Comparison among SASW, ReMi and PS-logging techniques: Application to a railway embankment

Itziar Pérez-Santisteban [a,*], Julián García-Mayordomo [a,b], Alfonso Muñoz Martín [c], Andrés Carbó [c]

[a] Laboratorio de Geotecnia, Centro de Estudios y Experimentación de Obras Públicas (CEDEX) c/Alfonso XII, 3 28014 Madrid, Spain
[b] Instituto Geológico y Minero de España (IGME) c/La Calera, 1 Tres Cantos 28760 Madrid, Spain
[c] Departmento de Geodinámica, Fac. Ciencias Geológicas, Universidad Complutense de Madrid (UCM), C.Universitaria, s/n 28040 Madrid, Spain

A B S T R A C T

Results obtained by SASW and PS-logging (in-hole) seismic techniques are compared with the relatively new ReMi (Refraction microtremor) method at a common site with a well-known soil profile: a recently constructed high-speed railway embankment. PS-logging is the most accurate technique in identifying the soil profile of the embankment followed by Re-Mi and SASW. Mean shear wave velocity estimations are also higher for PS-logging, followed by SASW and ReMi, while mean deviation is similar in each technique. The ReMi technique has provided very accurate results in the study of the embankment profile, which in addition to its high operability and its fast data processing, makes it a very convenient technique for extensive geotechnical surveys.

Keywords:
Geotechnics
Geophysics
Shear waves
Surface waves
Ambient noise
Railway embankment

1. Introduction

The determination of underground shear-wave velocity (Vs) is a very important issue in geotechnical and earthquake engineering because of its direct relationship with the stress and strain properties of soils. To date, there are a number of geophysical techniques commonly applied in civil engineering to the task of estimating the Vs profile at a site (e.g., borehole seismic techniques, Spectral Analysis of Surface Waves (SASW), Refraction Microtremor (ReMi), Multi-channel Analysis of Surface Waves (MASW)). The selection of one or the other is strongly conditioned by the nature and ambient conditions of the problem which the analyst confronts, as each one is characterised by fairly clear advantages and drawbacks. Among them, borehole methods are to be highlighted because of their accuracy, but they are expensive and their results limited to the vicinity of the borehole. On the contrary, surface wave methods are usually faster, cheaper and can also be fairly accurate (Anderson et al., 2007; Kuo et al., 2009; Stephenson et al., 2005; Xia et al., 1999).

The question of which technique is the most precise and what would be the scatter among them if used together is usually overlooked in regular engineering practice. The purpose of this paper is to carry out a comparative analysis of the results that SASW, PS-logging and ReMi (Refraction Microtremor) would provide when applied to a site where the soil profile is known accurately. The site is a section of a high-speed railway embankment located in the region of Madrid (Spain) (Fig. 1) where the Geotechnical Laboratory of CEDEX is monitoring its geotechnical behaviour. The section of the embankment is 15.5 m high, measured from the level of the subgrade layer on the axis of the track to the foundation level. The foundation of the embankment is formed by a cobble layer (material consisting of rock-fill) 2 m thick, placed on a geotextile. The natural ground consists of overconsolidated Miocene arkosic sands, known locally as "arena de miga", derived from the erosion of the surrounding granite massifs located north of Madrid.

The comparison is carried out looking first at the results obtained by each technique in relation to its accuracy in the identification of the embankment profile. This is made by comparing the Vs profile derived from each technique with the embankment structure, namely: the depth to the foundation layer, its thickness and the depth to the natural ground. Secondly, we focus on analysing the scatter among the different techniques by comparing the results obtained at the same point by the three different techniques. Lastly, the variance of each technique is analyzed by comparing the results obtained upon repeating the test several times at the same point.

2. Measurements by SASW, PS-logging and ReMi techniques

2.1. SASW

The SASW (Stokoe et al., 1994) campaign was carried out by the CEDEX Geotechnical Laboratory in June and July 2005 (Manzanas,

* Corresponding author. Tel.:+34 913357339, +34 619370227.
E-mail address: itziar.perez@cedex.es (I. Pérez-Santisteban).

