"REFRACTION MICROTREMORS (REMI), METHOD FOR DETERMINING SHEAR WAVE VELOCITIES IN THE SOIL AND GPR SURVEY ON THE BARCELONA CAMPUS"

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Abstract

ReMi is the refraction microtremor technique. In contrast to other methods, it provides a simplified characterization of much larger volumes of the shallow subsurface in mono-dimensional profiles of vertical depth.
ReMi is non-invasive and non-destructive technique, does not require any drilling, performed using surface wave (Rayleigh wave) generated by ambient noise, for example by human walk or transit of vehicles in urban areas. Combining seismic refraction method and ReMi, results can be collected by using the same geophone array configuration. The typical ReMi measured geologic material parameter, shear wave (s-wave) velocity, is a function of the module of the various material strata in the subsurface profile. Soil/rock contacts or contrasts between weaker and stronger geologic material horizons can be interpreted from ReMi data. Preliminary subsurface profiles can be developed from this information, and characterization of subsurface profiles between geotechnical borings, test pits and seismic refraction geophysical profiles can be accomplished. Second part of report deals with the practical lesson on the use of GPR equipment and devoted to the detection of buried utilities in an outdoor environment. The processing and interpretation of the collected GPR data through the commercial software REFLEXW is presented, as well.

I. INTRODUCTION

ReMi is a surface-performed geophysical survey developed by Prof. John Louie, based on previously existing principles of evaluating surface waves and in particular Rayleigh waves. Multi-channel Analysis of Surface Waves, or MASW and Refraction Microtremor or ReMi, are two of the most recently-developed surface techniques for determining shallow shear-wave velocity [1].
Both ReMi and MASW acquisition techniques require a linear array of vertically-oriented sensors using traditional seismic reflection/refraction equipment. Depth of investigation for both is primarily a function of array length and sensor resonant frequency. Although a preliminary data interpretation may sometimes be performed in the field, full interpretations are completed with a post processing of stored data.
(GPR) Ground Penetrating Radar is nowadays recognized as one of the most powerful, versatile and robust instruments for performing large-scale subsurface investigations [6]-[8]. Its main applications are the localization of buried pipes and services, as well as the detection of man-made or natural changes in the undersoil stratigraphy and the investigation of archaeological sites. It works by

generating an electromagnetic e.m. signal that is transmitted towards the soil by single or multiple transmitting antennas. Each discontinuity in the dielectric characteristics below the surface produces a reflection of the incident e.m. waves, and part of this scattered energy reaches the receiving antenna(s). Then, the collected radargram gives the user the possibility to detect the presence of buried obstacles in a completely non-invasive manner [4]-[5].
In order to promote throughout Europe the effective use of this safe and non-destructive inspection method, COST Action TU1208 focuses on the exchange of scientific-technical knowledge and experience of GPR techniques in Civil Engineering. Within the recent activities carried out during the life-time of the Action, a Training School on Non-Destructive Testing techniques applied to civil engineering was organized in Barcelona, Spain, on March 14-18, 2016 [4]-[5].
Besides some theoretical lessons on the basic principles of GPR and its use in Non-Destructive Testing, one practical lessons were devoted to familiarize the trainees with off-the-shelf GPR equipment. The practical training considered locating subsurface utilities and detecting voids with GPR, as well as the processing and interpretation of the collected GPR data [4]-[5].

II. Seismic wave

There are three main types of seismic waves: P-wave, S-wave and surface waves. P and S waves together are sometimes called body waves because, they can travel through the body of the earth, and are not trapped near the surface.

A P-wave is a sound wave traveling through rock, the particles are alternately squished together and pulled apart (called compressions and dilatations), so P-waves are also called compressional waves. Generally these waves can travel through solids, liquids, and gases. Figure 1.

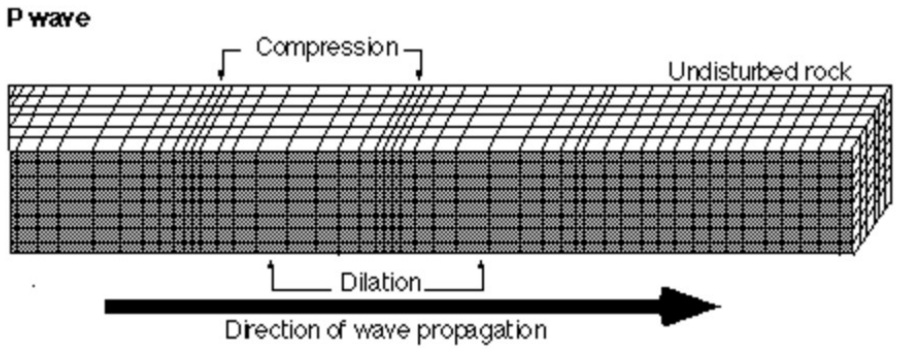


Fig. 1 – Model of P-Wave

S-wave or shear wave (sometimes called elastic S-wave) and is one of the two main types of elastic body waves.

