Vs30 structure of Murcia city (Southeast of Spain) derived from Mini-array observations, MASW measurements and the topographic slope method.

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Abstract

In order to develop a detailed seismic risk assessment of Murcia city, a classification of the shallow urban geological structure has been carried out in terms of the average S-wave velocity in the upper 30 m (Vs30). Three independent methodologies were applied to estimate the Vs30 values and the results were compared. The first one is the Mini-array method for analysis of ambient noise measurements. This method was carried out at 50 places spread over soils with different geotechnical properties on a 1000 x 1000 m square grid. The second method was the Multichannel Analysis of Surface Waves (MASW), in both the active and passive modes. This method was performed along 7.6 km of linear transects through the streets of Murcia, designed to sample different geological structures. Finally, a regional Vs30 distribution map was obtained from the topographic slope estimation (proxy method) from the digital elevation model, considering this zone as an active tectonic region.

From the geological point of view, the ground of Murcia city is mainly composed of Quaternary alluvial deposits with different sediment thicknesses. The lowest values of Vs30 (283±29 m/s) are found in the southern part of the city, around the Segura river, which correspond to materials of Holocene alluvial fans classified as EC8-C ground class. The higher values (588±12 m/s) are distributed along the northern part of the city (EC8-B ground class), mainly composed of conglomerates clays and sits with intercalations of limestones and dolomites. Vs30 values increase gradually from SE to NW in the metropolitan area of Murcia city.

The statistical comparison of the results obtained shows the weightiness of including indicator variables for the geologic units in the correlation between calculated Vs30 and the topographic slope.

Keywords: Ambient noise, Mini-Array, MASW, topographic slope, Vs30 structure.

1. Introduction

Murcia region is located in southeast Spain (Fig. 1). In spite of the low moderate seismic activity of this region in a worldwide context, this is the most hazardous seismic area of Spain, with active faults that can frequently generate small to moderate magnitude earthquakes (generally smaller than 5.5). The new seismic hazard map of Spain [1] reveals that the region of Murcia has areas with expected peak ground acceleration (PGA) on rock greater than 0.2g for a 475-year return period, reaching 0.23g in Murcia city.

The development of seismic assessment studies in the municipality of Murcia has been promoted after the May 11th, 2011 Lorca destructive earthquake (Mw = 5.2) with catastrophic consequences in Lorca town despite being a relatively small event [2].

The stiffness degree and thickness of geological materials are two key properties that modulate the strength of the earthquake shaking. The mean shear-wave velocity in the uppermost 30m ground thickness (Vs30) has been adopted as a representative site effect characteristic parameter [3]. The aim of this study is to obtain Vs30 structure of Murcia city from passive and active measurements using Mini-array [4] and Multichannel Analysis of Surface Wave method (MASW, [5]) methods, and compare the results with the topographic slope method [6].

2. Local Geology

The regional geological framework of Murcia city corresponds to the Betic Cordillera, a set of mountain ranges originated during the alpine cycle that extends in the South of the Iberian Peninsula. From a local perspective, the city is framed in the Vega Media of the Segura River, part of a tectonic accident of NE-SW tend responsible for the development of the set of Quaternary deposits distribution. This basin is inscribed in an intramontane environment of tectonic subsidence which limit coincides with important fault lines: The Lorca-Alhama fault and the Carrascoy fault.

The geological information at scale 1:50.000 [7] shows that the current river course runs on the sediments of its floodplain (Figure 1), whose substrate corresponds to deposits of alluvial fans, constituted by large bodies of gravels and sands, with silts and clays, which frequently show indentation relationships with alluvial deposits. Sedimentation in the central sector of the basin corresponds to in alluvial sedimentary environments and marginally in alluvial fans in their distal facies.

