Geotechnical site characterization of a flood plain by refraction microtremor and seismic refraction methods

Javier Olona-Allué
Javier A. Pulgar
Gabriela Fernández-Viejo
Juan M. González-Cortina

Departament of Geology, University of Oviedo. Oviedo, Spain
CONSOLIDER Team “Topo-Iberia”

Abstract

The objective of this study was the evaluation of quality $V_S$ models generated by refraction microtremor method (ReMi) testing 3 different seismic sources (1 passive and 2 active ones), and its comparison with $V_P$ models generated by seismic refraction tomography, in the geotechnical site characterization of a flood plain where 2 boreholes and 12 test-pits had been done in a previous geotechnical study.

Nine seismic profiles were deployed with different receiver spacing (60 geophones of 10 Hz spaced 2, 1 and 0.5 meters). In each of the lines we acquired data from ambiental noise and sledgehammer hits at the beginning and the end of the seismic line to model 3 $V_S$ profiles and one seismic refraction profile to model $V_P$ data.

The ReMi and seismic refraction methods gave us good results. On the whole, both $V_P$ and $V_S$ models allowed a complete geotechnical characterization of the flood plain. All the geophysical models were compared with the geological data profiles from boreholes and test-pits and permitted a 3-D overview of the study site.

Introduction

Due to its relatively simplicity and big reliability, seismic refraction has been the seismic method preferred to study shallow subsurface in the last decades (Lankston, 1989; Boadu and Long 1996; Rucker, 2002). This method uses first arrivals of seismic waves (in this study P wave) to provide a two-dimensional velocity profile in which it is possible to interpret subsurface horizont depths and geometries. However, the method has intrinsic limitations such as its inability to detect velocity reversals and poor s/n ratio in places with high ambiental noise.

Recently, Louie (2001) developed the refraction microtremor method which is based in the study of surface waves dispersion phenomena to model a one dimensional $S$ wave velocity profile (like SASW (Nazarian and Stokoe, 1984) or MASW (Park et al., 1999)) situated in the center of a geophone array. In this study surface waves were provided by an active source (sledgehammer or weight-drop), a passive source (ambiental and cultural noise) or both. The advantages of the ReMi method are its reliability in places with high ambient noise, and its capacity to detect velocity reversals. The acquisition is performed at the surface using the same conventional seismograph and vertical P-wave geophones used for refraction studies, allowing the recording of a $V_S$ and $V_P$ profile without the need of other type of seismic survey. This fact provides us easily $V_P$ and $V_S$ profiles where the different geological materials who conform the subsoil can be interpreted in base of their $V_P$ and $V_S$ velocities as well as, their geometries and distribution and their poisson ratio.

The principal objective of this study is the evaluation of quality 1 D $V_S$ profiles generated by refraction microtremor method (ReMi) testing 3 different seismic sources (1 passive and 2 active ones), and its comparison with 2 D $V_P$ models generated by seismic refraction tomography, in the geotechnical site characterization of a flood plain.
Geological settings

The study area is a flood plain, in the central zone of the province of Asturias (North of Spain), between the localities of Las Caldas and Caces (figure 1). In this area the alluvial deposits (sands, gravels and cobbles) are settled over a basement composed by the Valdateja Formation who consist of grey and ochre massive carboniferous limestone of fine grain that are affected by a high degree of karstification (Gutiérrez Claverol and Torres Alonso, 1995) either in the form of little dissolutions (decimetrics dimensions) to quite large skinholes (metrics dimensions).

We had geological information for twelve test-pits and two boreholes that provided direct data about the materials that compound the alluvial deposits and their disposition (figures 2 and 3). In all of them, it was differentiated a superficial topsoil (layer 1) with thickness of 20 to 50 cm over sands of medium to fine grain with silt (layer 2). Under these deposits a layer of cobbles and gravels (up to 40 cm diameter) (layer 3) was reached up to a depth of 13 meters (in borehole S1). In some sectors of the study zone (test-pits 5, 8, 9 and 12) a transit layer appears between sands and cobbles and gravels composed by gravel and sands. The limit between layers 2 and 3 is very irregular appearing at depths of 0.8 meters (C11) to 5 meters (S1), although in general, the thickness of layer 2 increases to the east.

Figure 1: Localization of study area.

Figure 2: Geological squeme of test-pits (C1 to C12) and boreholes (S1 and S2) made in the zone of study.
Figure 3: Location of test-pits, boreholes and seismic profiles in the study area.

**Acquisition and processing**

Nine combination seismic refraction and ReMi surveys (figure 3) were acquired using a Geometrics Stratavisor NX seismograph and 60 geophones of 10 Hz natural frequency. The geophone spacing vary from one line to other. Receiver spacing of lines 1, 2, 6, 7 and 9 was 2 meters (length of 118 meters), receiver spacing of lines 3, 4 and 5 was 1 meter (line length of 59 meters) and receiver spacing of line 8 was 0.5 meters (line length of 29.5 meters).