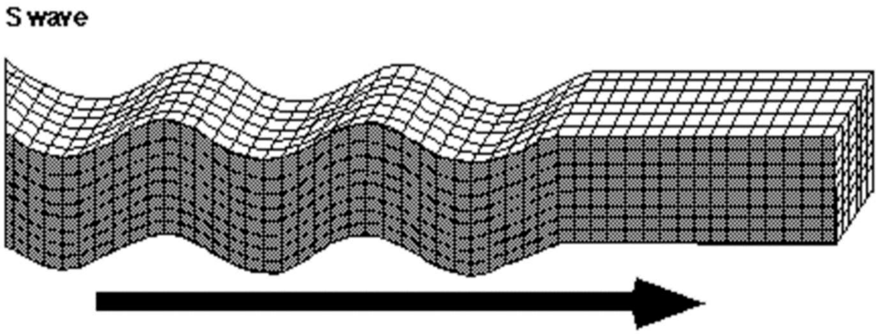


FIG. 2 – Model of S-Wave

The name S, is for secondary, comes from the fact that it is the second direct arrival on an earthquake seismogram, after the compressional primary wave, because S-waves travel slower in the rock.

Rayleigh waves are a type of surface wave that travel near the surface body of the earth. Rayleigh waves include both longitudinal and transverse motions that decrease exponentially in amplitude as distance from the surface increases.

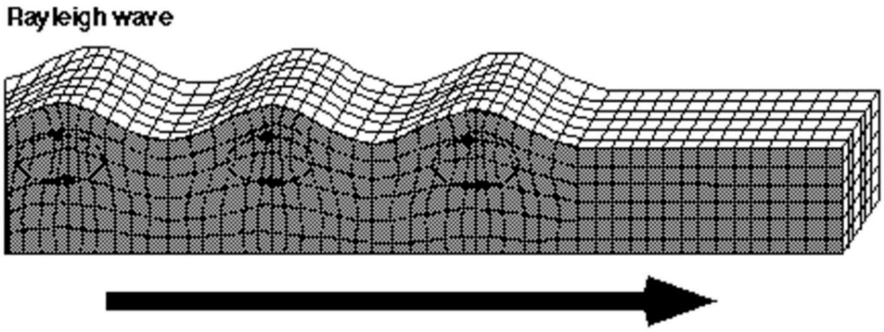


FIG. 3 – Model of Rayleigh-Wave

Seismic Refraction: The seismic refraction method, is performed by the measurement of the travel time of seismic waves, which are refracted at the interfaces between layers (L1) of different velocity. Seismic energy is provided by a source (S) located on the near surface and radiated out from the shot point energy, either travelling directly through the upper layer (direct arrivals), or travelling down to and then laterally along different velocity layers (L1) as refracted arrivals toward an array of geophones positioned in predetermined locations on the surface (G1, G2, etc.). Observation of the travel-times of the refracted signals provides information on the depth profile of the refractor.

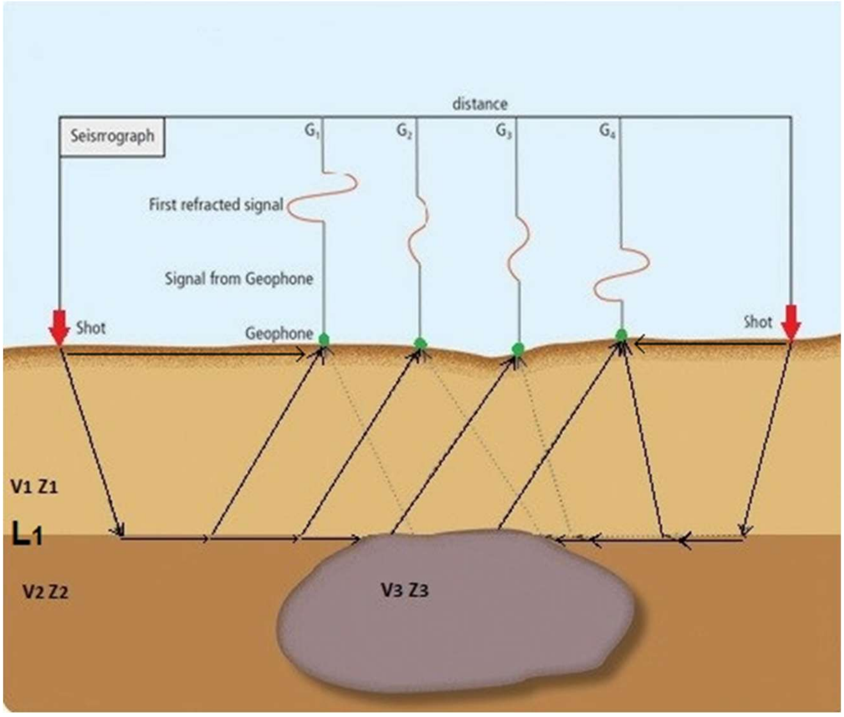


Fig 4 – Seismic Refraction Method

Refraction Microtremor: in the Refraction Microtremor method (ReMi), surface wave (Rayleigh wave) energy, generated using a passive (background) acoustic source, is recorded at predetermined receiver locations (R1, R2, etc.). A dispersion curve (phase velocity vs. frequency), generated from the acquired field data, is inverted and used to generate a 1-D shear wave velocity profile (generally "tied" to the physical centre of the receiver array). If additional ReMi data sets are acquired at adjacent locations, 2-D or 3-D shear-wave velocity models can be created. If environmental and structural features are known, these shear wave velocity models can be transformed into geological models. The ReMi technique is often used in tandem with the more traditional MASW technique as it enables to ability to gain information on subsurface dynamic moduli and shear wave velocity to greater depths than are achievable using MASW. However, as depth of investigation increases, spatial resolution decreases.