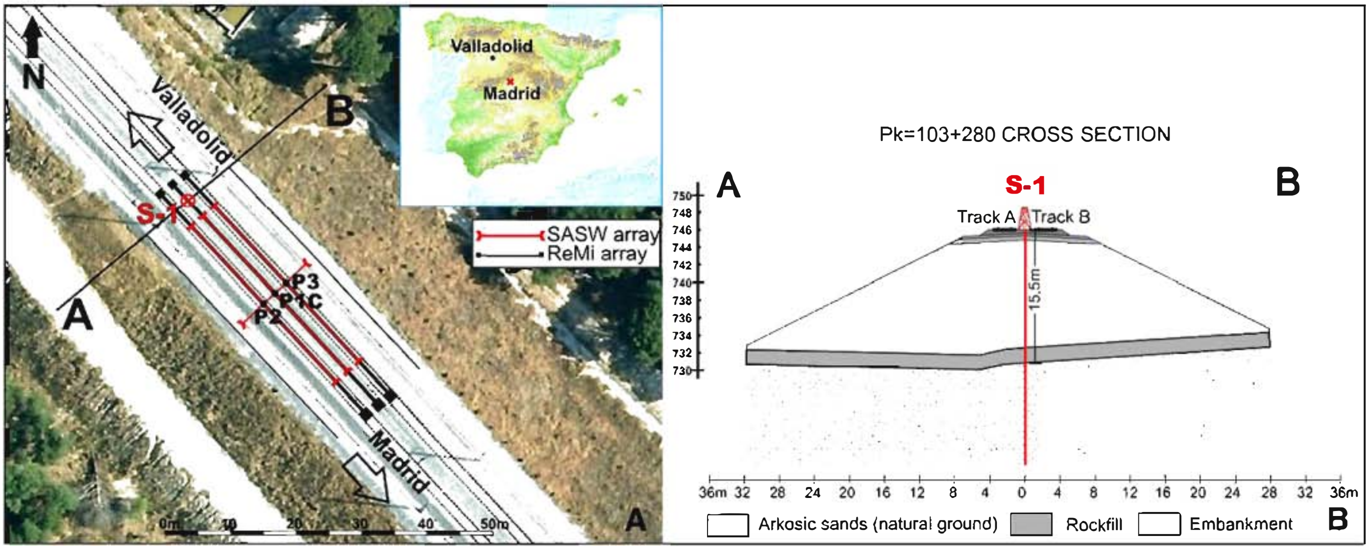

Fig. 1. A. Placement of the SASW and ReMi surveys on the embankment, and location of the borehole used for PS-logging (S-1). Inset shows the general location of railway embankment. 1.B. Cross section and soil profile of the embankment at the studied site.

2006). Data acquisition was performed at three specific points located on the same transversal section (Fig. 1): one point was located at the track's axis (point P1C), and the other two at the axes of the future railway line (points P2 and P3).

At each of the three sites (P1C, P2 & P3), the tests took place in four orientations perpendicular to each other, on the longitudinal and transversal directions of the embankment. Seven different separations were measured, following the sequence: 0.5, 1, 2, 4, 8, 16 and 32 m. At the transversal section, due to the lack of space on the embankment's platform, it was not possible to carry out tests on separations of 8 m or more. For separations of up to 4 m, the source was a linear frequency sweep through an electrodynamic Newton 500 vibrator model 812E/50LP that covers a range from 100 to 5000 Hz. For larger separations, the impact caused by the fall of a mass was used. This was produced by a device similar to a falling weight deflectometer, specially designed by the CEDEX Geotechnical Laboratory. Up to distances of 4 m, high frequency accelerometers were used as receivers, whereas 1 Hz geophones were used for longer distances. To make sure that the registered data was comparable, tests were carried out at a distance of 4 m with both types of receivers and sources. As the tests were positive, the survey went ahead using geophones as receivers and the fall of mass as a source.