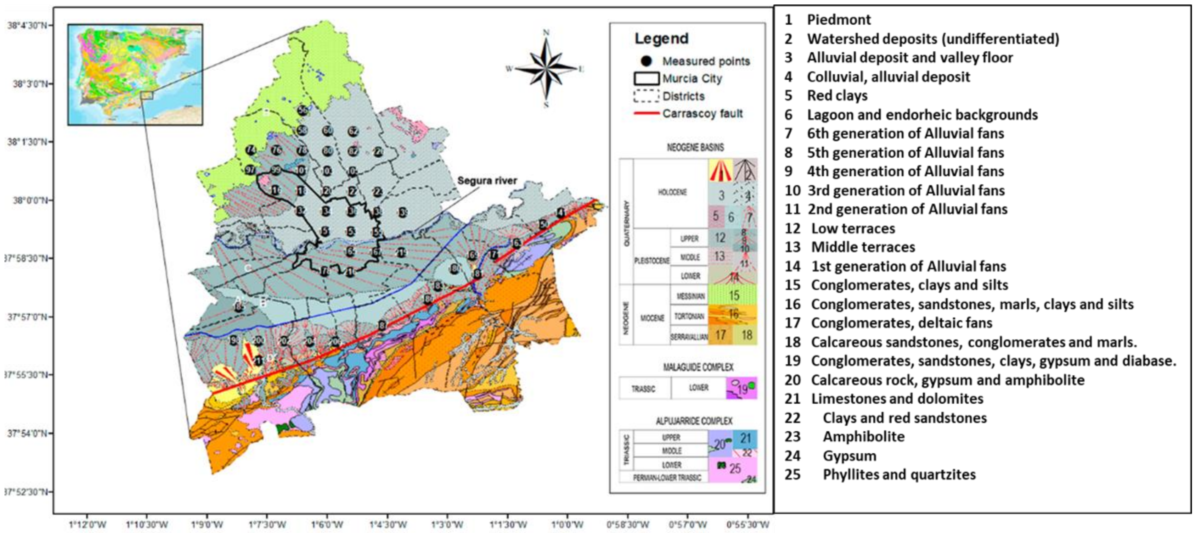

Fig. 1 – Location of Murcia and geological map of Murcia city (thick black line) and its districts (black dotted lines) at scale 1:50.000 [5]. The numbers represent the ID Mini-array measurements.

3. Methodology and results

3.1 Mini-array method

The Mini-array method for ambient noise [4] has been used in this study to analyze the shallow ground structure in Murcia. Rayleigh wave phase velocities (c_R) were identified up to wavelengths of several tens of meters using Centerless Circular Array method (CCA) [4].

At each place, six tri-axial JU410 seismographs composed of 3 JA-40GA04 servo accelerometers were placed on the ground surface, one at the center and 3 evenly spaced on a circumference of 60 cm radius. Other 2 seismographs were placed 5-10 m apart from the central one forming an irregular array (Fig. 2). Recording time was 16 min, and the signal was sampled with a rate of 200 sps.

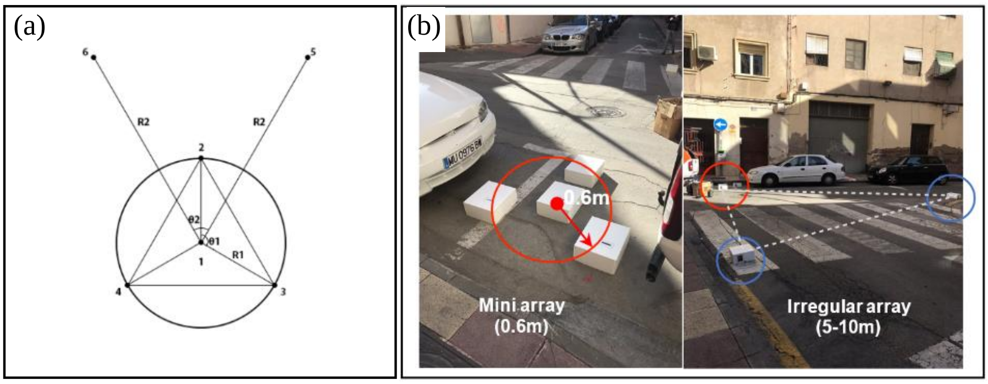

Fig. 2 – a) Scheme of the array; b) General view of an array observation in Murcia city.

A simple profile method (SPM) (e.g. Tokimatsu [8]) was applied to obtain the S-wave velocity profile at each site (Fig. 3) using the software described by Cho & Senna [9] and the Vs30 value was subsequently computed from that model.