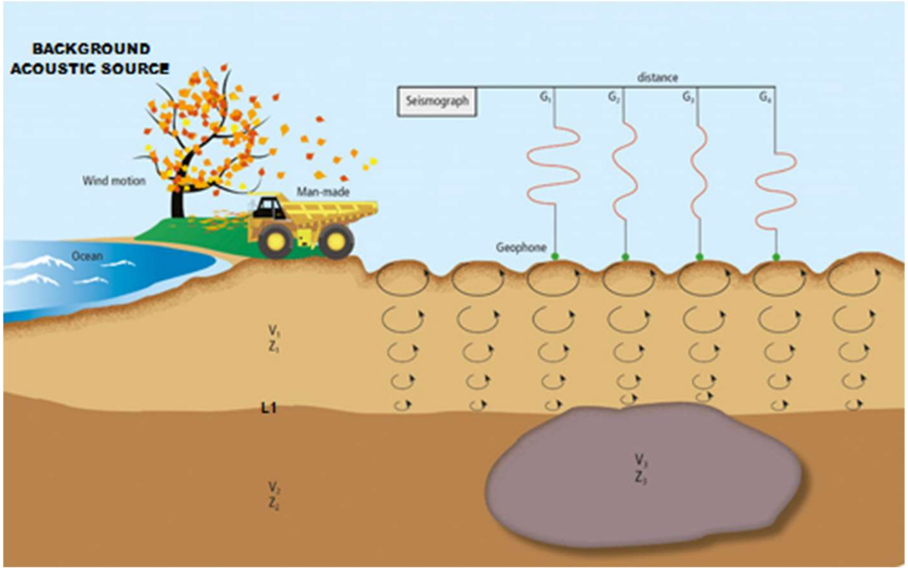


Fig 5 – Refraction Microtremor Method

III. ReMi Seismic Equipment in the Barcelona Campus

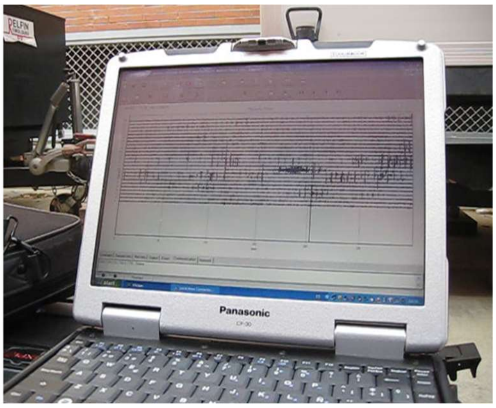
The equipment used in this environmental survey listed below in Figure 6.

a) Multi channel Seismograph, 1-D & 2-D shear wave velocity profiling to 30m+
b) Power supply (battery 12 V and power control system)
c) 12 channels geophones cables
d) Vertical geophone sensor with resonant frequency at 4.5 Hz
e) Traces on laptop
f), g), h) Detail of cables and sensors in the operating scenario

(a)

(b)

(c) (d)



(e) (f)

(g) (h)

Fig 6 – Equipment Used

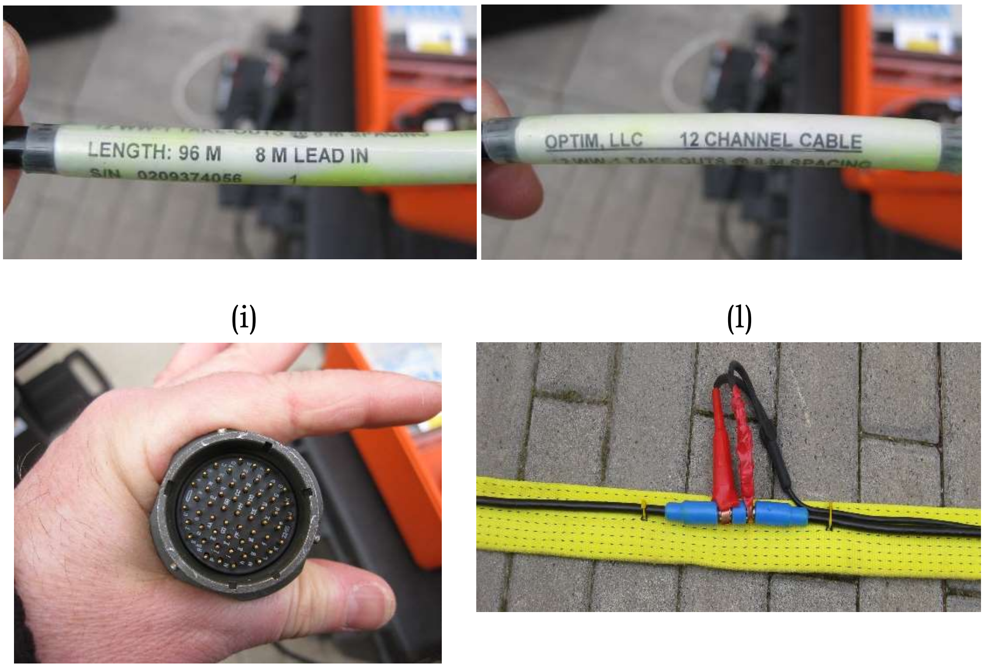
The standard of multichannel seismograph, has a capable of storing up to 16.000 samples per channel at sample intervals as long as 1 to 2 milliseconds in specific SEG2 or SEGY format can be used to collect ReMi data. In our particular case of study the system setup was:

1. Time window of acquisition data: 30 seconds

2. Sampling interval: 1 millisecond
3. Two geophone cables (12 channels) of 96 meters length each, with 12 geophones each, 8 meters spacing.