**Seismic refraction**

In seismic refraction acquisition, each seismic profile data was registered with a record length of 0.5 s with a 0.5 ms sampling interval, -10 ms pretrigger and 48 dB preamplifier gain. The source used was strikes of a sledgehammer of 9 kg on an iron plate. Shot points were made outside the recording array at maximum offsets of 50 m as well as inside the array (figure 4). In general, for lines with 2 meters receiver spacing (lines 1, 2, 6, 7 and 9) the source spacing was 10 meters, except in line 9 where it was 20 meters, and lines with 1 meter receiver spacing (lines 3, 4 and 5) the source spacing was 5 meters. In line 8 (0.5 spacing receivers) shot interval was 5 meters while inside the geophone
array and 10 meters when outside of the array. Seismic data showed a high quality signal of refraction waves that allowed accurate picking of first arrivals (figure 4).

![Seismic data](image)

**Figure 4:** Seismics profiles acquired and P wave first arrival time of line 3. Traces in meters 6, 20 and 45 shown high electronical noise make impossible the right record of seismic signal.

Modelling was made with tomography software SeisOptPro™ based in a nonlinear optimization method called simulating annealing (Pullammanappallil and Louie, 1994). The program uses first arrival travel time data and geometry acquisition as input (being not necessary an initial model) to model 2D seismic velocity profiles who can show velocity gradients in horizontal and vertical directions.

**Refraction microtremor**

Three different acquisitions were done depending of the source type used and its position. In the first one, ambiental noise (cultural and ambiental noise) was used as source. They were acquired 10 records with 30 seconds length, 2 ms sampling interval and 48 dB preamplifier gain. In the second and third acquisitions an active source was used (3 to 6 strikes of a sledgehammer of 5 kg in a iron plate in each record) at the beginning and at the end of the seismic line respectively. In both cases 10 records were acquired with 30 seconds length and 2 ms sampling interval. In order not to reach saturation in traces a preamplifier gain of 36 dB, was used in active sources. Source-reciever distance in all lines was 10 meters.

Seismic data processing and modelling was performed using the software SeisOpt® ReMi™. This software uses two modules:

- Module ReMiVspect: seismic field data are transformed into p-f spectrums (slowness-frequency) through 3 steps (Louie, 2001): a p-tau transformation or “slant stack” (Thorson and Claerbout (1985)), a Fourier transformation and spectral analysis. Then, fundamental dispersion curve trend of Rayleigh waves was delineated in p-f spectrum by point picks.
- Module ReMiVDisper: S waves velocity profile modelization by a curve manually adjusted to the point picks generated in module ReMiVspect. The program calculates automatically the 30 m average shear-wave velocity ($V_{S30}$), value in which the IBC (International Building Code) soil classification is based.

**Results**

*Refraction microtremor*

At the beginning in refraction microtremor three p-f spectrums corresponding to the three types of source were tested for each line, to determine which source gave the best results. In the p-f spectrum obtained for passive source, the signature of the fundamental dispersion curve of surface waves was continuous in the frequency range of study permitting to determine its trend accurately (figure 5). In the case of the active source, trends of fundamental dispersion curves in p-f spectrums are determined but their signature in low frequencies was more uncertain than in the passive source spectrums. It was observed that active sources increased the signal of higher modes masking the fundamental mode and, in some cases, obliterating totally the fundamental one. Another observation was that in general, for one line, the p-f spectrum obtained with active source applied at the beginning and the end of the line was similar, but in some cases (line 1) one showed the fundamental mode curve and the other one only showed the higher modes. This characteristic could be produced by a localized site effect because in both cases the source and source-receiver distance used was the same. Based on these results the passive source data were chosen for the $V_S$ modeling.

Fundamental curves of surface waves were determined in p-f spectrums in frequency ranges of 8 to 45 Hz and phase velocities of 110 to 900 m/s. $V_S$ profiles were obtained for all the lines except for line 5 where fundamental mode curve was not recovered in any of the three spectrums.

![Comparison between p-f spectrums obtained for line 1 and 6.](image)

*Figure 5:* Comparison between p-f spectrums obtained for line 1 and 6.
Modelled $V_S$ profiles of all lines are very similar, with comparable interface depths and layer velocities (figure 6). They show a superficial layer with $V_S$ of 112 to 121 m/s who correspond with sand velocities, a medium layer (259 to 328 m/s) that appears at depth of 2.3 to 2.6 m who S waves velocities correspond well with gravel and cobble materials and a third layer (velocities of 1133 to 1257 m/s) that appears at 7.8 to 8.2 meters depth with high S wave velocities who may correspond to bedrock (limestone). Maximum depth of investigation is between 45 (for largest arrays) to 18 meters (for the smallest array). It was calculated with the formula $Z_{\text{max}} = C_1/(2 f_1)$, where $Z_{\text{max}}$ is the maximum depth investigation, $C_1$ is the phase velocity of surface wave at the frequency $f_1$, and $f_1$ is the lowest frequency analyzed.