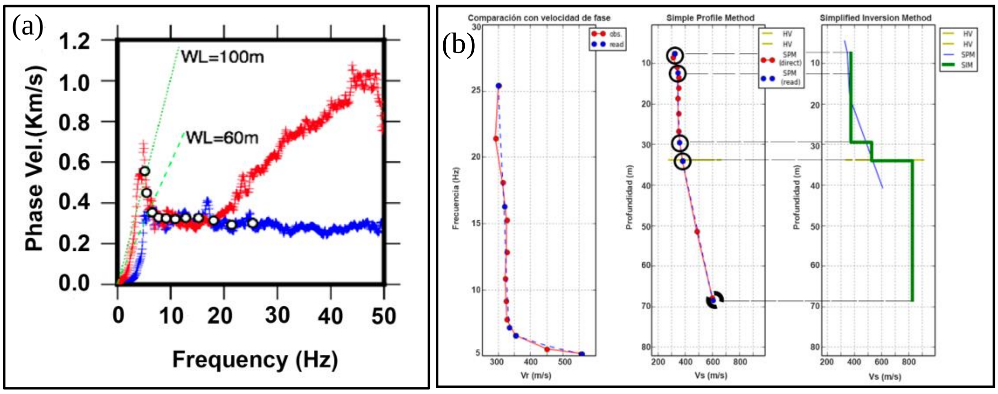

Fig. 3 – (a) Example of Rg-wave dispersion curves obtained from the small regular array (blue color) and irregular array (red color); (b) Example of 1D Vs model.

The Mini-Array method was applied at 50 places with different geotechnical properties. A 1000 m x1000 m grid was used in the metropolitan area of Murcia city and in surrounding populated areas. Spacing of 1000 m was also used for measurements along Carrascoy fault, the boundary between Segura river basin and Carrascoy mountain range (see Fig. 1).

The dispersion curves obtained from Mini-array method show a frequency range from 5 to 50 Hz and phase velocities between 215 and 760 m/s. The Vs30 values vary between 243.7 m/s and 772.6 m/s in Murcia city (Fig. 4). Along Carrascoy fault, close to the mountains, the Vs30 values range from 360.8 m/s to 816.9 m/s.

In general, the smallest Vs30 values are concentrated in the southern part of Murcia city, around Segura river, composed by Quaternary alluvial deposits. At the northern part of the city, also on Quaternary alluvial deposits, Vs30 values are between 438.9 m/s and 591.1 m/s. This result could be interpreted as the influence of Miocene conglomerates in the zone. Along Carrascoy fault, the places located on alluvial fans show the lowest Vs30 values of around 320 m/s. However, the places located near Carrascoy Mountain show the highest values (Fig. 4).

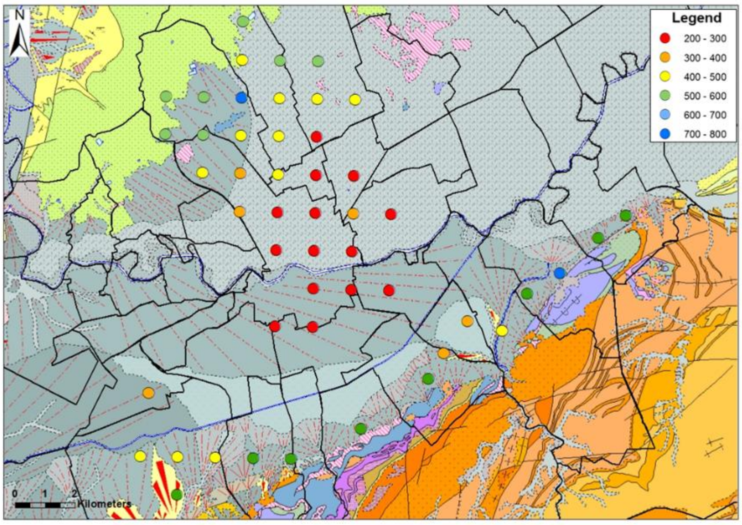

Fig. 4 – Vs30 values distribution maps in Murcia from Mini-Array observations.

3.2 MASW method

This method was applied on 7.61 km of linear transects through the streets of Murcia. These linear transects were chosen with the objective of crossing the main geological structures which are well known from previous geological data [7]. The MASW method was performed in both the active and passive modes [5]. This combined use of active and passive forms allowed greater penetration depths and better resolutions of the Vs profiles [10].

Sledge hammer was used as seismic source (Fig. 5a). For the purpose of recording seismic data at high productivity a towed land-streamer was developed and built using a heavy-duty fire hose (Fig. 5b). A total of 24 geophones of 4.5 Hz natural frequency were mounted into the rubber hose and screwed onto metal plates with a geophone spacing of 2 m. The offset was 4 meters and the acquisition array of 46 m in length was displaced 10 meters between consecutive shots using an off-road vehicle (Fig. 5c). The recording unit was the SUMMIT II Compact unit from DMT, Germany, and the software used to process the seismic data was the SurfSeis software package from the Kansas Geological Survey, USA.