The 'Tomaonda' software developed by the Geotechnical Laboratory was used for the field data logging. For each distance and each orientation, an average of 10 measurements was taken. The test was repeated several times varying the upper limit of the registered frequency with the aim of gaining a representative number of cycles and/or increasing the precision of the measurements. Data analysis was carried out on the basis of the theoretical modelling of the dispersion curves using CEDEX Geotechnical's SASW programme (Roesset et al., 1991).

The inversion analysis was made both with and without fixing the contact of the embankment with the natural ground at a depth of 15.5 m (Fig. 2.). For the first case, the contact is clearly stressed by a strong increase in the Vs of up to an average 520 m/s (Fig. 2.A.). However, the 2 m thickness rock-fill layer, approximately located at a depth of 12.5 m was not detected. On the other hand, Fig. 2.B. shows the results of the inversion analysis without fixing the contact of the embankment with the natural ground. For this exercise only the average of the 3 points tested was used. The layer model shows similar Vs to those of the first analysis, although the number of layers and their thickness do not match between models.

2.2. Suspension PS-logging

The PS-logging (Kitsunezaki, 1980) probe test was carried out on 27th February 2006 in a borehole specifically perforated for that purpose across the axis of the track, some 20 m away from the section where the SASW tests were performed (Fig. 1). The borehole's diameter was 90 mm, had PVC casing and was 27.20 m deep. It penetrated approximately 11 m into the Miocene ground.

The seismic measurements were taken using a Suspension PS-Logging 3302A probe manufactured by OYO. After completely flooding the borehole and confirming that leakage was minimal, the test was performed at every meter, from depths of 21.8 m to 1.8 m. The test was carried out using two different pulse widths: 0.4 ms (test #1) and 1.6 ms (test #2). The pulse width controls the energy released by the source. The energy released is bigger the wider is the pulse.

Fig. 3 shows the shear wave velocity profile with the depth obtained for test #1 and #2, as well as the average of both measurements. The picking of the S-wave was made using the Oyo PS-Log software package.

The average Vs of the embankment's compacted materials falls within the range of 300 to 400 m/s up to a depth of 12 m. Vs shows substantial variations once it reaches the rock-fill. This fact could be attributed to the nature of the rock-fill, as it is formed by dumped cobbles. Because PS-logging measures the Vs of the ground adjacent to the walls of the borehole, high Vs values are obtained when the probe is in contact with cobble (Vs = 650 m/s) and lower values when it is in contact with the space in between cobbles.

2.3. ReMi

ReMi (Louie, 2001) is a relatively new seismic method for measuring in-situ shear-wave velocity profiles. As SASW technique, ReMi is base on obtaining the dispersion curve of the Rayleigh waves, but in this case using ambient seismic noise or microtremors. Standard refraction equipment is used, usually a linear array of 12 or more geophones sensors channels that register surface waves at low frequency. A two-dimensional slowness- frequency (p-f) is applied to the microtremor record to distinguish Rayleigh waves from other arrivals waves. On the resulting p-f diagram, the dispersion curve is manually picked along the lowest-velocity envelope to avoid apparent velocities. Finally, a Vs model is created using the picked dispersion curve.

The ReMi survey was carried out on 24th January 2007 by the Geophysics Group of the Faculty of Geological Sciences of the