In Figure 7, are displayed some details of the cables.

i) Multi channel cables
l) Multi channel cables
m) Multi channel cables connector
n) Supply connectors



(i) (l)

(m) (n)

Fig 7 – Cables and Connectors Used

IV. REMI PROCEDURES

Once the system was mounted with the exact setup, a primary test needed, was the verify of correct functioning of all geophones. If the system provides a positive response, so is possible to start data acquirement.

Is possible to combine ease ReMi and the SASW (Spectral Analysis of Surface Waves) technique, with high resolution typical of MASW (Multi-channel Analysis of Surface Waves) measures obtaining good performance.

The principle of SASW and MASW techniques is associated with the dispersive nature of Rayleigh waves when they cross stratified half. In particular the dispersion occurs when different frequencies travel at different speeds, based on this hypothesis is possible by analyzing typical frequency ranges, to define the acoustic properties of soil at various depths.

The SASW examination consists of measuring the phase velocity of surface seismic waves for different wavelengths. These measurements are used to

estimate the dispersion curve of the site studied. The phase velocities are extracted by means of direct comparison of the amplitude spectrum of each pair of seismometers.
The resonant frequency of geophones is 4.5 Hz and the typical recording time of the system is 30 seconds. Using A/D converter high accuracy (with a typical dynamic range of about 100-140 dB) is possible to record frequencies as low as half the resonant frequency of the geophones (2.25 Hz). The bandwidth of the system is (2-25 Hz), sufficient to define the profile of shear-wave velocities, extended to about one hundred meters deep.
In the first analysis a rough elaboration has been made by the seismograph system, data files are transferred from the seismograph to the interpreting computer, by using the current SeisOpt ReMi software package Version 4.0.

This software works in two modules:
In the first module: Vspect [2] the recorded traces are converted from domain *x-t* (distance-time), see Figure 8, to the domain *p-f* (slow-frequency), see Figure 10, in which the power spectrum is clearly visible,

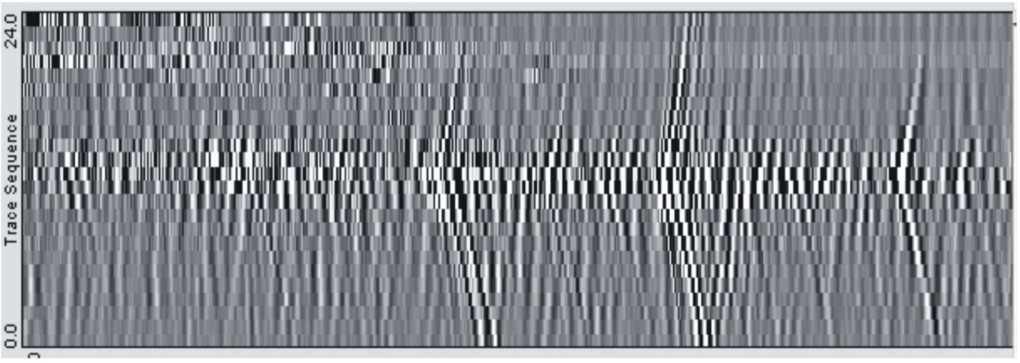


Fig. 8 – Example of Trace Sequence, *x-t* domain. Traces of 24 geophones in the time window of 30 seconds

The conversion from *x-t* domain to *p-f* domain, is carried out by the following procedure:

Transformation: $(x,\ t) \Rightarrow (p,\ \tau)$

$$A(p,\tau) = \int_X A(x, t = \tau + px)dx$$

$$p = \frac{dt}{dx} \qquad \text{(Slowness, Inverse of apparent velocity)}$$

Next step is to make a discretization time space of the observed domain, as shown in Figure 9.

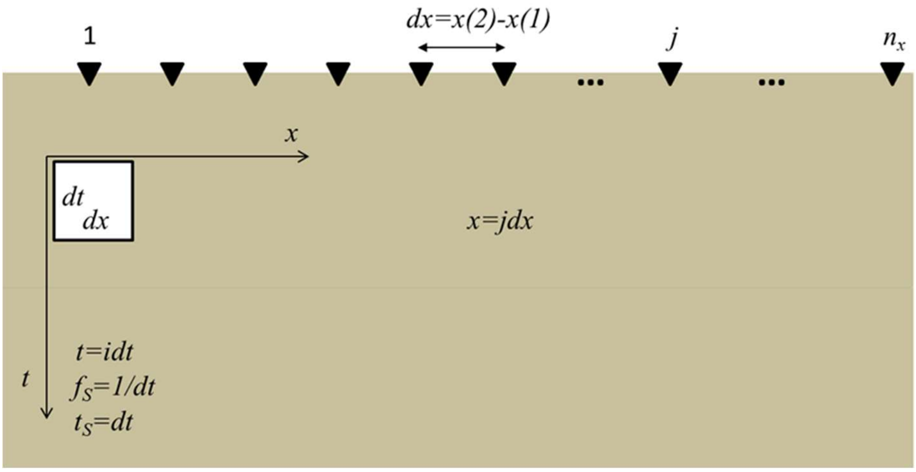


Fig. 9 – Discretization of Observed Domain

By replacing the variables, the equations are:

