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 differents 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 borehole and 12 test-pits had been done in a previous geotechnical study.

Nine seismic profiles were deployed with different reciever 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 prefered 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 posible to interpret subsurface horizont dephts and geometries. However, the method has intrinsic limitations such as its unability 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 adquisition 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 whithout 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 differents 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, graves and cobbles) are settled over a basement composed by the Valdeteja 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).

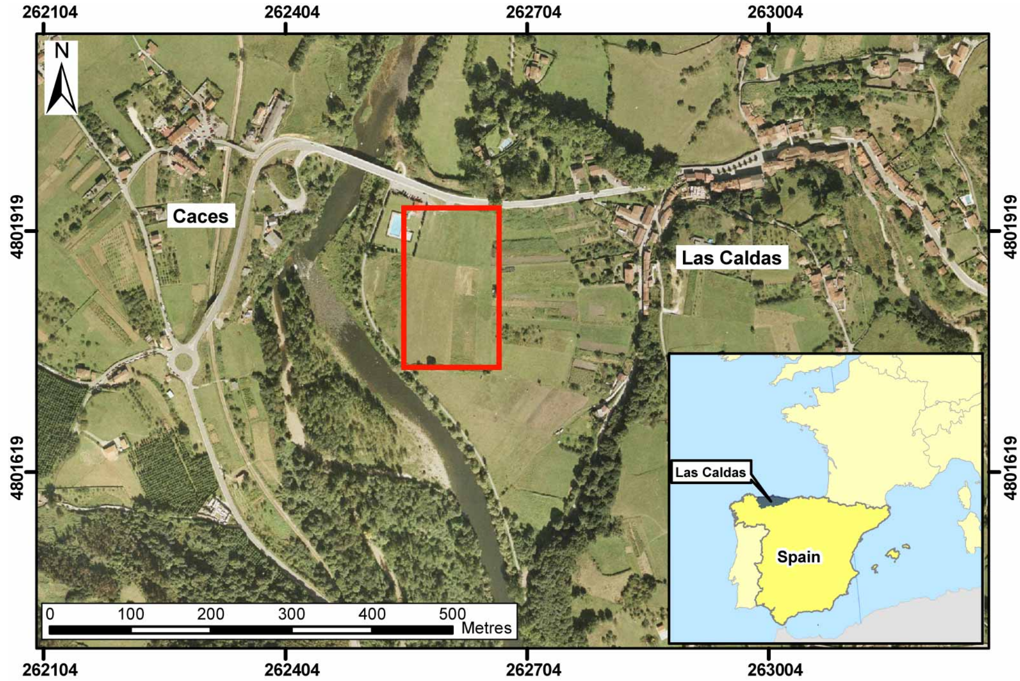

Figure 1: Localization of study area.

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 diametre) (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.

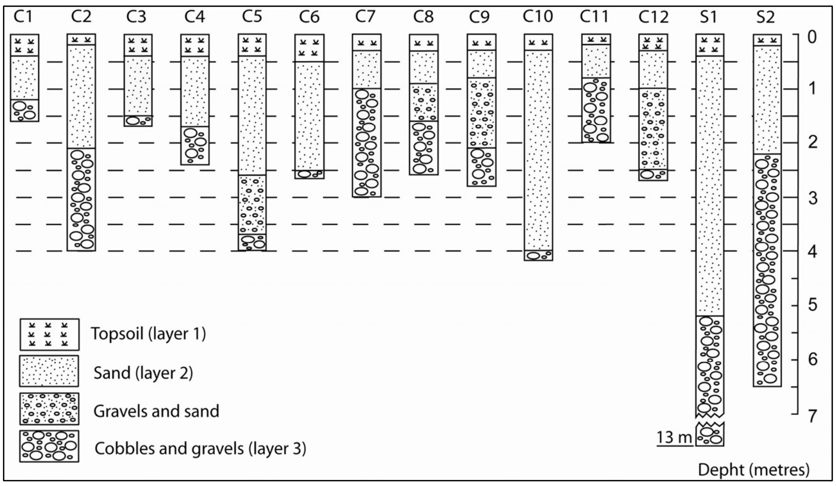

Figure 2: Geological squeme of test-pits (C1 to C12) and boreholes (S1 and S2) made in the zone of study.