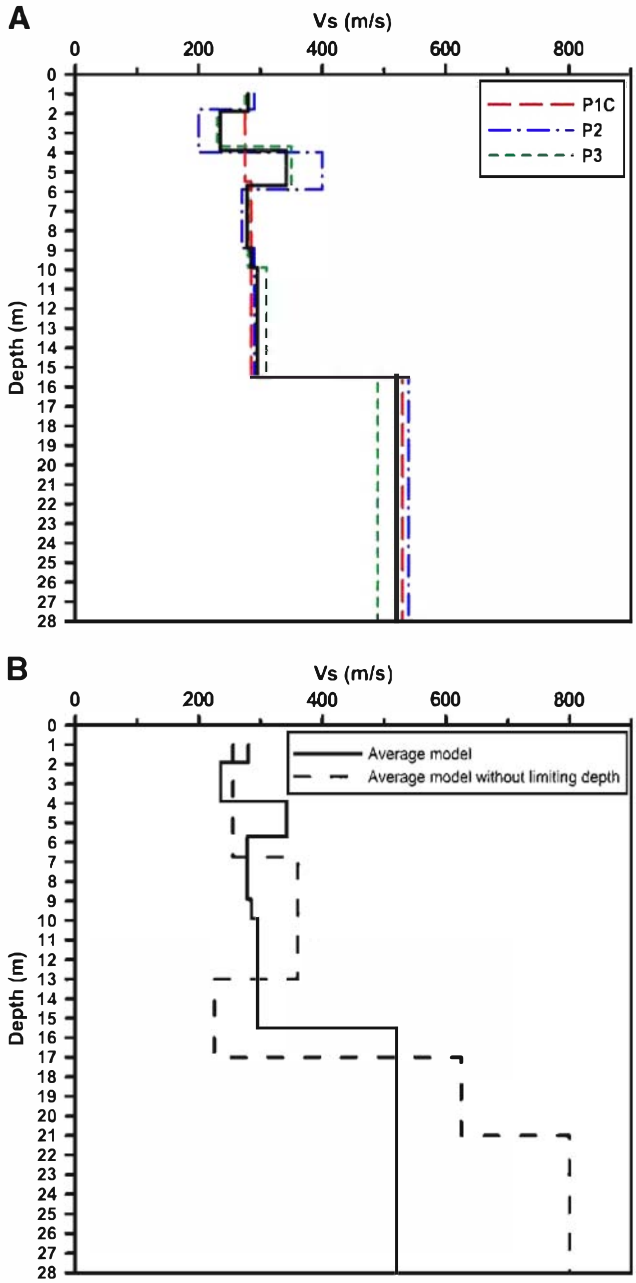

Fig. 2. A. Shear wave velocity models obtained by SASW at the three points studied when constraining the contact with the natural ground (modified from Manzanas, 2006). The average model is also shown. 2.B. Comparison between the average layer models obtained by SASW with and without constraining the depth of the embankment in the inversion analysis.

Complutense University of Madrid. Since at that time the embankment surface was covered by a 30 cm thick layer of sub-ballast, it was not possible to thrust the geophones into the ground, so they were placed inside plastic flowerpots filled with moistened soil. The tests were carried out at the same points studied in the SASW campaign (Fig. 1). At the centre of each point, 24 10-Hz geophones were placed in a row at intervals of 2 m, connected to a 24 bit of dynamic range DAQLink II seismograph. At each point, ten 30-second noise records were taken with a sampling interval of 2 ms. It was found that the natural ambient noise produced an insufficient signal, so noise was produced by driving a four-wheel-drive vehicle along the row of geophones, and also by hitting a metal plate with a sledgehammer. The whole operation, including the placing and withdrawal of the equipment and the data

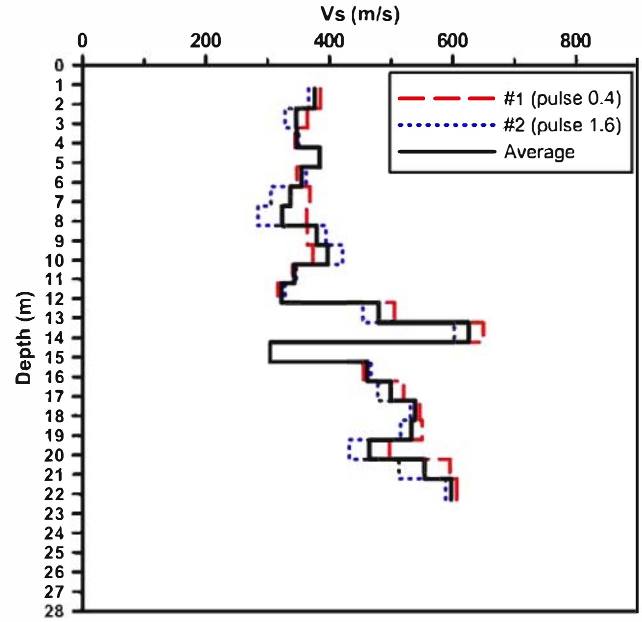

Fig. 3. Shear wave velocity models obtained by PS-logging for two different pulse widths (modified from García-Mayordomo, 2006). The average of both tests is also shown.

logging took around two hours. Data processing and interpretation was performed using the Optim SeisOpt ReMi software package.

