuration example, (b) its response (*E(A)*) in a specific direction (1D) and (c) the array response patron in 2D (symbolic scale colour). If a wave front is detected, the central maximum suffers a displacement proportional to its velocity and frequency. [4]

The waves wavelength detection limit of the array will be determined by its width: the wavelength must fit between stations at least with half a period in order to be detected as an independent wave front, if not aliasing is produced. The dimension of the array will stablish then the maximum depth explored: The longer a wavelength is implies that more information can get, because the wave can reach deeper subsoil layers [6].

Finally, the more azimuthal angle covered with geophones will imply a better resolution, being able to characterise more noise wave fronts [4].

III. APLICATION

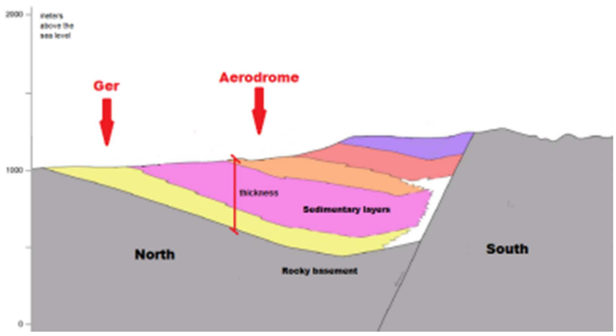
A. Instrumentation

For data acquisition in seismic arrays seven Sara SL06 digitizers were used. Each of them was connected to a triaxial Lennartz sensor on the ground. The sampling time was fixed in 200Hz, which is a sample every 0.005 seconds. Finally, it was imperative to reach a high time synchronization between stations, in order to correlate signals later, consequently the stations time were controlled by GPS timing equipped in each one of them.

B. Site description

The Cerdanya Basin is on the Eastern Pyrenees, and concretely the arrays were situated in Ger town (on the rocky mountain) and in the aerodrome (on the valley), between Ger and Alp towns (fig.2).

The basin is filled with unconsolidated sediments from Tertiary, when originally the basin was formed. Mainly gravel, conglomerates and lutites are the different layers before reaching a rocky basement (limestone and slates) that conform also the surrounding mountains. To determine the depth of the rocky basement is the main goal of this study. There is also the Cerdanya fault quite close from the study area along which the basin was conformed (fig.2, first).



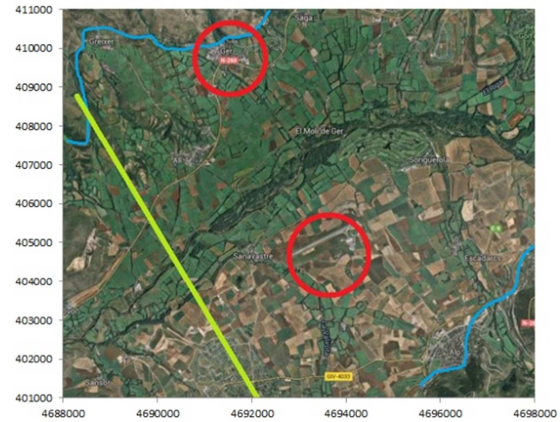


FIG. 2: First: Geological structure profile of region from previous geological works [2]. Red arrows approximate Ger and aerodrome locations. Second: Ger and aerodrome locations (red circles), the basin mountain limits (blue) and the profile showed (green).

C. Seismic arrays and data acquisition

For the F-K technique, the two arrays used were conformed by seven stations for each measure: one in the centre and six around conforming two concentric triangles rotated 60º between them, to cover the most azimuthal directions possible, with two successive radii for each registration. The distance chosen for each radius were 25-55-100-250-400 meters from the central sensor, moving for each measurement the inner sensors to the outer perimeter. Doing this, with seven sensors we can obtain measurements with small and long arrays. As we said in II.C, the wide arrays are good for long wavelengths, which reach deeper layers of the subsoil, and small arrays are good for high frequencies (low wavelengths).

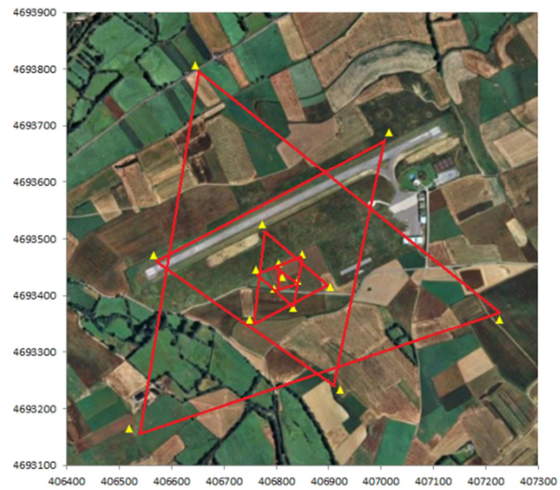


FIG. 3: Final arrays realised in the aerodrome (red). Stations (yellow) expect to be as equidistant from the centre as possible. Absolute coordinates scale [2].