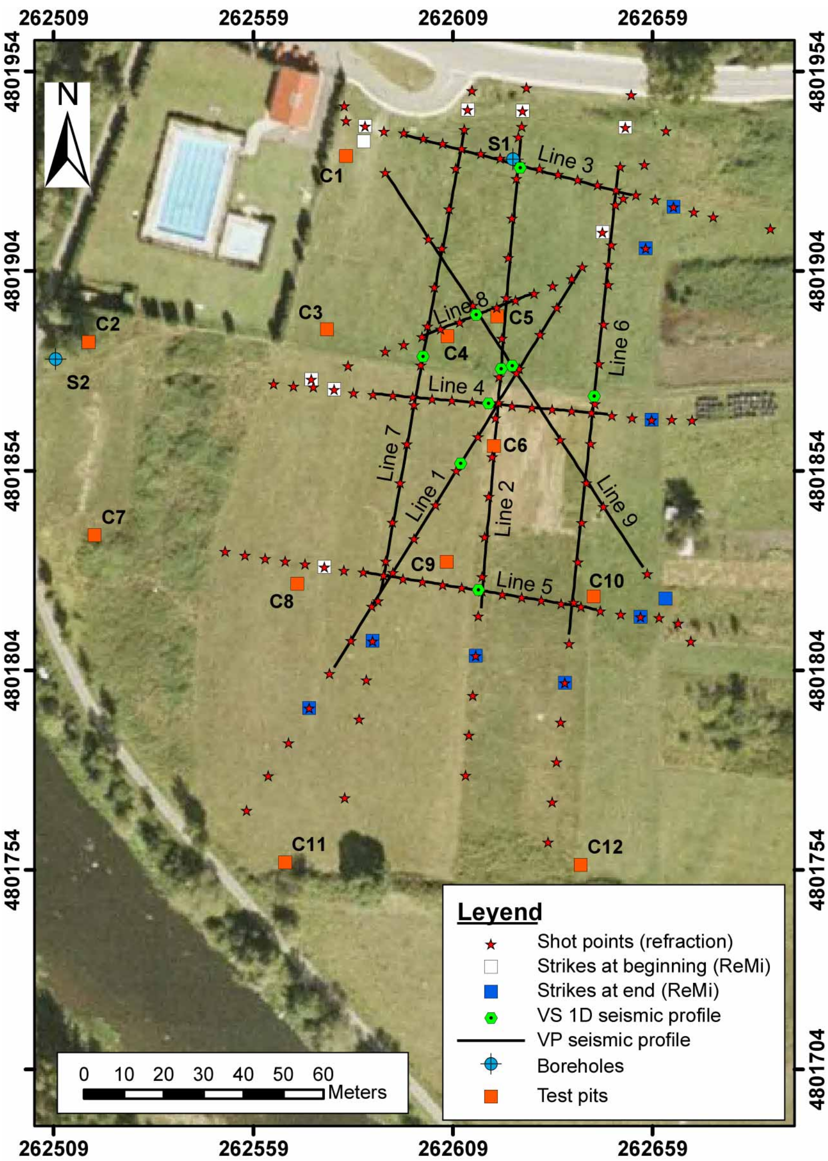

Figure 3: Location of test-pits, boreholes and seismic profiles in the study area.