As in the case of the SASW technique, the interface with the ground in the inversion analysis was initially placed at a depth of 15.5 m (Fig. 4.A.). This contact point is characterised by a strong increase of Vs up to 534 m/s. At 12.5 meters there is also an important increase of Vs that corresponds to the rock-fill layer. At point P2 this contact is not detected, and so the entire embankment is included in the same Vs layer (249 m/s). At points P1C and P3, the 30 cm thick sub-ballast layer was also identified, with low Vs of around 109 m/s.

When the inversion analysis was carried out again without constraining the depth of the embankment, no contact was detected either with the rock-fill or with the natural ground, although very similar Vs values were obtained for the body of the embankment itself (Fig. 4.B.).

3. Comparative analysis of the results obtained by each technique

3.1. Analysis of the accuracy of each technique

Fig. 5 brings together the average results obtained from each of the three techniques studied. The average result shown is the average shear wave velocity, which in the case of SASW and ReMi is the average of the three tested points (P1C, P2 & P3), and in the case of PS-logging is the average of the two tests made with different pulse width in the same survey.

We analyzed the accuracy of the techniques when recognizing a soil profile. To do so, the models obtained by each technique are compared with the embankment's structure: its thickness, the depth of the foundation layer (rock-fill) and its thickness, and the depth of the contact with the natural ground (Fig. 1).

The technique that provides the greatest accuracy is PS-logging (Fig. 3). Some irregularities are detected inside the body of the embankment including a drop of Vs from 375 to 346 m/s in the 2-4 m section; an increase at the 4-5 m section of up to 355 m/s, and an increase at the 8-10 section from 323 to 397 m/s. Vs experiences important variations once it reaches the rock-fill, moving from values of around 650 m/s to values of around 300 m/s. The natural ground