The measurements were done with two different radii simultaneously for each registration (fig.3). Because of the location limitations, the Ger array was able to extend enough for two measurements: 25-55 meters, and 55-100 meters. While in the aerodrome the array reached the 400m of distance: 25-55m, 55-100m, 100-250m and 250-400m.

This method allows using the seismic noise recorded by the F-K method for the H/V study, only activating the horizontal axes registration in each station during the study.

The data acquired in time series of at least one hour for each array, only stopping the recording to move the sensors to form the next bigger triangle. The central sensor kept registering all the time. So, finally, obtaining recordings from one to two hours for each pair of radii, we are able to join all the seismic signals in the data processing to obtain the results of all the arrays, achieving good frequency coverage at the same time we have obtained an acceptable azimuthal coverage.

D. Data processing

F-K data processing required Geopsy, Max2curve and Dinver software. H/V is carried out only with Geopsy.

Geopsy software is used to align the different signals registered in order to detect the wave fronts, and tries to construct the dispersion curve of these Rayleigh waves. The software analyses the signals using time windows, and it give us the option of choosing their wide which in our case was from 1Hz to 4Hz.

The process of the H/V gives us the spectrum in frequency of the subsoil amplification (1). Here, the program also works separating the noise recordings in time windows, which in our case were from 50s to 150s long.

With Max2curve, used for FK method, we can clean the dispersion curve, deleting the false velocity signals out of the main dispersion curve, due to aliasing. Also we superpose the array detection limits to the curve and we cut its mean taking only the reliable part (fig.4, right). This detection pattern only depends on the array extension, so for each pair of array radii we will have different limits.

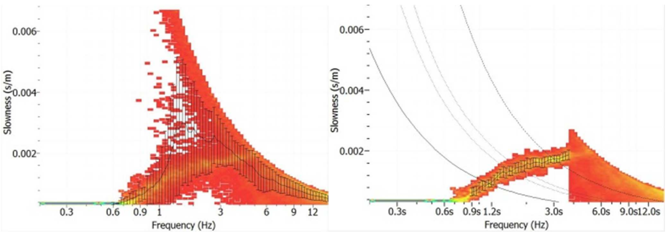


FIG. 4: Processing dispersion curve example in symbolic scale colour. Left: with detection limits without cleaning aliasing. Right: curve cleaned and ready to inversion.

Finally, Dinver does the inversion of the dispersion characteristic, obtaining a shear wave velocity model. It's done by trying different models and finding the misfit of each one compared with the experimental dispersion curve.

IV. RESULTS

A. H/V Results

The spectrum obtained by the H/V analysis shows clearly a different behaviour between the two arrays:

- The aerodrome array shows a peak for the resonant frequency, which median between the stations is 0,43Hz (fig.5, left), with low dispersion between stations.
- The Ger array, on the other hand, is less resolute and the resonant frequency goes from 0,70Hz to 1,28Hz in average (fig.5, right).

The dispersion increases in both arrays if we study lower frequencies than 0,2Hz. It is caused by the sampling rate of the geophones.

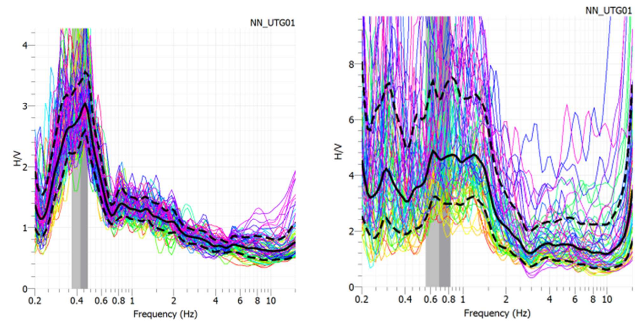


FIG. 5: Left: the 5th station in the 4th ring of the aerodrome. Right: the 5th station in the 2nd ring in Ger array. It is easy to appreciate the difference in peak resolution between locations.