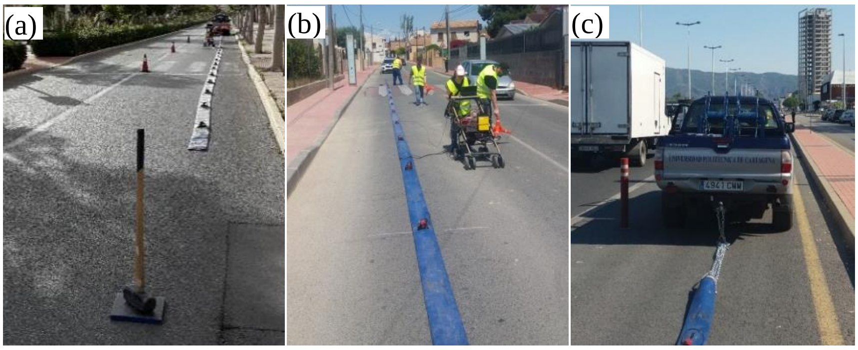

Figure 5 – Equipment to develop the MASW measurements. a) Sledge hammer; b) Land-streamer; c) Off-road vehicle.

That software package allowed us to retrieve a dense series of Rg-wave dispersion curves through an appropriate straightforward inversion process [1, 12]. Then, the 1D S-wave velocity model in the middle of each receiver spread was determined from the inversion process and the 2D cross-section (Fig. 6) was interpolated [11].

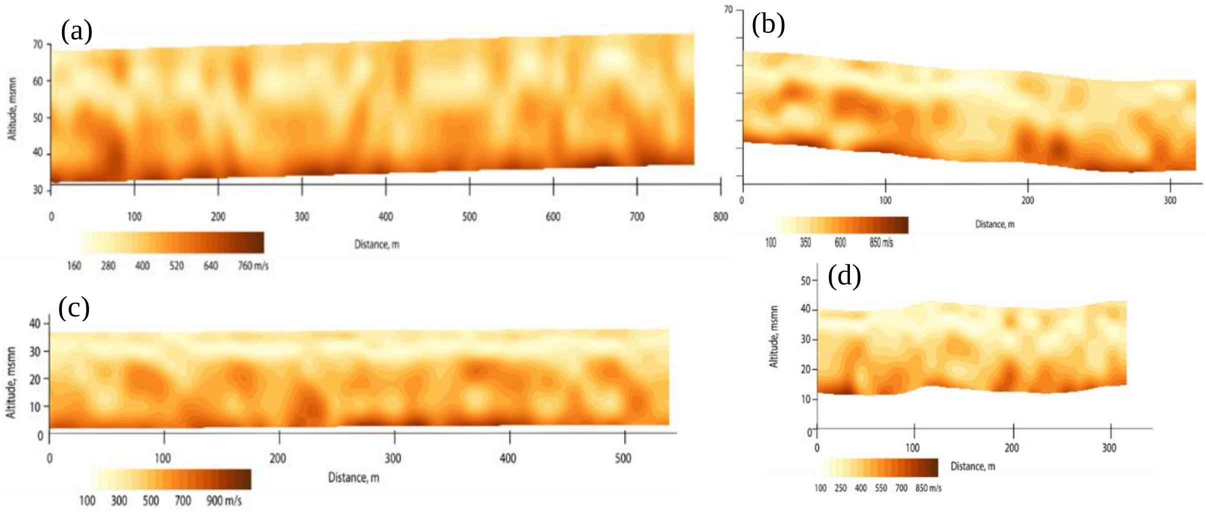

Fig. 6 – Examples of 2D S-wave velocity sections. a) M1; b) M2; c) M3.4; d) M4.4 (see locations in Fig. 7)

The average Vs30 values calculated for each section of the MASW profiles (Fig. 7) show good correlation with the distribution of geological materials. The lower values are located around Segura river, with soils composed of alluvial fan_1 deposits, with a mean of Vs30 of 303±28 m/s, growing in the south-north direction up to 559±46 m/s in the alluvial fan_2 deposits.

