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Determinación de Tipo de Suelos por SPT y MASW en Departamento 9 de Julio – provincia de San Juan - Argentina

Type of Soil Determination by SPT and MASW in Departamento 9 de Julio - San Juan province - Argentine

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Abstract

A geophysical study of Multichannel Analysis of Surface Waves (MASW) was carried out in a sector where seven boreholes were made with available data of N number of blows from Standard Penetration Tests (SPT) in all of them, with the objective of determining soil stability and classification in a sector of some 10,000 m2 where a work of civil infrastructure is planned to be installed. The site is located south of 9 de Julio Department, in the province of San Juan, Argentina. Eight MASW were recorded, and S-waves´ 1-D profiles were calculated to depths near 30m at critical points of the study area.

The type of soil was determined with experimental data along with calculated values of VS. With available data of N and VS in three boreholes where both MASWs were carried out very close from each other, the law of variation of VS with N for each case was calculated through an adjustment algorithm, comparing the expressions with other ones already published. Finally, this equation was employed to calculate (predict) VS based on N for those boreholes where there were only data of N from SPT.

Keywords

S waves, Rayleigh waves – SPT - MASW

Resumen

En un sector con 7 perforaciones realizadas, con datos disponibles de número de golpes N a partir de ensayos SPT en todas ellas, se llevó a cabo un estudio geofísico de análisis multicanal de ondas superficiales (MASW) con el objetivo de determinar tipo de suelos y variaciones en los mismos en un sector de unos 10.000m2 de superficie, predio donde se proyecta instalar una obra de infraestructura civil. El sitio se encuentra ubicado al sur del Departamento 9 de Julio, en la provincia de San Juan, República Argentina. Se registraron 8 MASW, calculándose perfiles 1D de velocidades de ondas S hasta profundidades cercanas a los 30m en puntos críticos de la zona de estudio..

El tipo de suelos se determinó con datos experimentales en conjunción con valores de VS calculados. Con los datos de N y VS disponibles en tres perforaciones donde se efectuaron sendos MASW muy cercanos, se calculó la ley de variación de VS con N para cada caso a través de un algoritmo de ajuste, comparándose las expresiones con otras ya publicadas. Finalmente se aplicaron esta ecuaciones para calcular (predecir) VS en función de N para aquellos pozos donde solo se disponía de datos de N a partir de SPT.

Palabras clave

Ondas S - Ondas Rayleigh – SPT – MASW

1. INTRODUCTION

In geophysics applied to geotechnical site investigations, shear S wave velocity is an essential parameter for evaluating the dynamic properties of soil in the shallow subsurface. Some types of geophysical methods have been developed for near-surface characterization and measurement of shear wave velocities. The most recently and extensively used is Multichannel Analysis of Surface Waves (MASW) (1-3). It is based on surface Rayleigh waves analysis' and appears as a more efficient method for determining the shallow subsurface properties (1, 2, 4). MASW is a non-destructive seismic method that is extensively used for geotechnical site characterization (1, 5, 6), particularly for the measurement of shear wave velocity to calculate dynamic modules and other geotechnical properties, and for identification of underground layer boundaries. The method is based on the identification of each seismic wave type on a multichannel record, based on the normal pattern recognition technique that has been used in oil exploration for several decades (7). The identification leads to an optimum field configuration that assures the highest signal-to-noise ratio (S/N). Effectiveness in signal analysis is then further enhanced by diversity and flexibility in the data processing step (7). Finally, this method has been successfully applied to various types of geotechnical and geophysical projects such as mapping 2-D bedrock surface and for shear modulus determination of overburden materials (5), generation of shear-wave velocity profiles (2) and seismic evaluation of pavements (8).

This project was developed in the northwest of 9 de Julio Department, San Juan province, covering approximately an area of 10000m2. Eight profiles 1D of Vs up to 30 m were determined with MASW; where 3 of them coincide in location with SPT boreholes. Besides, 7 boreholes were previously made, being available in all of them, the penetration resistance N blows through SPT (Standard Penetration Test) procedure up to approximately 30 m. N parameter is the number of blows required to drive the split spoon for the last 300 mm of penetration.

The use of SPT tests available on all boreholes in the study area allowed at first the construction of a relation between SPT N value and S wave velocity varying with depth, when the MASW surveys were near the boreholes. This would enable to predict VS in other neighbor boreholes.

The study was ended assigning soil classification for seismic local site effect evaluation from VS values, so the determined from MASW, as those predicted from the formulae.

2. SURVEY AREA AND ITS GEOMORPHOLOGY

9 de Julio Department has a surface of 185 km2 and is located in the central south area of the province of San Juan, about 15 km eastwards of San Juan capital city. Its limits are Santa Lucía and San Martín Departments to the north; 25 de Mayo and Rawson Departments to the south; Caucete and 25 de Mayo Departments to the east and Rawson Department to the west.