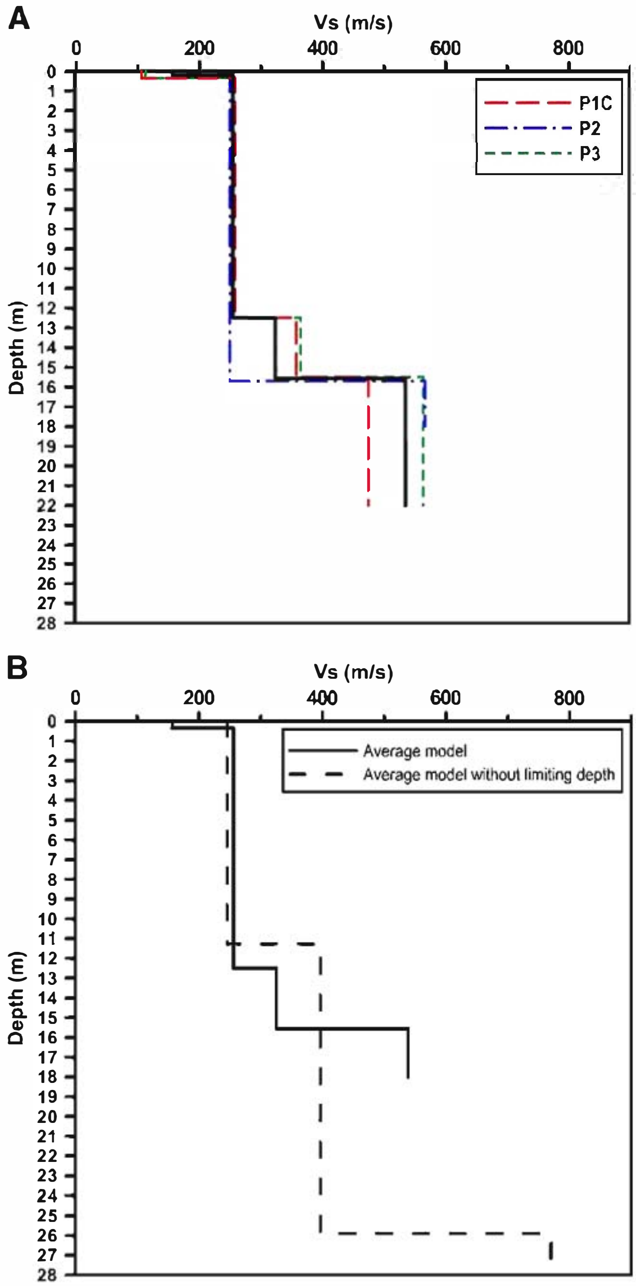

Fig. 4. A. Shearwave velocity models obtained by ReMi in the three points studied when constraining the contact with the natural ground. The average model is also shown. 4.B. Average shear wave velocity models obtained by ReMi with and without constraining the depth of the embankment in the inversion analysis.

presents higher Vs than the embankment body, with an average value of around 500 m/s.

ReMi is the second most accurate technique since it detects precisely the position of all the interfaces in the structure. In sites P1C and P3 it detects the sub-ballast layer which is just 0.3 m thick and has low Vs, and determines the contact with the rock-fill at a depth of about 12.5 m, which is represented by an increase in the value of Vs of approximately 100 m/s. At P2, surface layers are not as well identified probably due to the lack of high frequency noise during data acquisition. As in the case of the SASW technique, in the inversion analysis the interface with the ground was fixed at a depth of 15.5 m. The contact is evidenced by an increase in the values of Vs from the 323 m/s of the rock-fill, to the 534 m/s in the first meters of the ground itself.

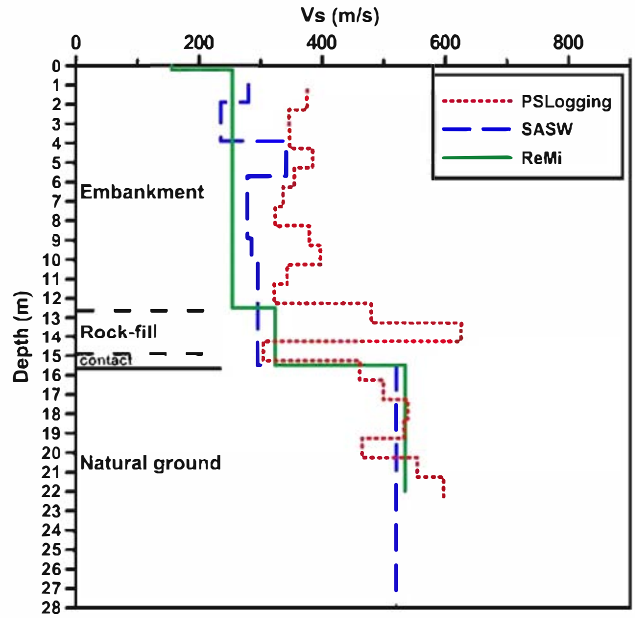

Fig. 5. Comparison of the average shear wave velocity models obtained by each technique with the cross section of the embankment.

We consider SASW the least accurate technique because it was not able to detect the contact with the rock-fill foundation. However, it is capable of detecting the same Vs irregularities in the embankment's body that PS-logging detected. Specifically, SASW also detects a drop in Vs at the 2-4 m section, an increase at the 4-6 m section, and once again, an increase, albeit slight, at the 8-10 m section.

3.2. Analysis of the average velocities and their deviation

Table 1 shows the average velocities, and their mean deviations, obtained by each technique for the different ground layers considered. The results of the PS-logging are considered to be comparable to the ones acquired at points P1C, P2 and P3 by SASW and ReMi, even though the borehole was located approximately 20 m away from P1C. This assumption is admissible since the embankment profile barely changes over such a short distance.