Acquisition and processing

Nine combination seismic refraction and ReMi surveys (figure 3) were adquired using a Geometrics Stratavisor NX seismograph and 60 geophones of 10 Hz natural frecuency. The geophone spacing vary from one line to other. Reciever spacing of lines 1, 2, 6, 7 and 9 was 2 meters (length of 118 meters), reciever spacing of lines 3, 4 and 5 was 1 meter (line length of 59 meters) and reciever spacing of line 8 was 0,5 meters (line length of 29,5 meters).

Seismic refraction

In seismic refraction adquisition, 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 y 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 y 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 out side of the array. Seismic data showed a high quality signal of refraction waves that allowed accurate picking of first arrivals (figure 4).

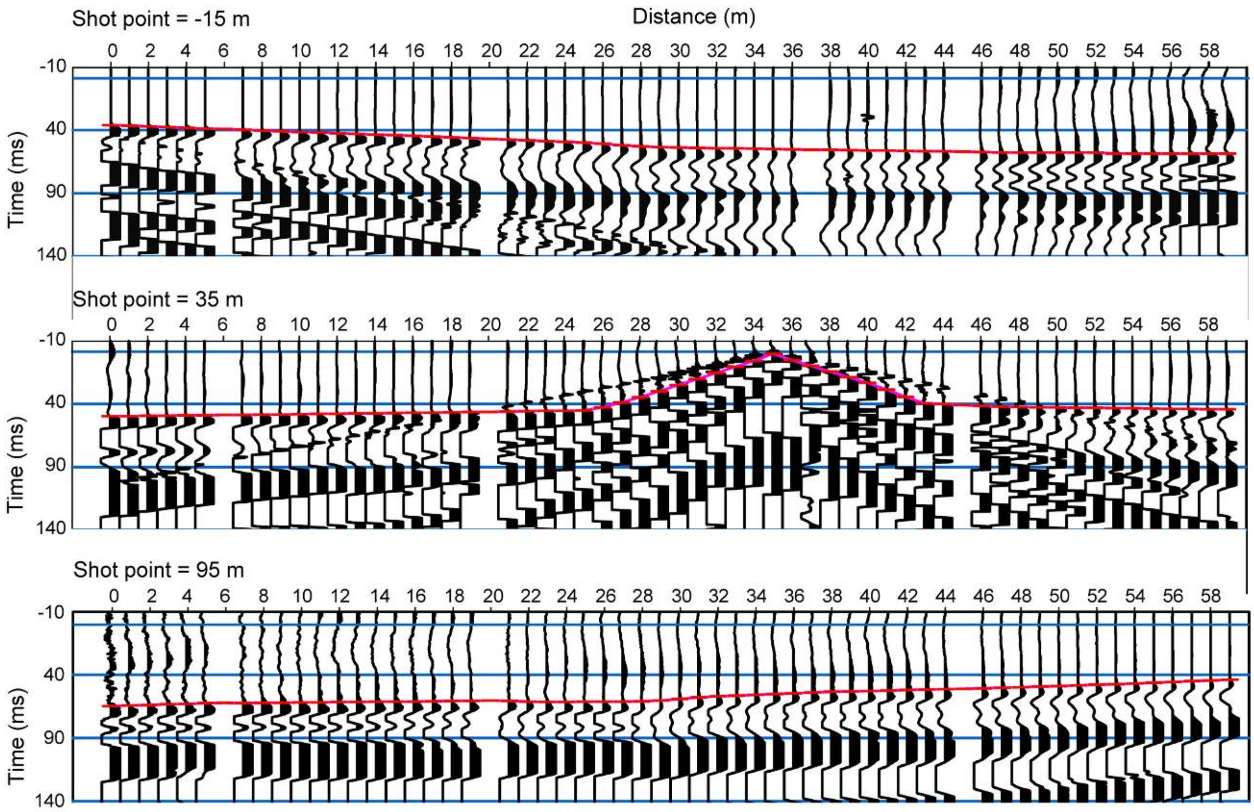

Figure 4: Seismics profiles adquired and P wave first arrival time of line 3. Traces in meters 6, 20 and 45 shown high electronical noise make impossible the right record of seismic signal.