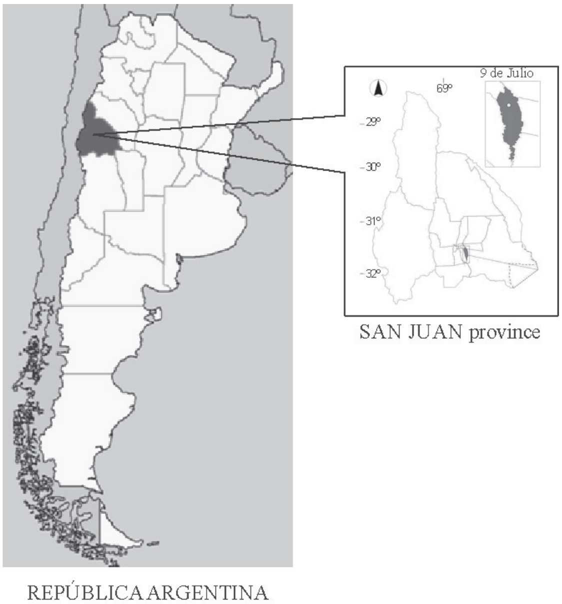

Figure 1. Sector of study

9 de Julio is part of Valle del Tulum oasis, enclosed by San Juan River to the East and Agua Negra water stream to the West, an area where a relief of plains sloping eastwards predominates. Its landscape combines oasis areas fed by rivers and desert areas, usually located south of the Department.

The area investigated by test pits and drilling in the region studied corresponds to the modern alluvial plain of San Juan River. It appears as a flat area with a southwards gentle slope and a S-SE lower component, covered by very salty soils bearing very fine sand to silt, and a slightly profuse vegetation cover of halophytes and small-sized xerophytes plants.

3. METHODOLOGY

3.1 Multichannel Analysis of Surface Waves (MASW)

The MASW method is based on time of arrival detection of the Rayleigh surface waves in every seismic signal, from the place where they are generated up to the different observation points (geophones) across a multichannel record.

The equipment employed for MASW consisted of a Geode digital seismograph and 24 single component 4.5 Hz natural frequency geophones. The seismic waves were generated using a 15 kg sledgehammer striking an aluminum plate.

Eight one-dimensional (1-D) MASW surveys of 24 channel each were performed, with locations showed in Figure 2. About 3 MASW (M1, M8 and M5) were very close to SPT borehole locations S1, S2 and S3 respectively (Figure 2).

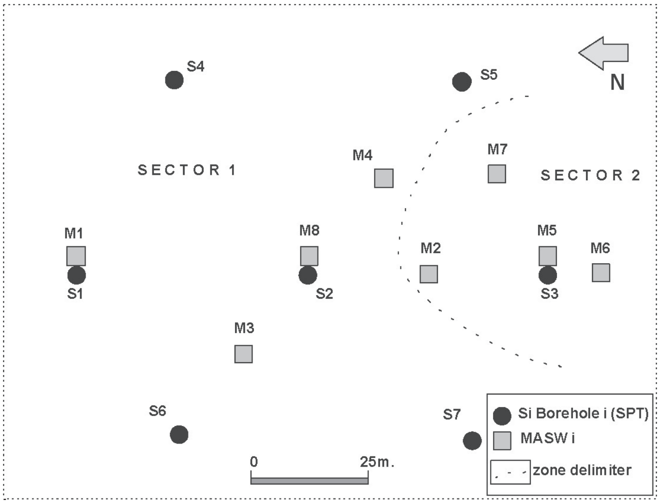

Figure 2. Location of boreholes and geophysical survey

The optimum field parameters, such as source to first receiver, receiver spacing, and spread length of survey lines, were selected in such a way that the required depth of information can be obtained. Figure 3-a shows geometry of seismic lines. For each test 3 offset were used: 1, 3 and 5 meters from shot points to first geophone. Besides, a 3 m spacing among 4.5 Hz geophones was always used. These source distances help