B. F-K Results

The dispersion curves inversion allows us to compare the velocity between the sedimentary layers and the rock basement. As in H/V method, there is substantial contrast between locations:

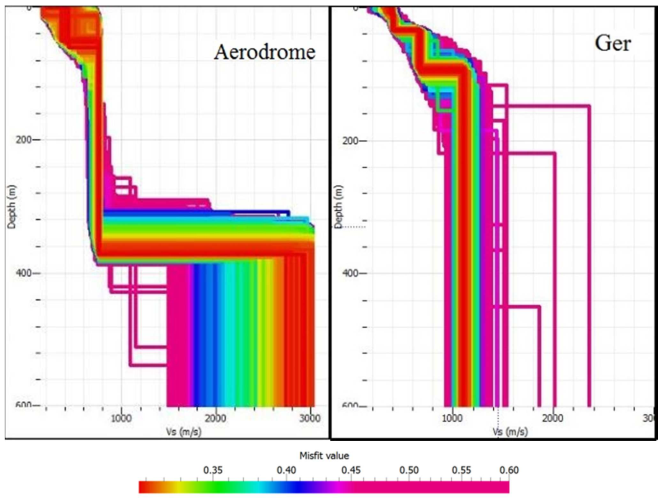


FIG. 6: The two velocity profiles, with the *misfit* scale.

- In the aerodrome we can identify a clear velocity step around the 360m depth. It's observable that the velocity limit for the S waves is around 3000m/sin the deepest layers.
- Ger shows this velocity jump around the 100m, and the velocity limit between 1100m/s and 1400m/s.

C. Combined method

From expression (2), thickness can also be calculated combining H/V fundamental frequency and F-K average velocity of Rayleigh waves, which is referred to the interface between the rocky basement and the sedimentary materials. This last one has been found of 700m/s for the two arrays.

The median for all the stations results:

- 171 ± 18m for Ger and
- 448 ± 62m for the aerodrome.

V. INTERPRETATION

From H/V results, the differences between both locations are easily visible: In Ger array the fundamental frequency is higher than in the aerodrome, so we can assume that rock basement is deeper in the aerodrome. As well, the main amplification remains maximal for a range of frequencies, not just for one as we see on the aerodrome. This can be caused by a 3-dimensional interface topography between rock and sediments: the amplified horizontal waves come from different thicknesses, so H/V detects more than one peak. Seeing that the maximum value is constant along the frequency range, we can consider the fact of being detecting a continuous range of rock depths, like a leaning rocky plane. The geological profile showed in figure 2 predicts this leaning, and the analysis of the frequency limits of the range could provide the depth range observed.

F-K gives us a clearer view of the results in form of graphic. Despite the final rocky bed velocity does not match between locations (around 1200m/s in Ger and above 1400m/s in aerodrome), it is clear there is a big step in some depth in both graphics: 360m and 100m respectively. This is a trusting indicator for the thickness. Also, the velocity of rock in both cases remains above 1000m/s, which is typically rocky (table 1), and then it falls to 800-700m/s. So it can be considered that the step is due to a pass from rock to soft materials, and not another type of materials. Finally, in aerodrome the dispersion makes impossible to obtain a clear rock propagation velocity, which might be caused by the high depths studied.

The more superficial layers that appear in the patterns need to be studied with littler arrays, because of the low resolution of big arrays for low depths (low wavelengths).

The results for the combined method support those obtained with F-K method: in aerodrome, the calculated depth approaches with 88m of misfit to the analogous F-K pattern (448 to 360 meters) and the error covers part of this misfit. This relative high error obtained can be attributed to the low resolution of the 400m array at these high depths. In Ger the difference is similar: combining F-K with H/V the measure goes from 100m to 171m, this time with little error and far to avoid the 71m difference. Despite this, the results have quite similar magnitude and a final clear depth for the basin rocky basement can be approximated at each location.

VI. CONCLUSIONS

- The H/V method presents multiple advantages versus F-K, being able to measure the fundamental frequency of the soil with a single triaxial station. The resonant frequency is a useful indicator of sedimentary layers' thickness in basins. Although, it cannot provide a numeric value for it by itself; we need in this case the wave propagation velocity. Furthermore, sometimes the strong dependence on basins geometry makes it impossible to obtain a single frequency peak, as it can be seen on Ger H/V results, where a leading geometry is found.
- F-K has proved to be an extraordinary tool for subsoil characterisation: in addition to allowing the interpretation of rock depth, it can detect other intermediate layers if the array has sufficient resolution (low distances) as well as if these layers have a wide enough velocity step to be detectable. Also, as part of the procedure, we obtain the noise Rayleigh wave velocity, which can be useful later in the combined analysis.
- The results from expression (2) approximate those with H/V and F-K, and because of the procedure simplicity it is an auxiliary method to consider for characterisation, although it requires a way to estimate the surface waves velocity. So, it is not achievable if we only have a single station.
- A possible extension for the research would be applying the magnetotelluric method, another non-invasive technique, on the same region. It would provide reliable results to compare with, and the added value of obtaining a subsoil 2D profile that would complement the seismic study.

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