Modelling was made with tomography software SeisOptPro^{TM} based in a nonlinear optimization method called simulating annealing (Pullammanappallil and Louie, 1994). The program uses first arrival travel time data and geometry adquisition 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 adquisitions 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 adquired 10 records with 30 seconds length, 2 ms sampling interval and 48 dB preamplifier gain. In the second and third adquisitions 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 adquired 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^{TM}. This software uses two modules:

- Module ReMiVspect: seismic field data are transformed into p-f spectrums (slowness-frecuency) throught 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 wich the IBC (International Building Code) soil classification is based.

Results

Refraction microtremor

At the begining 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 frecuency 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 frecuencies 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 begining 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 localizated 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 determinated in p-f spectrums in frecuency 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.

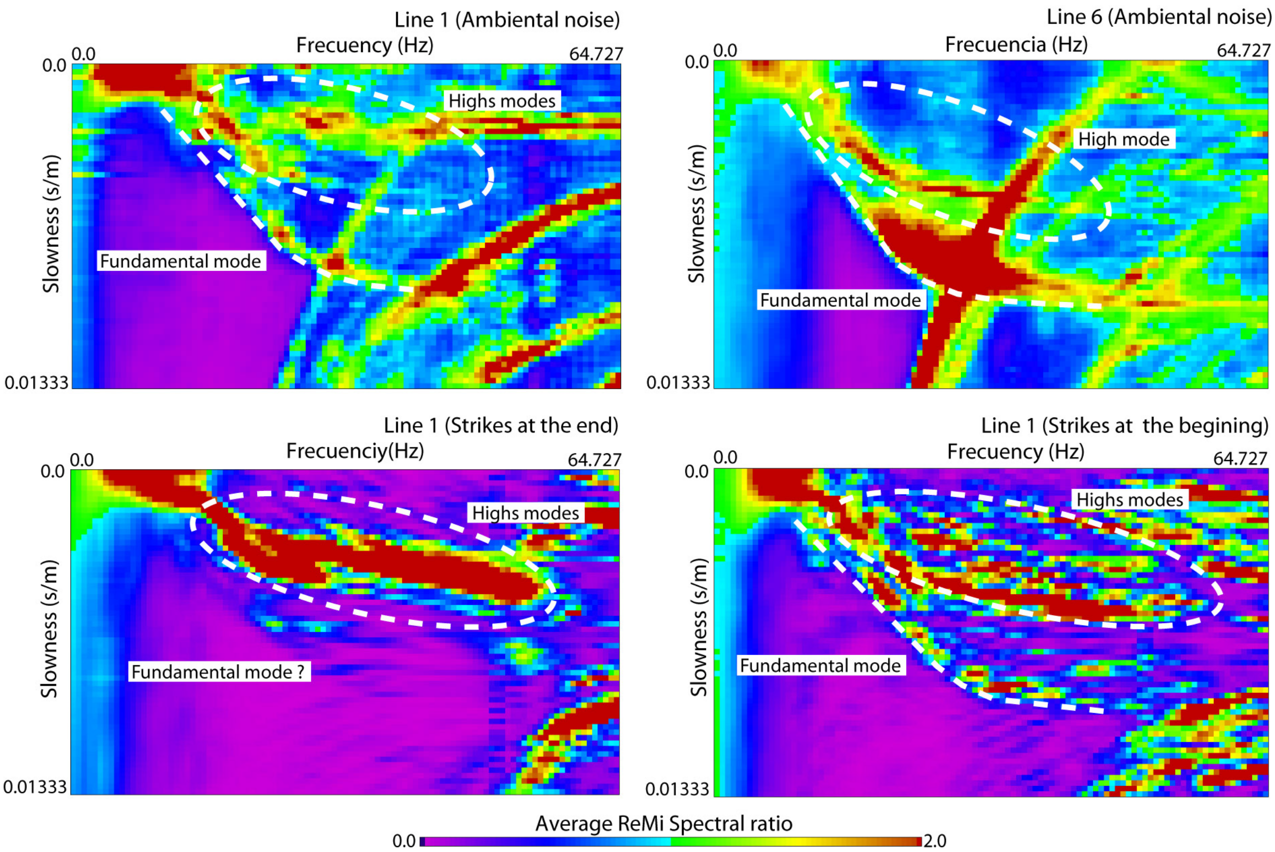

Figure 5: Comparison between p-f spectrums obtained for line 1 and 6.

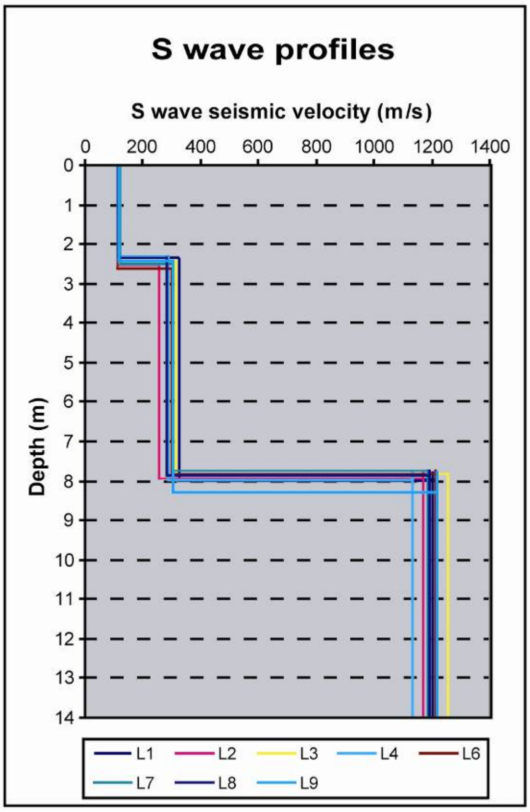

Figure 6: V_S profiles of all lines.

Modelled V_S profiles of all lines are very similar, with comparable interface dephts 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 $Z_{max} = C_1/(2f_1)$, where Z_{max} is the maximum depth investigation, C_1 is the phase velocity of surface wave at the frecuency f_1, and f_1 is the lowest frecuency 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).

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.