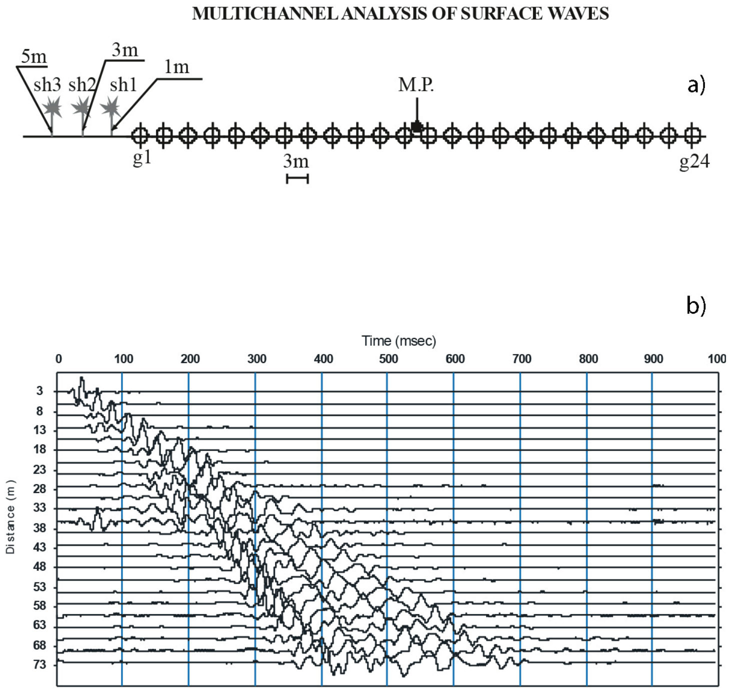

Figure 3. (a) MASW array survey line; (b) MASW Typical recording

ensure good signals in very soft soils. Xu et al. (3) suggested offset distances for a) very soft: 1-5 m; b) soft: 5-10 m; c) hard soil: 10-15 m, respectively. Typical recorded surface wave arrivals using a source to first receiver distance of 3 m with recording length of 1,000 ms is shown on Fig. 3-b.

The recorded waves were analyzed using Seisimager software, designed to calculate VS data (in 1-D format for this work) using a simple three-step procedure:

1) Reading of multichannel record and picking Rayleigh waves (using Figure 3-b type records)
2) Calculation of the dispersion-curve analysis (using Figure 4-a type graphs)
3) Inversion, estimating at the beginning an initial guess model for the profile; VS, and depths (using Figure 4-b type curves)

In MASW method the dispersion curve must be calculated for, through its inversion, obtain the Vs-depth profile (1-D for this work). A dispersion curve is generally displayed as a function of phase velocity versus frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record.

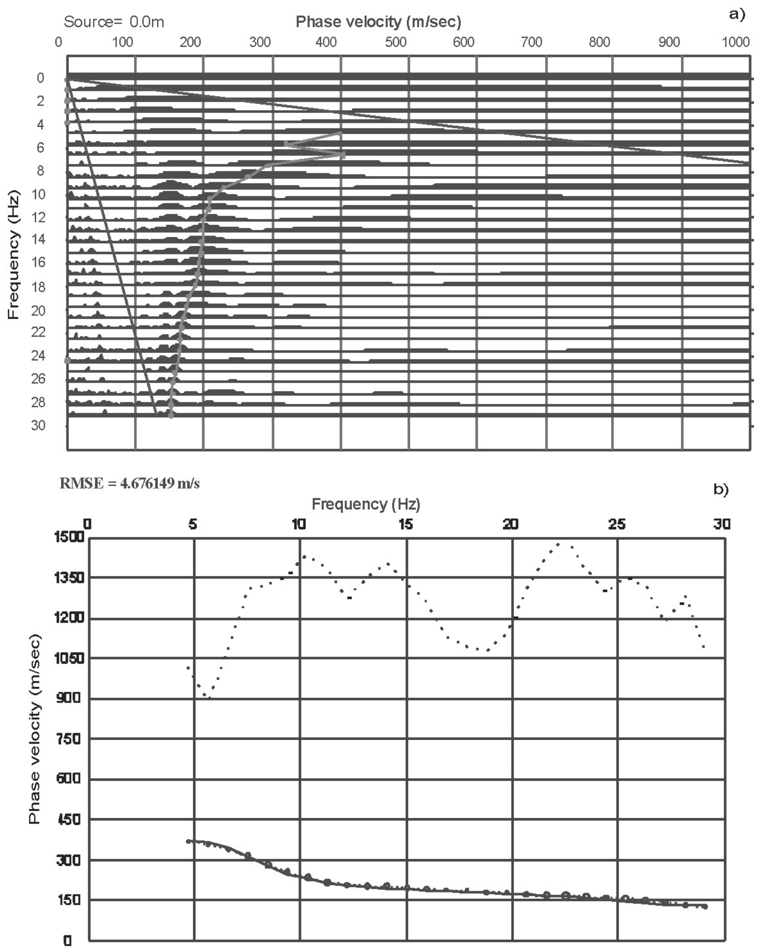

Figure 4 a-b

The lowest analyzable frequency in the dispersion curve is around 4 Hz (the natural frequency of the receivers used was 4.5 Hz) and the highest frequency considered here is about 30 Hz. A typical dispersion curve is shown in Figure 4-a. A Vs profile has been calculated using an iterative inversion process that uses the dispersion curve developed before as an input. A least-squares approach allows automatic iteration of the process (2). It is necessary to input an initial earth model to begin the inversion process. The output model consists of velocity S-wave and depth parameters. Shear wave velocity is updated each iteration. An 1-D Vs profile resulting from MASW is shown in Figure 5 for survey location S1.