$$\begin{cases} x = jdx \\ t = idt \end{cases}$$

$$\begin{cases} p = p_0 + l\,dp \\ \tau = k\,dt \end{cases}$$

For each trace *(p,τ) is:*

$$A(p = p_0 + l\,dp, \tau = k\,dt) = \sum_{j=0}^{n_x-1} A(x = jdx, t = \tau + px)$$

Second transformation: *(p,τ)⇒(p,f)*

$$FFT\,[A(p,\tau)] \Leftrightarrow S_A(p,f) = F_A^*(p,f) \cdot F_A(p,f)$$

The total power spectrum is given by:

$$S_{TOT}(p,f) = \sum\nolimits_n S_{An}\,(p,f)$$

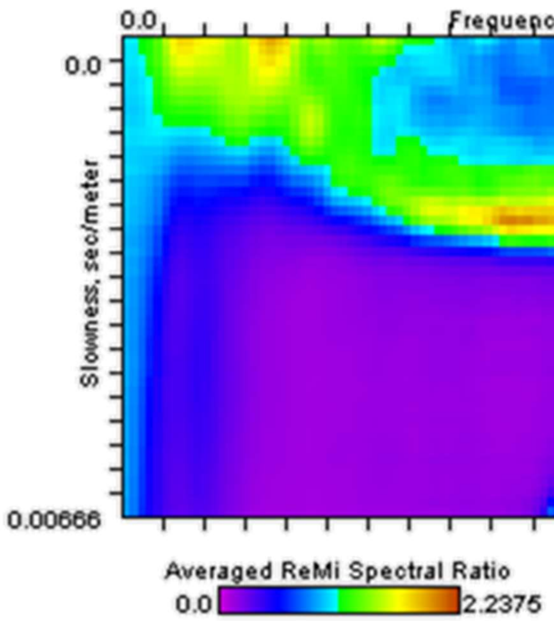


Fig. 10 – Power Spectrum in the *p-f* Domain

After choosing the *(p,f)* domain image that displays the most coherent Rayleigh-wave dispersion, the next step is to pick the dispersion curve and save the picks for input into the interactive velocity-modeling (second module), SeisOpt ReMi Disper.

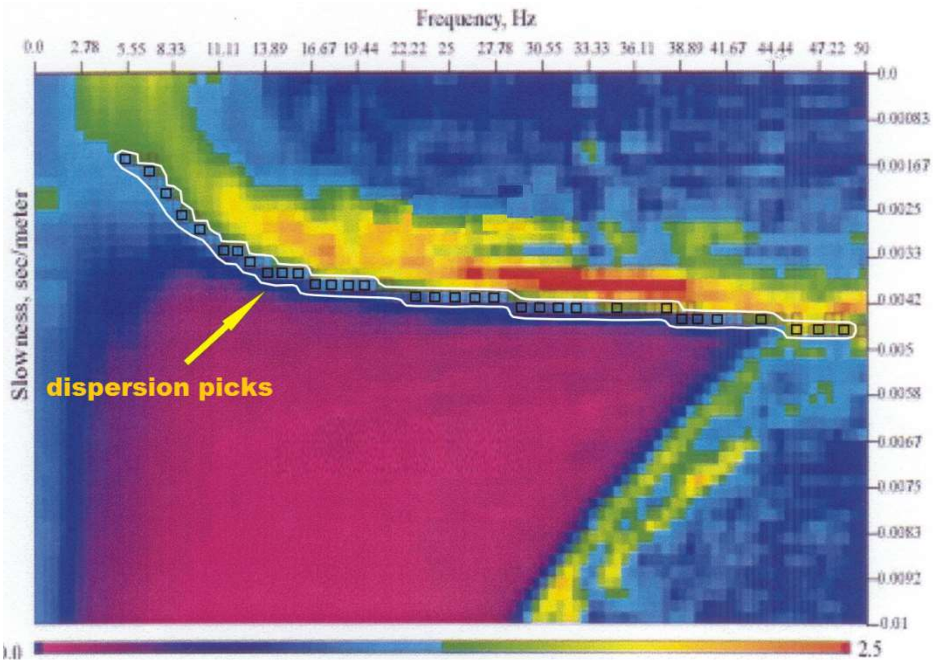


Fig. 11 – Picking of the Power Spectrum in the *p-f* Domain

The operator then selects a dispersion curve consisting of the lower bound of the spectral energy shear wave velocity versus frequency trend.

The picking operation is carried out along the envelope with the slowest velocity because provides the best accuracy of sampling of the Rayleigh fundamental wave to avoid the sampling of environmental noise.
The second module allows the operator to model a dispersion curve diagram with multiple layers and s-wave velocities by using SeisOpt ReMi Disper [2].