Out of the three techniques, the PS-logging produces the highest Vs values (Fig. 5). In regard to the body of the embankment, the PS-logging estimates an average Vs of 355 m/s up to 12 m, a value that differs from the 288 m/s of the SASW and the 254 m/s of the ReMi.

The SASW and ReMi estimations of Vs are very similar for each layer, with differences that vary from 18 to 35 m/s.

The scatter of the SASW and the ReMi techniques were studied on the basis that the measurements at points P1C, P2 and P3 represent in fact three tests carried out at a single location. This assumption is admissible given that the distance between the three points is only 2.20 m (Fig. 1). Hence, the scatter of each technique is calculated by using the mean deviation of the Vs data compiled at the three studied sites.

Table 1
Average shear wave velocities and their mean deviations (in brackets) for specific ground thicknesses.

Layers	Depth (m)	PS-logging (m/s)	SASW (m/s)	ReMi (m/s)
Embankment	2-4	356 (±16)	235 (±27)	254 (±3)
	4-6	370 (±15)	342 (±44)	
	6-11	350 (±30)	288 (±8)	
	11-13			
Rock-fill	13-14	553 (±73)		323 (±49)
	14-15.5	304 (±1)		
Natural ground	15.5-22	509 (±38)	520 (±20)	534 (±40)

The actual variance of the results of the PS-logging test was studied by calculating the mean deviation of the Vs values obtained with both pulse widths.

Taking into account the three techniques, the mean deviations of the Vs values are around 10-40 m/s (Table 1). An important exception is the mean deviation of the Vs in the rock-fill (±73 m/s) in the case of PS-logging.

4. Discussion

Both SASW and ReMi techniques are based on the assumption of a 1D structure (flat, horizontally layered Earth). The studied structure infringes this principle because it has a topographic elevation of 15.5 m. For this reason, and to avoid resonance problems, the SASW and ReMi arrays were set up in such a way that it could be considered a 1D structure. In the ReMi survey, only parallel arrays to the embankment were deployed, at least 6 m away from the embankment's edge. In SASW, in addition to the parallel arrays, perpendicular lines were also deployed. These perpendicular arrays were only up to 4 m long, and so were not affected by the embankment's limits. In addition, in both techniques the source was line up with the arrays. With this set up, the distortion in the results was avoided and no resonances were found on the spectrum.

PS-logging has been shown to be the most accurate of the three techniques in identifying the profile of the embankment, followed by ReMi and SASW. We consider that the precision and the resolution are equivalent as we have not tried to find the exact Vs (there are no independent measures of Vs), but a model as close as possible to the real. These techniques measure Vs variations with depth, but the most remarkable changes in Vs have to match the changes in the structure's layers. PS-logging has been the most precise technique as it has obtained a model very close to the real, with the layers in the exact spot, so that we can correlate it with data from boreholes.

The PS-logging has been the most accurate because it implies a meter-by-meter study and it is not dependent on the depth of the measurement as the vibration source is part of the probe itself. On the other hand, SASW and ReMi techniques obtain an average of all the shear-wave velocities along the array. This seems to be the reason why the SASW technique has not been able to detect the change of rigidity that the rock-fill foundation implies.

Due to the different sources used, SASW (active source technique) has usually been employed to study superficial meters and ReMi (passive source technique) for deeper (Jin et al., 2006; Liu et al., 2005). During the ReMi test in this comparative study, the distance between geophones was only 2 m, and high frequency noise was produced to verify its accuracy in the shear wave velocity characterization of a shallow ground profile (15.5 m). ReMi technique has shown great accuracy in these conditions, detecting the sub-ballast layer which is just 0.3 m thick. Nevertheless, at point P2 no contact with the rock-fill was detected. This resolving problem is due to the lack of noise. This technique is conceived to be used in urban areas, and this embankment was far from any source of noise. Although noise was produced throughout the 3 tests (through hammer blows and driving a four-wheel-drive vehicle), it is possible that, during the survey at site P2, this noise was not enough or was wrongly oriented.