3.2 Standard Penetration Test (SPT)

SPT was carried out in each borehole by repeated blows of a standard split spoon sampler using a 63.5 kg hammer, falling through 750 mm. The boreholes had a diameter of 75 mm and were drilled using rotary hydraulic drilling down up to 30m depth. The penetration resistance N is the number of blows required to drive the split spoon for the last 300 mm of penetration from a total length of 450 mm at each interval. The penetration resistance during the first 150 mm of penetration was ignored.

The value of preliminary N must be corrected by several parameters; the formula used for this purpose was (9):

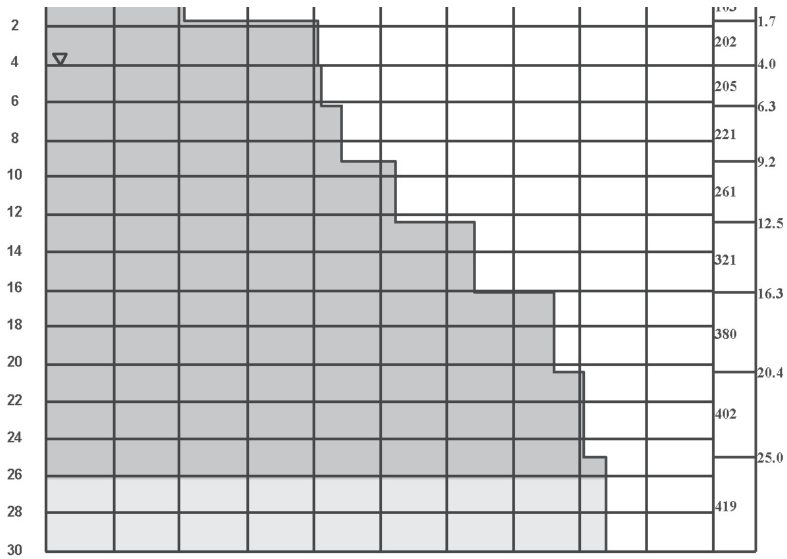

Figure 5

TABLE 1.

Shear wave Vs listing from all interpreted MASW

Prof (m)	Vs (MASW1)(m/s)
-1.3	138
-2.5	177
-3.8	197
-5.1	212
-6.3	212
-7.6	208
-8.8	218
-10.1	214
-11.4	248
-12.6	293
-13.9	293
-15.2	307
-16.4	351
-17.7	351
-18.9	361
-20.2	386
-21.5	386
-22.7	391
-24.0	394
-25.3	394
-26.5	396
-27.8	396
-29.1	398
-30.3	398

Prof (m)	Vs (MASW8)(m/s)
-1.3	144
-2.5	153
-3.8	168
-5.1	175
-6.3	179
-7.6	183
-8.8	193
-10.1	192
-11.4	210
-12.6	210
-13.9	233
-15.2	240
-16.4	262
-17.7	262
-18.9	268
-20.2	272
-21.5	272
-22.7	283
-24.0	285
-25.3	285
-26.5	286
-27.8	286
-29.1	286
-30.3	283

Prof (m)	Vs (MASW3)(m/s)
0	141
-1.5	139
-3	220
-4.5	267
-6	255
-7.5	251
-9	230
-10.5	261
-12	320
-13.5	343
-15	406
-16.5	415
-18	450
-19.5	460
-21	465
-22.5	465
-24	468
-25.5	470
-27	470
-28.5	470
-30	470

Prof (m)	Vs (MASW4)(m/s)
0	136
-1.5	154
-3	189
-4.5	202
-6	196
-7.5	196
-9	220
-10.5	254
-12	269
-13.5	310
-15	327
-16.5	335
-18	345
-19.5	351
-21	355
-22.5	356
-24	360
-25.5	361
-27	363
-28.5	363
-30	363

Prof (m)	Vs (MASW2)(m/s)
-1.3	140
-2.5	160
-3.8	191
-5.1	204
-6.3	203
-7.6	202
-8.8	214
-10.1	216
-11.4	260
-12.6	306
-13.9	306
-15.2	328
-16.4	346
-17.7	346
-18.9	360
-20.2	368
-21.5	368
-22.7	373
-24.0	375
-25.3	375
-26.5	375
-27.8	375
-29.1	375
-30.3	375

Prof (m)	Vs (MASW5)(m/s)
-1.3	145
-2.5	187
-3.8	182
-5.1	173
-6.3	177
-7.6	198
-8.8	214
-10.1	230
-11.4	248
-12.6	250
-13.9	250
-15.2	247
-16.4	245
-17.7	245
-18.9	239
-20.2	234
-21.5	217
-22.7	217
-24.0	212
-25.3	212
-26.5	207
-27.8	207
-29.1	207
-30.3	207