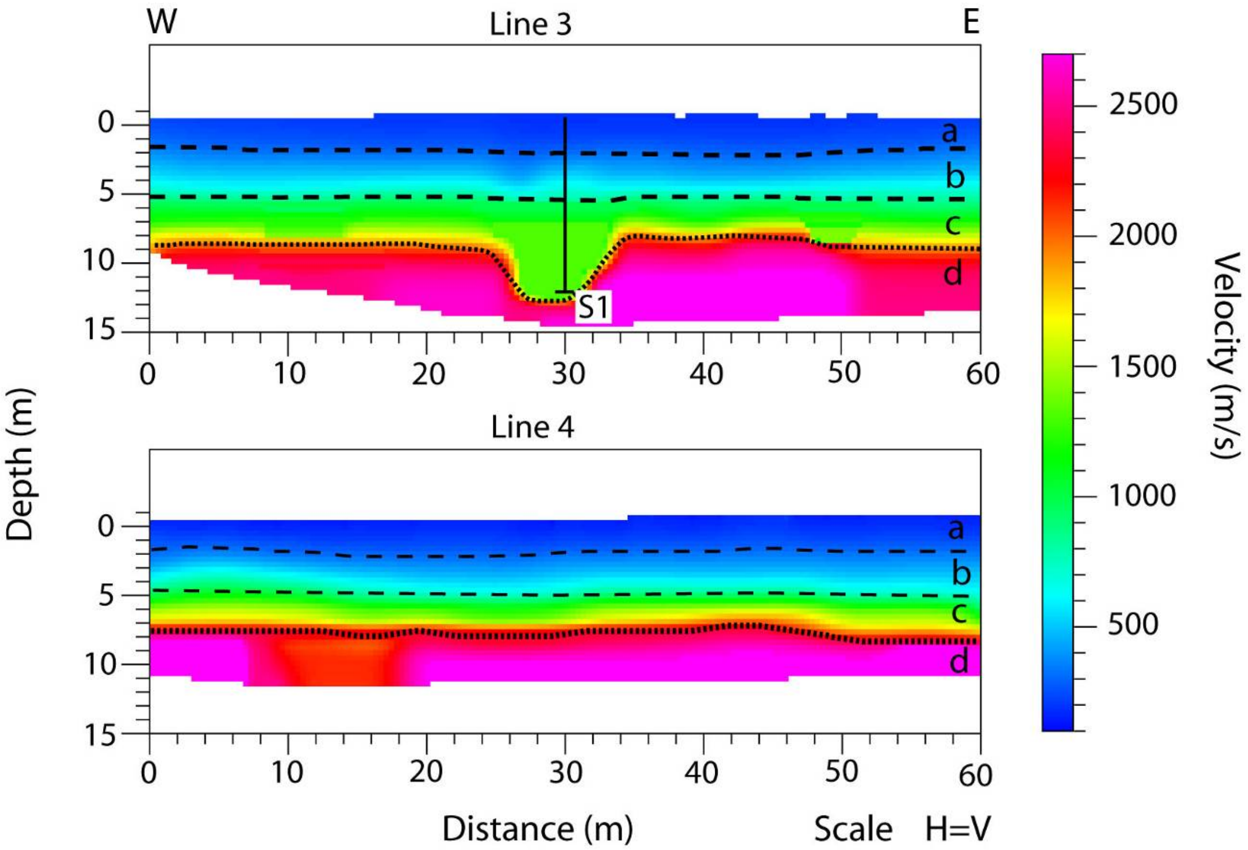

Figure 7: Interpretation of V_P seismic profiles of lines 3 and 4. S1 marks the position of borehole 1.

Comparison V_S and V_P models

Comparison of V_P and V_S models for each seismic line shows that both are very similar. The two contacts of layers modelizated 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).

Material	V_P (m/s)	V_S (m/s)	V_P/V_S	Poisson ratio
Sand	300	114	2,63	0,42
Cobble and gravel dry	700	280	2,50	0,40
Limestone	2300	1150	2,00	0,33

Table 1: Posisson ratio of each material calculated by V_P and V_S.