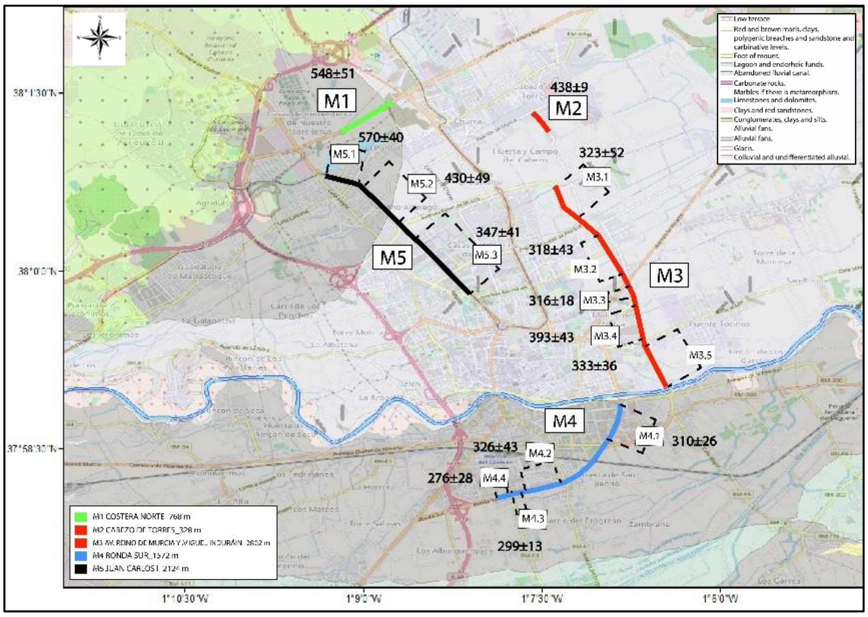

Fig. 7 –Mean Vs30 values from MASW method.

3.3 Topographic slope method

The topographic slope method is an innovative, fast and very low-cost technique to estimate the Vs30 from the morphological characteristics of the surface. This method is based on the relationship between this quantity and the slope of the ground, which can be easily obtained through a Digital Elevation Model (DEM) for most parts of the world. The relationship found by Wald and Allen [6] is shows in Table 1.

Table 1 – Slope ranges for NEHRP Vs30 categories.

NEHRP Class	**Description**	**Vs30 range (m/s)**	**Slope range (m/m)**	
			Active tectonic	**Stable continental**
A/B	Rock	> 760	> 0.14	> 0.025
C1	Very dense soil and soft rock	620-760	0.10-0.14	0.018-0.025
C2		490-620	0.05-0.10	0.013-0.018
C3		360-490	0.018-0.05	7.2×10^{-3}-0.013
D1	Stiff soil profile	300-360	0.010-0.018	4×10^{-3}-7.2×10^{-3}
D2		240-300	3.5×10^{-3}-0.010	2×10^{-3}-4×10^{-3}
D3		180-240	3×10^{-4}-3.5×10^{-3}	2×10^{-5}-2×10^{-3}
E	Soft soil profile	<180	$< 3 \times 10^{-4}$	$< 2 \times 10^{-5}$

Using the topographic slope method applied to a digital elevation model with resolution 200 m (Fig. 8), it has been possible to obtain the map of estimated Vs30 values shown in Fig. 9. This map reveals a good correlation with the distribution of geological materials (see Fig. 1). The estimated Vs30 ranges from 180 m/s in alluvial fan deposits located on Murcia basin to 1130 m/s in Carrascoy Mountain mainly composed of limestones and dolomites. The estimated Vs30 distribution in the area of Murcia city shows the same trend obtained in the case of Mini-array and MASW results, i.e. values grow in the south-north direction.

The mean Vs30 values estimated for each geological unit located in Murcia city ranges between 244±29 m/s in the southern part of the city, around the Segura river, and 482±104 m/s distributed along the northern part.