Prof (m)	Vs (MASW6)(m/s)
-1.3	150
-2.5	165
-3.8	179
-5.1	182
-6.3	187
-7.6	191
-8.8	197
-10.1	197
-11.4	210
-12.6	226
-13.9	226
-15.2	230
-16.4	235
-17.7	235
-18.9	252
-21.0	256
-23.2	259
-25.4	266
-27.6	265
-30.7	266

Prof (m)	Vs (MASW7)(m/s)
0.0	130
0.8	132
1.7	143
-2.6	158
-3.7	165
-4.5	165
-6.1	166
-7.4	164
-8.8	163
-10.3	188
-11.8	197
-13.5	210
-15.3	223
-17.1	235
-19.0	244
-21.1	252
-23.2	257
-25.4	261
-27.6	265
-30.0	265

$$N_{60} = \frac{N.c_H.c_B.c_S.c_R}{60} \quad (1)$$

where: *cH*: hammer efficiency (%); *cB*: correction by borehole diameter; *cS*: correction by sampler and *cR*: correction by drilling rod length.

In granular soils the value of *N* is affected by effective pressure, so that another correction must be done to relate it to a standard value of it, according to the expression:

$$(N_1)_{60} = c_N \cdot N_{60} \quad (2)$$

All correction factors were carefully calculated. It must be emphasized that in all cases when N is mentioned, reference is made to the corrected $(N_1)_{60}$.

TABLE 2.
N and N1(60) for three boreholes nearest to MASWs M1, M8 and M5 respectively..

Depth (m)	S1		S2		S3	
	N	*N1(60)*	*N*	*N1(60)*	*N*	*N1(60)*
1.00	5	6	11	13	3	4
2.00	3	3	3	3	6	6
3.00	5	5	7	7	8	8
4.00	12	11	12	11	9	8
5.00	10	8	19	16	21	17
6.00	7	5	9	7	6	5
7.00	10	7	8	6	10	7
8.00	10	7	6	4	10	7
9.00	14	10	7	5	4	3
10.00	7	5	28	19	12	8
11.00	9	6	20	13	11	7
12.00	10	6	9	6	9	6
13.00	9	6	11	7	11	7
14.00	13	8	10	6	19	12
15.00	19	11	20	12	21	13
16.00	21	12	25	15	25	15
17.00	19	11	25	15	20	12
18.00	51	28	45	26	27	16
19.00	20	11	34	19	14	8
20.00	10	5	28	15	18	10
21.00	31	16	8	4	21	12
22.00	21	11	36	19	27	15
23.00	25	13	59	31	31	17
24.00	36	18	47	24	32	17
25.00	100	48	69	34	47	24
26.00	61	29	100	49	81	41
27.00	69	32	84	40	100	49
28.00	100	46	90	42	15	7
29.00			100	46	20	10
30.00			100	45	13	6
31.00					15	7
32.00					13	6

Among the 8 MASW testing points, 3 of them were close to the SPT borehole locations. These 3 MASW (M1, M8 and M5, Fig. 2), related to S1, S2 and S3 boreholes have been used to generate afterwards the relationship between Vs and the N values available.

Table 2 presents a list of boreholes S1 to S3 with their respective N coefficients and $(N_1)_{60}$ corrected ones.

Although information provided by SPT tests is not area but punctual related, thereby not reflecting an area of study; and despite the importance of VS measurement whose determinations are far more economic since they do not need boreholes, normally it is until today, more frequent the use of numerous SPT tests in some countries, mainly for historical reasons. Always the ideal consists of a mixture of both methodologies, employing intensive VS testing together with a couple of wells with SPT tests (according to the area of study).

Therefore, sometimes it becomes necessary to establish a relationship between VS and N for subsequent geotechnical calculation purposes, to minimize the number of boreholes and thus the cost of the project.

In this study two algorithms were designed in matlab. The first one interpolated VS values obtained from MASW, so as to calculate them at the same depth intervals for which N values were taken.

Later, another algorithm generated an adjustment between N and VS in order to establish a law of variation of VS depending on N (that are data in other boreholes). With this data it is possible to: a) Predict VS values in adjacent wells; b) Compare it with other equations previously developed by other authors.

4. RESULTS

4.1 Analysis of VS

At first, eight graphs showing variation of VS with depth for all MASW (Figure 6) were constructed. The spatial distribution of them (Figure 2), show the presence of two sectors with distinctive variations of surface waves velocities. The first, northeast, with higher maximum VS values (M1, M3, M8 and M4), and the other southwest (M2, M5, M6 and M7) bringing lower VS values. At surface, in general, shear wave velocities presented small variations, rounding 120-180 m/s.