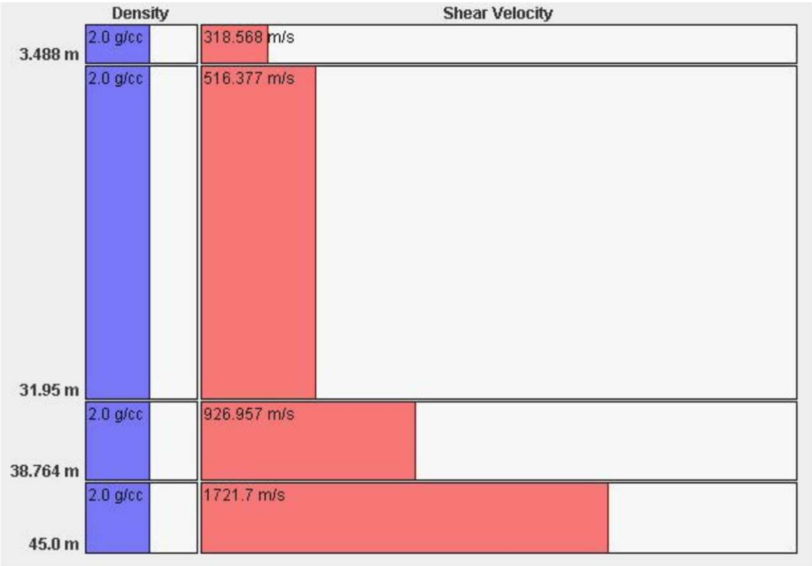


Fig. 12 – Bar Graph of SeisOpt ReMi Disper Module

The operator interactively varies layer velocities and depths until the resulting dispersion curve best matches the previously selected dispersion points of Figure 11.

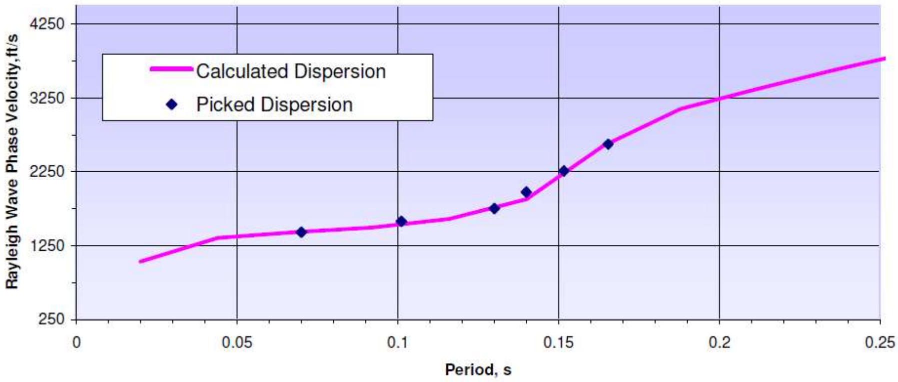


Fig. 13 – Comparison Between Calculated and Picked Dispersion Curve

V. GPR Survey

Dr Vega Pérez-Garcia gave instructions to the trainees on how to carry out the survey. During survey were used Mala GPR system with two types of shielded antennas 250 MHz and 500 MHz. Trainees used GPR around the building to detect utility.