The Ps-logging survey obtained higher Vs values than SASW and ReMi tecniques, probably due to the different volumes of soil that each technique measures. For example, in the case of PS-logging the sample surveyed consists in 1 m of the ground adjacent to the walls of the borehole, irrespective of depth. On the other hand, increasing the depth of the sampling in the case of the SASW technique involves sensors being placed at greater distances from each other in order to register longer wave-lengths, and, as a consequence, this means that a larger volume of ground is surveyed. In the case of ReMi, where geophone arrays are used along tens of meters, the volume of ground sampled is much bigger.

The SASW and ReMi techniqueres produced similar results for the embankment's materials when the depth of the contact with the natural ground was given. When the data interpretation was repeated without fixing the depth, the results of both techniques were not very precise. The Vs obtained was similar in both analyses, but the model did not coincide neither in the number of layers nor in its thickness (Figs. 2 and 4), which shows the importance of having a lithological column to compare with the test results. When the model is not constrained, the changes in the layer's thickness are compensated with different Vs. This way, the Vs of any terrain's thickness that includes different layers is measured. With the constrained model, the Vs that correspond to each layer are obtained, which are more useful in geotechnical engineering. The inaccuracy of the non-calibrated results may be the consequence of the difficulties encountered during the exercise. In the ReMi technique, difficulties included the lack of ambient noise, the need to place the geophones in flowerpots instead of thrusting them into the ground, and the usage of 10 Hz geophones. Problems relating to SASW included its complex interpretation process and its high sensitivity to ambient noise.

It is very difficult to resolve which technique offers results with less scatter. Despite repeating the different tests at the same point a number of times, no conclusion was reached. The deviation may be caused for different reasons. The presence of noise in SASW and PS-logging techniques may cause difficulties when interpreting the data. On the contrary, in ReMi technique, the lack of noise implies the absence of a source.

As for the functionality of the techniques, SASW and ReMi have the advantage that they are neither destructive nor specific, and that they deliver global values for a thickness of ground. In the ReMi technique data acquisition in the field is quite fast. For this study, it took only two hours for the setting up and the data logging. Furthermore, no signal needs to be produced in ReMi since it registers ambient noise, which makes it especially advisable for urban areas where other non-passive seismic methods may have problems. However, it is advisable to enhance the high frequencies (>60 Hz) content through hammer blows to improve the definition of layers closer to the surface. In SASW, data acquisition is considerably more time-consuming as the receivers have to be moved during the data acquisition process and the signal has to be produced, which makes it inconvenient for studying large areas. Finally, PS-logging is the most accurate technique and is especially appropriate for detailed studies, although the need to keep the borehole flooded during surveying can be a problem in some terrains.

5. Conclusions

In this study it has been shown that the most accurate technique for the purpose of characterizing the Vs profile of an embankment is PS-logging, followed by ReMi and SASW.

The SASW and ReMi techniques produced accurate results only when the depth of the embankment was fixed in the inversion analysis. When the inversion process was repeated without this information constraint, similar Vs values were obtained although the layer models were different. This highlights the importance of constraining the shear wave velocity model with information from borehole observations.

ReMi technique has shown great accuracy in characterizing the shear wave velocity profile of a shallow structure, provided a small distance between geophones is set and hammer blows are produced in order to enhance the high frequency noise.

The average values of Vs estimated by SASW and ReMi are very similar, but lower than the average from the PS-logging tests.

Finally, our study is not conclusive regarding which technique provides the most stable and least scattered measurements when a test is repeated at the same location. The mean deviations of the Vs values obtained by the three techniques studied here vary from 10 to 40 m/s.

Acknowledgements

The authors are in debt to J. Manzanas (CEDEX) for providing part of the SASW data used here and for interesting discussions carried out in the preparation of this paper. J. M. Ruiz Fonticiella and E. Asanza (CEDEX) are thanked for reviewing an early version of the manuscript. J. Muiños and M. Geijo (CEDEX) are thanked for their valuable assistance in the field. A. Olaiz, from the Group of Geophysics of University Complutense of Madrid, is thanked for their assistance during the Re-Mi data acquisition.

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