Generally, the trend in the velocity profiles is increasing with depth, with exception in the south sector referred, where VS tends to get lower (Figure 6, sector 2). This probably represents very soft fine grain soil deposits underlying soil more firm with the presence of a somewhat greater grain size (gravel and sand) in the study area.

There are precise levels of VS. A first layer of about 5 m depth with VS increments between 150-200 m/s. Below, a level with constant VS of 200 m/s, being supported this seismic situation in the whole study area.

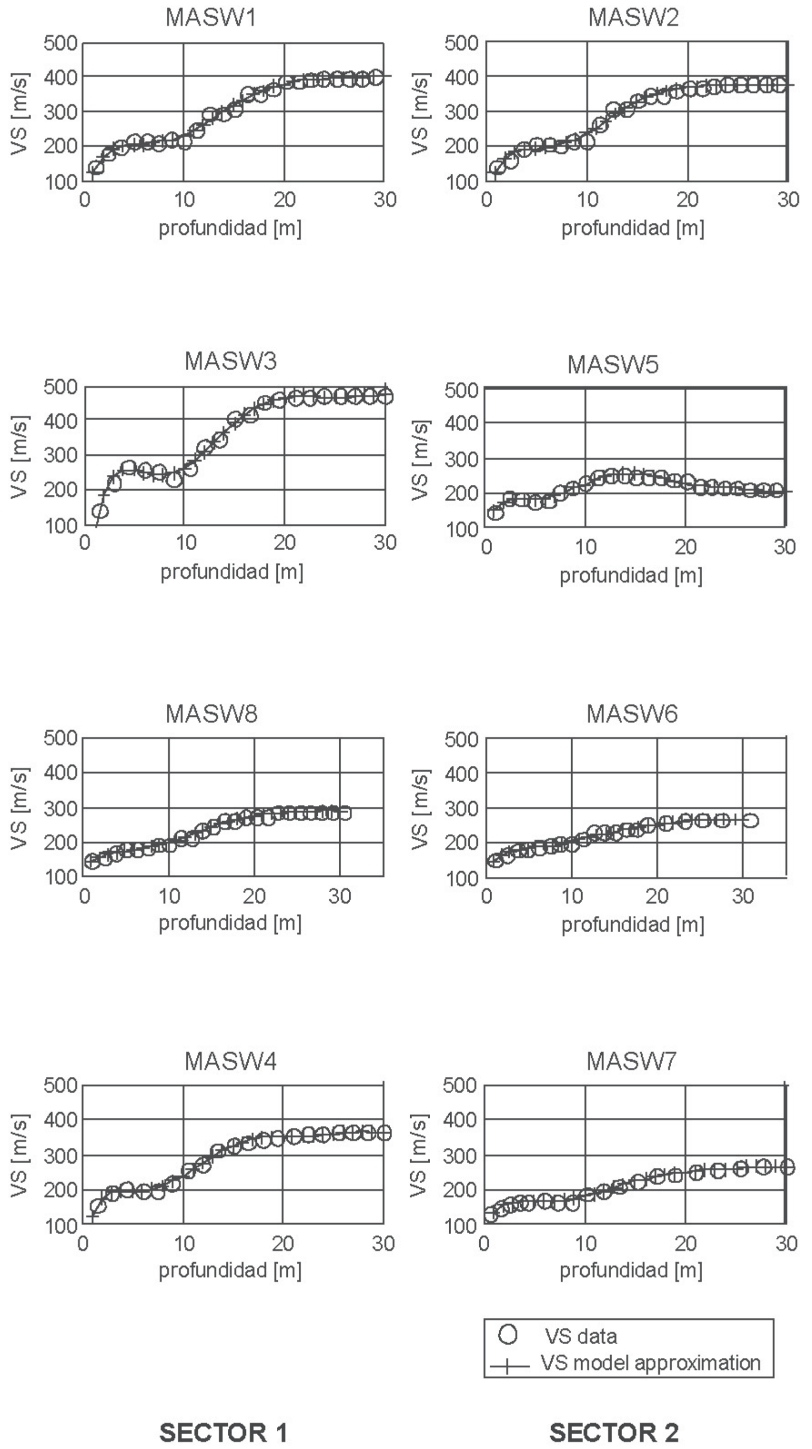

Figure 6. Resulting models from all eight MASW, separated in sectors 1 and 2. (see also Figure 2)

What makes it possible to identify two different sectors is what is presented below the 11.5 m depth approximately, where the VS versus depth curves change, being the values of VS lower towards the south (sector 2).

By analyzing the information of soil samplings from boreholes with VS values obtained, two soil profiles could be constructed, shown in the diagram of Figure 7. It should be noted that the saturated level remained roughly constant around 5 m depth (marked as NF in Figure 7).