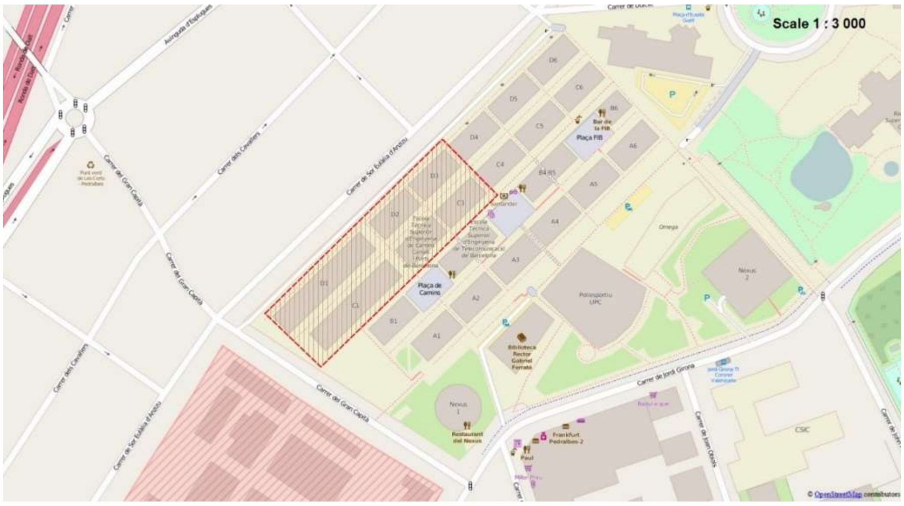


Fig. 14 – Survey area - Campus Nord, Universitat Politècnica de Catalunya

Fig. 15 – Dr. Vega Perez-Garcia describing GPR system

Fig. 16 – GPR mounting

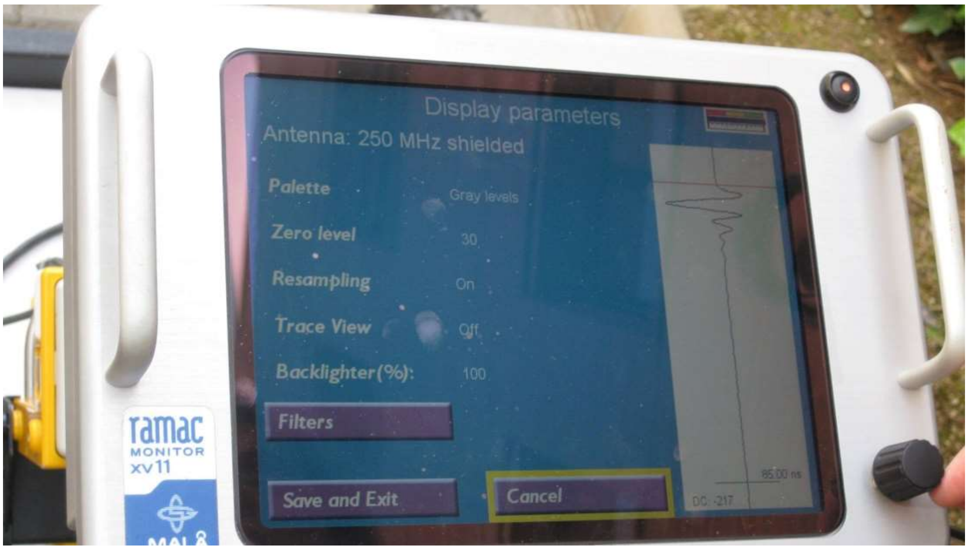


Fig. 17 – Survey parameters

Fig. 18 – During survey

VI. GPR DATA PROCESSING AND INTERPRETATION

After lunch during next session acquired data was imported inside the commercial software REFLEXW by considering Mala input file format and a 32 bit floating point output format. Unfortunately data collected in the university was in time mode. During the processing session were taken decision to use other data collected before in archaeological purposes.

As a preliminary processing, the first temporal part of the collected traces was removed by accurately determining the zero time in the "Wiggle Window" View. Next procedures 1D Dewow, Gain, Background Removal (2D), Bandpass butterworth (100 MHz – 800 MHz), final Kirchhoff Migration (100 traces, velocity0.06 m/ns) [9], [5].