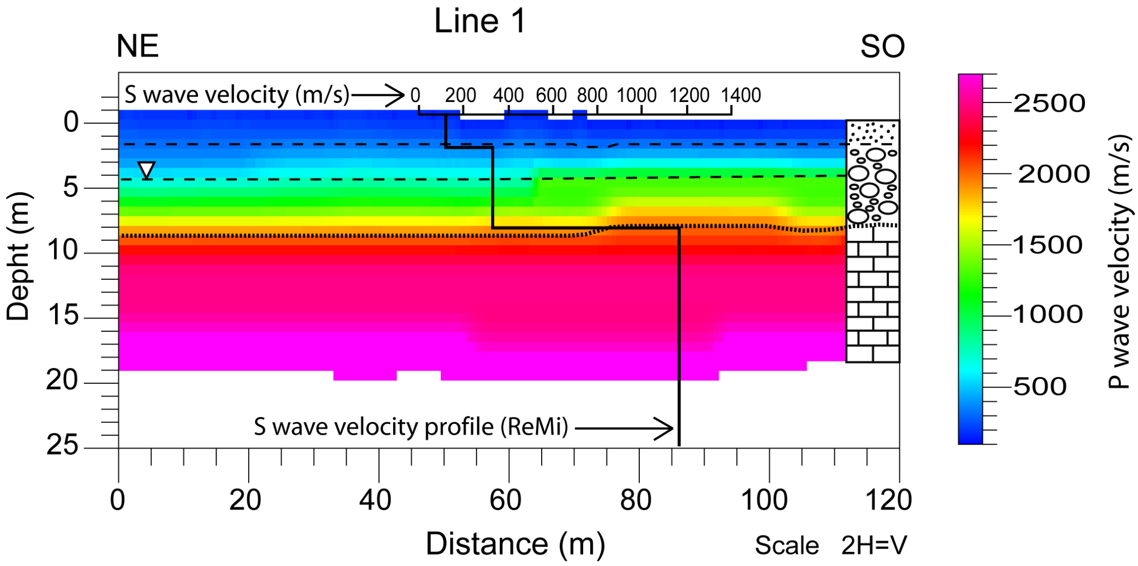

Figure 8: Comparative between V_P model and V_S models and geologic interpretation based on both at line 1. Discontinuos and dotted line are interpreted interfaces in seismic refraction. The discontinuous line with a triangle marks suspected groundwater table.

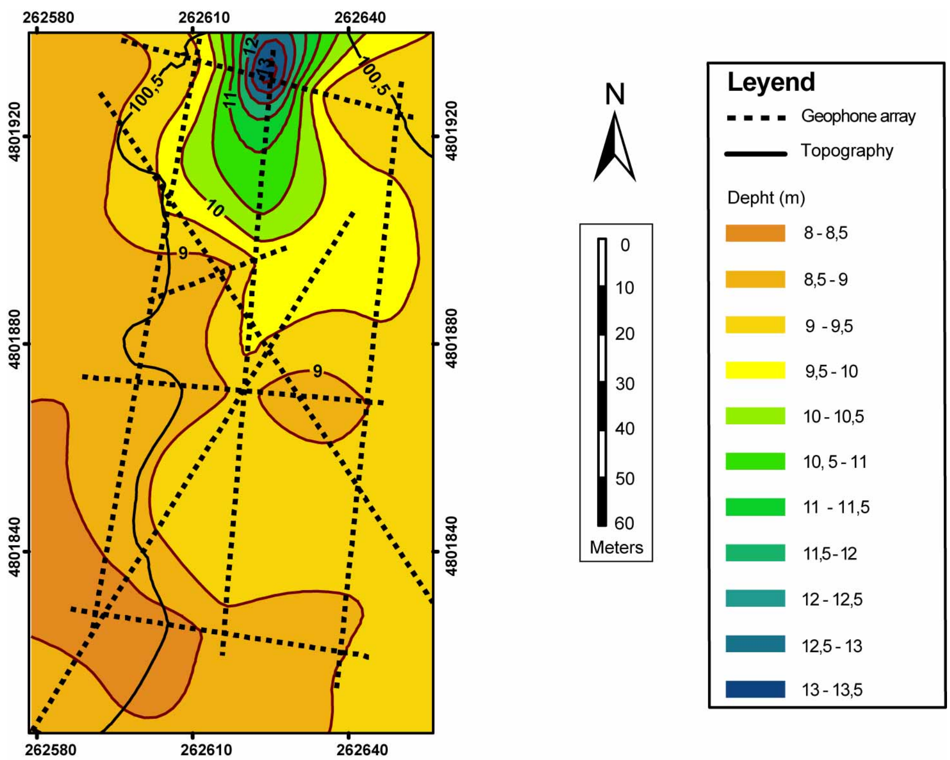

Figure 9: Contour depth map of limit between alluvial deposit and bedrock (limestones).

Conclusions

Aplication of seismic refraction and refraction microtremor methods in the study of a flood plain have demostrated to be very useful. Acquisition data of both methods was made with a standard seismic refraction equipment, permitting to adquire in a day (for two lines) the necessary data to model V_S and V_P profiles.

We have create 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 Goverment (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 provide us the information of test pits and boreholes.

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