4.2 Analysis of N from SPT and its relation with VS

Figure 8 represents Survey 1 with indication of type of soils (10) and N1 (60) from SPT.

Table 2 shows SPT test results for the 3 wells (S1, S2 y S3). Also, Figure 8 shows type of present soil designation, determined only through sample analysis in situ for S1. Also the related N1(60) from SPT is represented. Finally, the VS profile calculated from MASW.

Correlation of the 3 integrated graphics allows to infer the strict correspondence between the calculated models by different methodologies (cf. Figure 7).

The relationship between N1(60) and the soil profiles and VS is in general good.

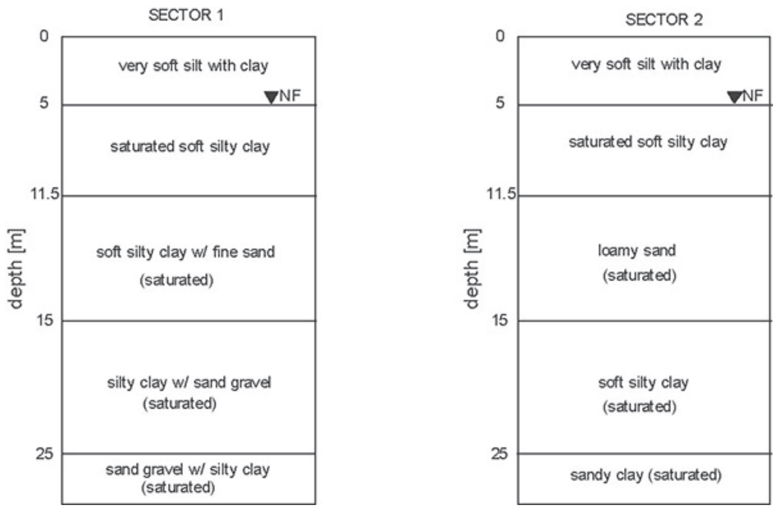

Figure 7. Inferred subsoil profile sketch

4.3 Relation between N y VS

Considering N and VS data obtained from boreholes S1 to S3, it was possible to construct through a matlab algorithm, three curves relating them, which are showed