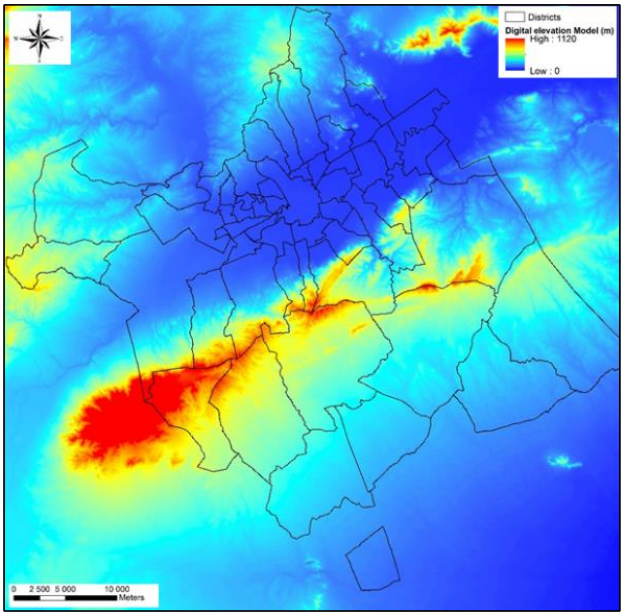

Fig. 8 – Digital Elevation Model of Murcia area with resolution 200m.

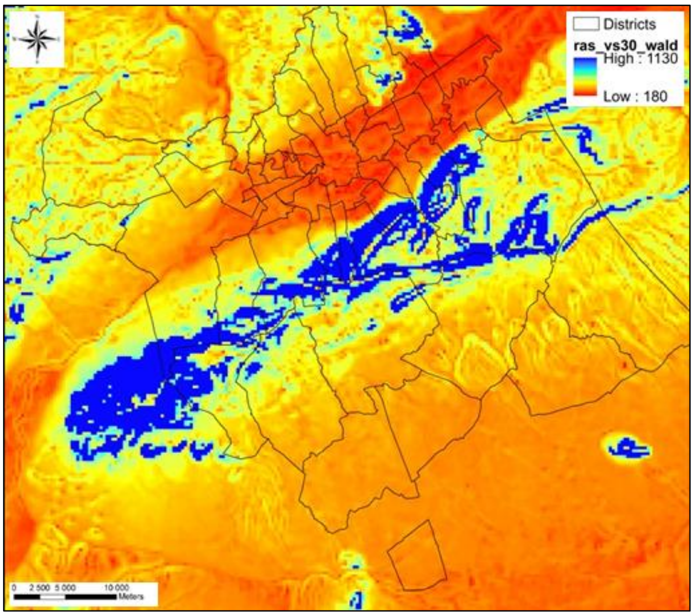

Fig. 9 – Vs30 distribution map in the municipality of Murcia from the topographic slope method.

4. Statistical comparison

4.1 Mini-array vs. MASW

The average Vs30 values calculated from Mini-array and MASW methods have been compared for different geological units (Fig. 10, Table 2). In general, a good correlation between them is observed. In both cases, the lower values are located in the south of the study area, below Segura river, composed of alluvial fan deposits. The values grow as we move towards the north of the city, where conglomerates outcrop.

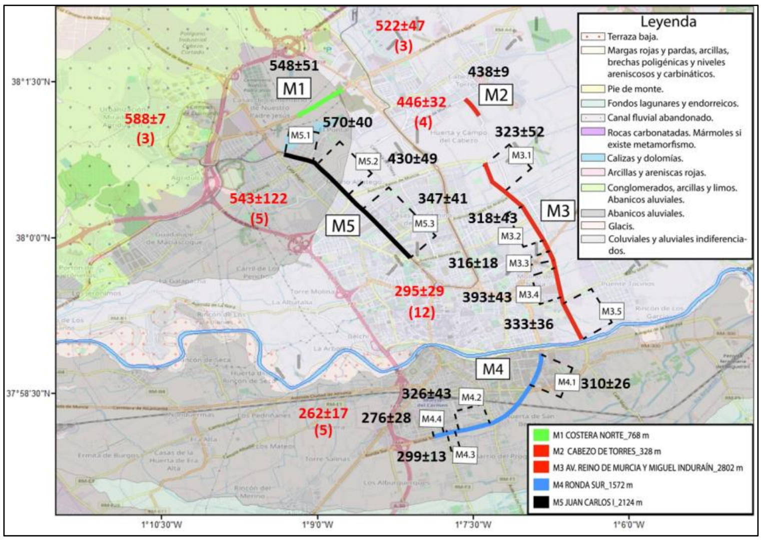

Fig. 10 – Average Vs30 values obtained from MASW method (black labels) and Mini-array measurements (red labels).

In order to analyze the deviation between the Vs30 values derived from Mini-array and from MASW profiles, a number of points have been selected considering equal distance to the nearest Mini-array and

MASW measurements (Fig. 11). Subsequently, the deviation of the difference in the results obtained with each model at these test points was calculated. The results show a mean deviation of 43.3 m/s.