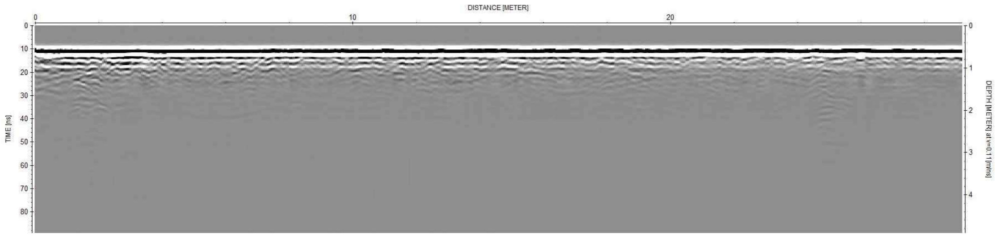


Fig. 19 – Imported raw data to ReflexW

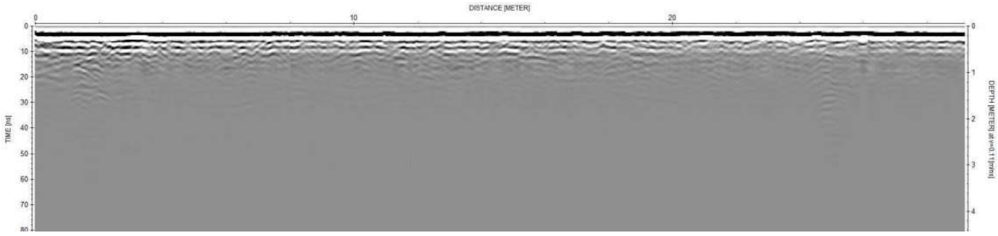


Fig. 20 – Move startime 8 ns

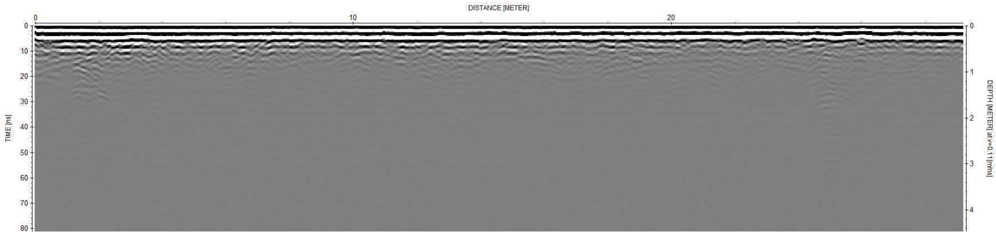


Fig. 21 – Dewow 2 ns acc. To 500 MHz antenna

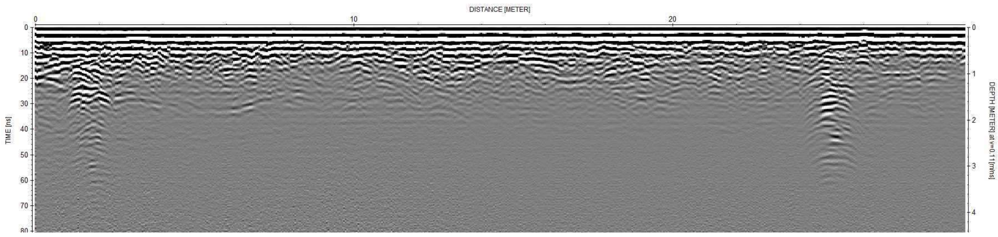


Fig. 22 – Gain function

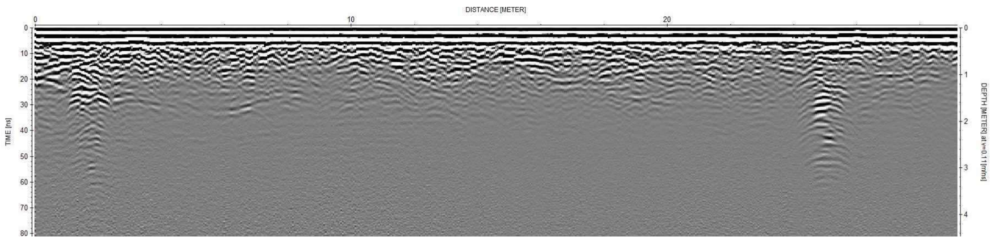


Fig. 23 – Background removal

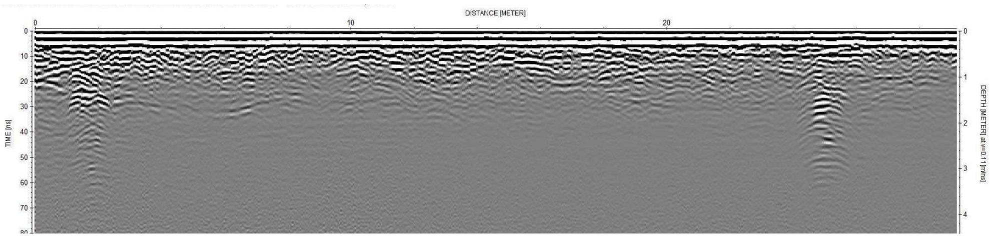


Fig. 1 – Bandpass butterworth 100 - 800 MHz

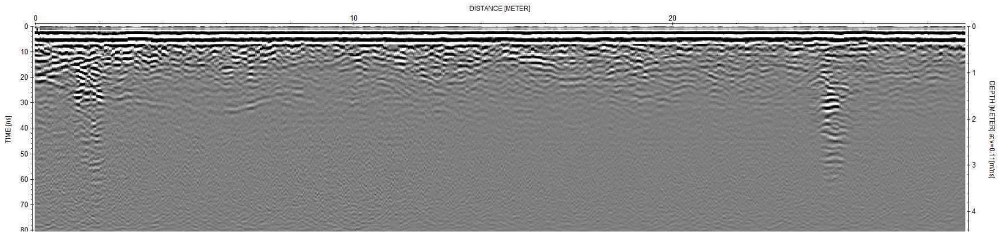


Fig. 25 – Kirchhoff migration, 100 traces, velocity 0.06 m/ns

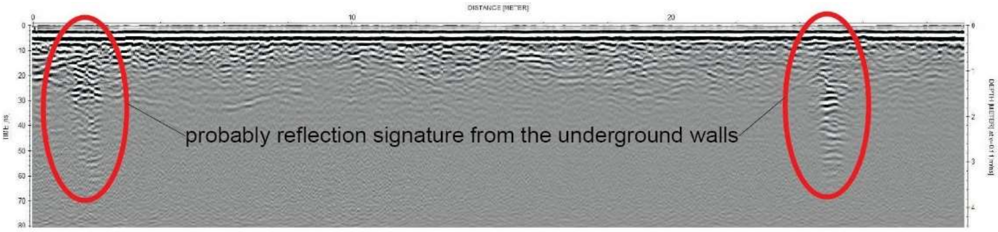


Fig. 26 – Two walls which can indicate old building structure

VII. GPR CONCLUSION

Ground Penetrating Radar method is one of the most powerful electromagnetic tools for imaging subsurface area. Depending on what we expect to image, we have to carefully choose antenna frequency which is directly connected to the depth of survey and resolution [4].

However, even though the GPR is an excellent em. wave method, in some cases it is useless due to high conductivity of shallow subsurface layers, wet or strong saline ground, where wave is strongly attenuated. It is important to remember that GPR method has restrictions and in some cases we cannot apply it [4]. Survey is the first step of GPR imaging. The next most important thing is processing and interpretation of the data. Processing uses advanced algorithms to filter coherent and non-coherent noise, signal gain, spherical divergence compensation, frequency filtration, FK analyses and many others. Final step is migration, which is the most advanced computational method to move reflection to proper position on the radar sections. Of course, these are some examples of processing procedures; in the Reflexw processing software we can find hundreds of procedures which satisfy the most demanding users [4], [9].

Interpretation mostly covers recognition and description of what we actually imaged. We can present data in a flexible way in B-scan and 3D distribution, generate cross sections of whatever we want, timeslices and many other spatial plots [4].

This method is commonly used in environmental engineering, geology, archeology, forensic investigation, mineral exploration and others, where the need to use non-destructive method arises. GPR is a fast and efficient method which can be used instead of, e.g. expensive and destructive drilling methods. This method is constantly under dynamic development, as it can be seen by the increasing number of manufactures producing GPR equipment and the numbers of scientists involved in researches. Year by year, we can see the rapid growth of market and many new commercial purposes [4].

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