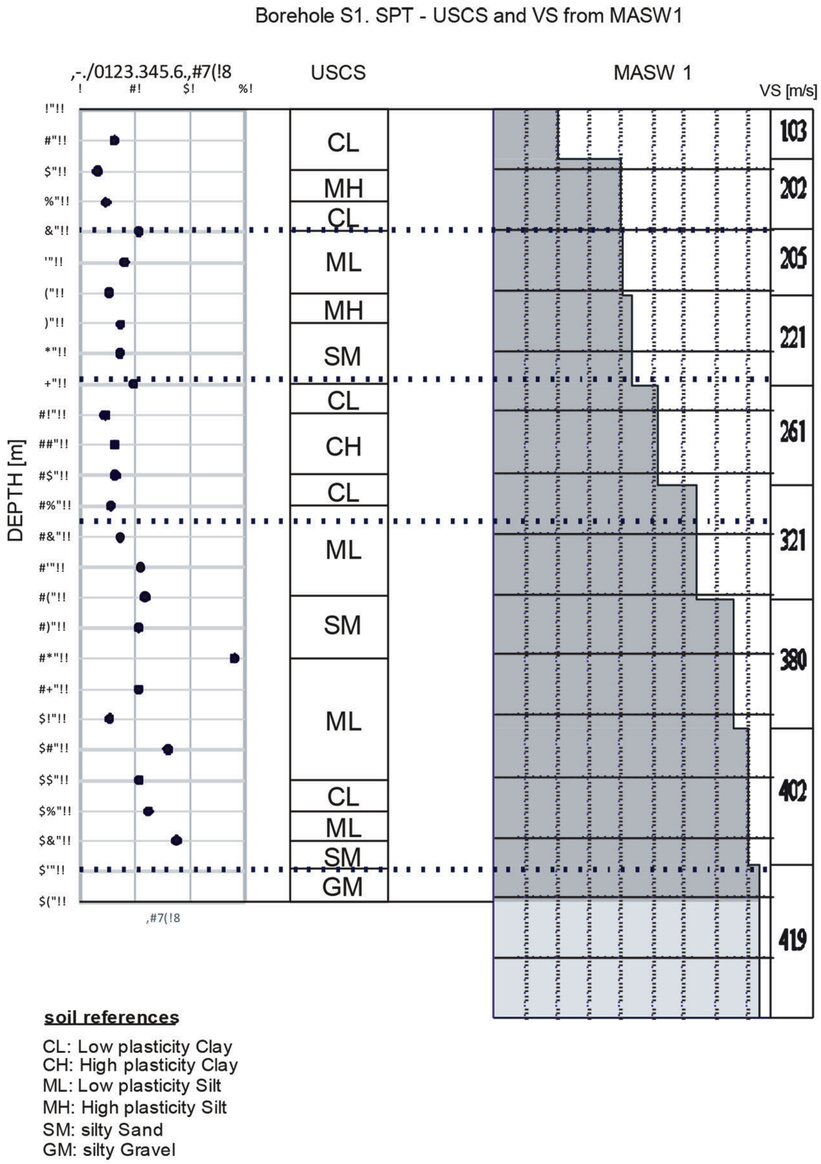

Figure 8. Models Borehole 1 related (from left to right): N from SPT; Unified

in Figure 9 (a-c) respectively. The mathematical expression that best fitted to experimental data was:

$$V_S = a.N^b \tag{3}$$

As it was discovered, for the type of soil found in field, there are two types of particular areas that provoked that adjustments constants a and b would be different in both cases.

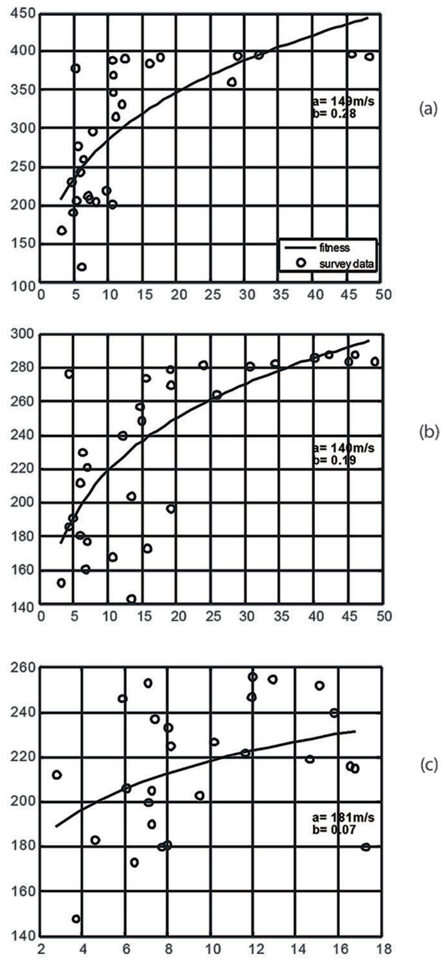

Figure 9. Vs curve fitting related to N

It can be seen that both curve (a) and (b) belong to the same Area 1 and therefore, as it was expected, they have a numerical adjustment with similar constants; which made it possible to calculate an average:

$$\bar{a} = 144.5\ \frac{m}{s}$$

$$\bar{b} = 0.235$$

This situation corresponds to so-called normal soils, in that there is an increase of VS and N with depth that follows an exponential law, having similar results concerning several authors (Table 3) relating the same type of materials found.

TABLE 3

Author	Equation	Notes
Imai y Yoshimura(1970)	$V_s = 76 \cdot N^{0.33}$	
Ohba y Toriumi(1970)	$V_s = 84 \cdot N^{0.31}$	
Imai(1977)	$V_s = a \cdot N^b$	a=102;b=0.29;HoloceneClay a=81;b=0.33;HoloceneSand a=114;b=0.29;PleistoceneCl a=97;b=0.32;PleistoceneSnd
Ohta y Goto(1978)	$V_s = 85.34 \cdot N^{0.348}$	every soil type
okamoto et al(1989)	$V_s = 125 \cdot N^{0.3}$	Pleistocene Sand
Japan Road Association (2002)	$V_s = 80 \cdot N^{0.33}$	sand
	$V_s = 100 \cdot N^{0.33}$	clay
Vs=shear wave velocity (m/s);N=SPT blow number		

Nevertheless, in Sector 2 southwards, the situation changes as verified, and thus also the constants:

a=181 m/s

b=0.07

In short, Table 4 allows to calculate V_S values from N for each of both sectors, in those wells where there are no available V_S data.

TABLE 4.

Expressions to predict V_S from N

Sector	Equation	Boreholes
1	$V_S = 144.5. N^{0.235}$	S1 – S4 – S6 – S2 – S5 – S7
2	$V_S = 180. N^{0.07}$	S3

5. CONCLUSIONS

It was possible to integrate different methodologies to obtain consistent results. The MASW technique proved to be very accurate to determine soil types from shear waves velocities' determination.

Also, having data of N and VS from MASW in some boreholes, it was possible to establish a law of variation of VS with N, so as to be able to predict values of shear waves in those places where there is no such information.

Due to the existence of two types of profiles for the subsoil, two different laws were determined for VS variation related to N; one to the north of the study area, and the other to the south.

According to them it was concluded that the soil stability conditions worsen southwards.

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