Table 2 – Comparison of average Vs30 values from Mini-array and MASW methods for different geological units.

Geological Unit	Lithology	Vs30 (m/s)	
		Mini-array	MASW
1	Alluvial fan_1	262±17	303±28
2	Alluvial fan_2	543±122	559±46
3	Colluvial_1	295±29	338±39
4	Colluvial_2	446±32	434±25
5	Colluvial_3	522±47	-
6	Conglomerates, clays and silts	588±7	-

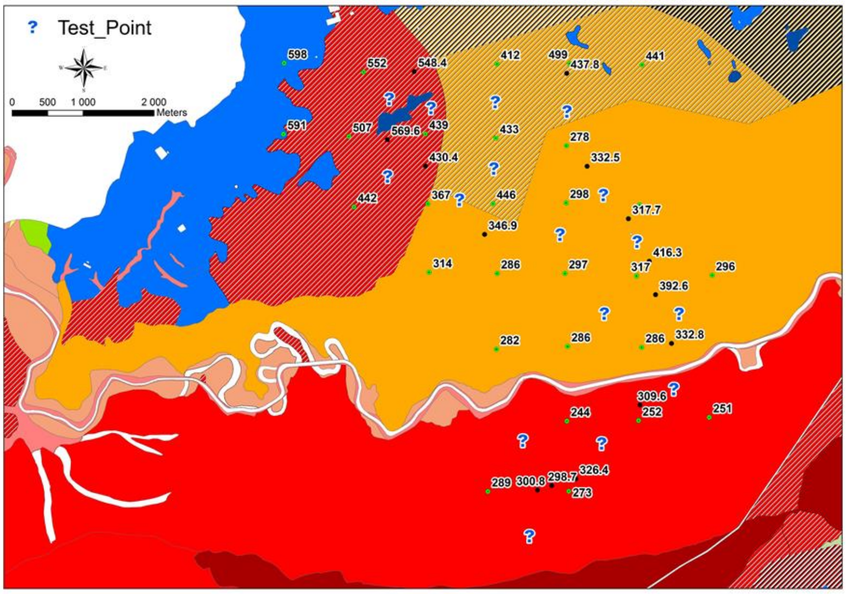

Fig. 11 – Selected points to analyze the deviation of Vs30 values obtained from Mini-array and MASW methods.

4.2 Mini-array vs. topographic slope.

The relationship between the calculated Vs30 and the slope has been fitted assuming log-normal distribution [14]. The ordinary least squares (OLS) has been applied and two possible functional forms: a) lineal relationship between calculated Vs30 and topographic slope (Eq. 1); b) lineal expression including dependence for the geologic units (Eq.2).

$$\text{Log (Vs30)} = \beta_0 + \beta_{slope}\,\log(\text{slope}) + \text{residual} \quad (1)$$

$$\text{Log (Vs30)} = \beta_0 + \sum \beta_i\, x_i + \beta_{slope}\,\log(\text{slope}) + \text{residual} \quad (2)$$

where: x_i are indicator variables for the geologic units, β_i, and β_{slope} are the coefficients to be calculated using least squares regression, Vs30 is the observed data in m/s and *slope* is computed from the DEM in m/m.

The metropolitan area of Murcia was divided in four geological units considering the Vs30 values obtained from Mini-array (Fig. 12) and the mean value of Vs30 for each geological unit [15] was obtained.

If the Eq. 1 is used for the relationship between calculated Vs30 and slope, the reliability evaluating by Multiple R Squared (MRS) is 75.7%. This result is lower than that obtained considering indicator variables associated to the geological unit (Eq. 2). In this case the reliability is 89.3%.

The statistical indicators of Vs30 values obtained from (Eq 1) and from (Eq 2) have been compared. The results show smaller range of Vs30 values and lower standard deviation in the second processing. The average standard deviations are 69.2 m/s and 15.7 m/s respectively.