Lines 1, 2, 6, 7 and 9, with depth investigation larger than 30 meters enabled the site classification by the IBC (BSS, 1998) code (based in $V_{S30}$), as very dense soil and soft rock (site class C).

Figure 6: $V_S$ profiles of all lines.

Seismic refraction

In all lines, according to P wave velocities obtained in seismic refraction results were interpreted 4 horizonts (figure 7):

a. A superficial layer with velocities between 100 to 300 m/s consistent with sands (layer 2).

b. A second layer with velocities between 300 to 900 m/s that appears at depth of 2 to 3 meters that correspond with gravel and cobble material (layer 3).

c. A third one with velocities between 900 to 1800 m/s that appears at depth of 5 to 7 meters. In this case P wave velocities could indicate relatively competent material or an alluvial saturated material below the groundwater table.

d. The last layer with velocities between 2000 to 3500 m/s in general appears at depth of 7 to 10 meters, except in the begining of line 2 and in the central zone of the line 3, where a skinhole exist that displace this layer at maximums depths of 16 meters. P wave velocities correspond to limestones affect by karstification.

Limits between layers defined are subhorizontal with some minor irregularities (1 to 3 meters) only broken in the zone of the skinhole.

The maximum depth of investigation depends on the length of seismic lines, being 17 to 22 meters for lines with lengths of 118 m, 12 to 15 meters for lines with lengths of 59 m and 11 meters for the line with length of 29.5 m.
Comparison VS and VP models

Comparison of \(V_P\) and \(V_S\) models for each seismic line shows that both are very similar. The two contacts of layers modelized in \(V_S\) models match well with two of the three contacts interpretated in the \(V_P\) models (figure 7), but P wave velocities show an increase at 5-6 meters depth that does not appear in the \(V_S\) profiles. Taking into consideration that P wave velocities are profoundly affected by fluid saturation (water table), and S wave velocities are softly affected by it, the difference between both sets of values could be the result of the presence of the water table at this depth. The interfaces that match in \(V_S\) and \(V_P\) models have been interpreted like changes on lithological characteristic (figure 8). First interface may indicate the sand - gravel and cobble contact and the second one would mark the alluvial - bedrock contact.

With this final interpretation a 3D geological model was created (figure 9) permitting an overview of the study site where the interfaces interpreted are subhorizontal except in the referred area of the skinhole in the north.

Finally having \(V_P\) and \(V_S\) values for each layer we could proceed to calculate poisson ratio for alluvial and bedrock materials (table 1).

<table>
<thead>
<tr>
<th>Material</th>
<th>(V_P) (m/s)</th>
<th>(V_S) (m/s)</th>
<th>(V_P/V_S)</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>300</td>
<td>114</td>
<td>2.63</td>
<td>0.42</td>
</tr>
<tr>
<td>Cobble and gravel dry</td>
<td>700</td>
<td>280</td>
<td>2.50</td>
<td>0.40</td>
</tr>
<tr>
<td>Limestone</td>
<td>2300</td>
<td>1150</td>
<td>2.00</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 1: Poisson ratio of each material calculated by \(V_P\) and \(V_S\).
**Figure 8:** Comparative between $V_P$ model and $V_S$ models and geologic interpretation based on both at line 1. Discontinuous and dotted line are interpreted interfaces in seismic refraction. The discontinuous line with a triangle marks suspected groundwater table.

**Figure 9:** Contour depth map of limit between alluvial deposit and bedrock (limestones).

**Conclusions**

Application of seismic refraction and refraction microtremor methods in the study of a flood plain have demonstrated to be very useful. Acquisition data of both methods was made with a standard seismic refraction equipment, permitting to acquire in a day (for two lines) the necessary data to model $V_S$ and $V_P$ profiles.
We have created a 2D and 3D geological model where we can observe the depth and distribution of different alluvial materials that form the flood plain, including bedrock and groundwater table. This model fits accurately to geological features observed in the field with direct test pits and boreholes.

Active and passive sources were tested for ReMi method determining that in p-f spectrums obtained with passive sources the fundamental mode curve of surface waves were much better represented than in the ones obtained from active sources.

Acknowledgments

The present work has been supported by the project MFOM-06-1 funded by the Ministry of Public Works of Spanish Government (National Program of Construction, R & D National Plan 2004-2007), and by the Consolider-Ingenio 2010 Programme under project “Topo-Iberia” CSD2006-0041. During this work Javier Olona Allué enjoyed a Ph. D. grant awarded by Ministry of Education and Science. We are grateful to Gregorio del Santo and the company CADESA for providing us the information of test pits and boreholes.

References