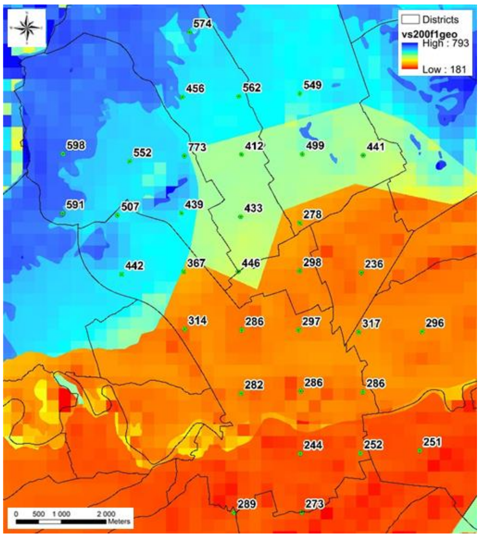

Fig. 12 – Comparison between Vs30 values from Mini-array (green dots) and from Topographic slope method (color scale).

4.3 MASW vs. topographic slope.

Considering the average Vs30 values in the center of each MASW profile (Fig. 13) and comparing with ground slope in the two versions indicated above. The MRS correlation coefficient is 68.2% using Eq(1). If the dependence for each geological units is considered (Eq. 2), the MRS correlation coefficient is higher: 85.2%. The comparison of statistical indicators of Vs30 values obtained from both process shows that the smaller range of Vs30 values and lower standard deviation are found if indicator variables for geological units are considered. The average standard deviations are 45.2 m/s and 21.5 m/s respectively.

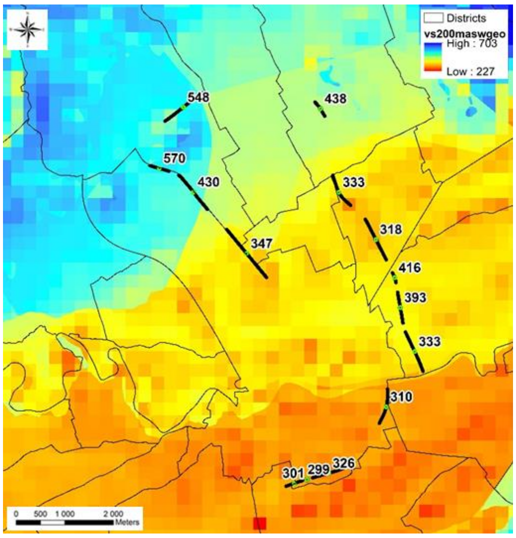

Fig. 13 – Comparison between Vs30 values obtained from MASW (green dots) and from topographic slope method (color scale)

4.4 Mini-array and MASW vs. topographic slope.

The Vs30 values obtained from Mini-array and MASW have been compared to the results from slope method using Eqs. (1) and (2). For the first one, the reliability estimated as the Multiple R Squared (MRS) is 71.4%, while for the second, the reliability is 83.6%.

A raster map of Vs30 has been drawn using the correlation with slope and geological units characteristics in the areas where said geological units have been identified, and only the correlation with slope in the rest of the zones (Fig. 14). The comparison of statistical indicators of Vs30 values obtained from Eq.(1) and Eq.(2) show that the smallest range of Vs30 values and lowest standard deviation are obtained considering the dependence on the geological units. The average standard deviations are 61.7 m/s and 21.4 respectively The correlation between log(Vs30[m/s]) and log(slope[m/m]) has been represented in Fig. 15a. When indicator variables for the geologic units are considered, The relationchips shown in Fig. 15b are obtained.

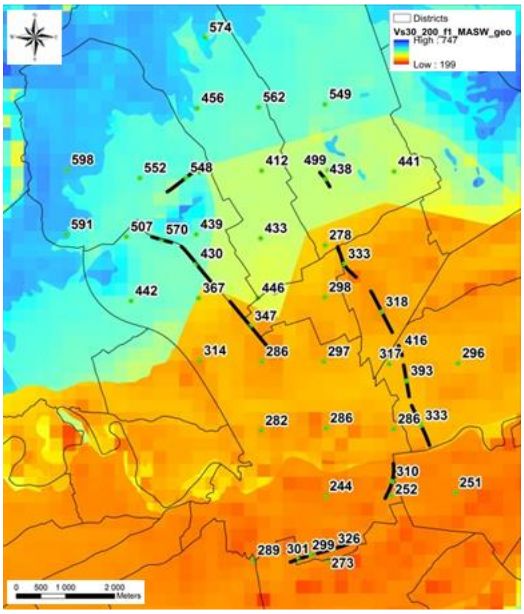

Fig. 14 – Comparison of Vs30 values obtained from Mini-array and MASW method with the results of the topographic slope method.

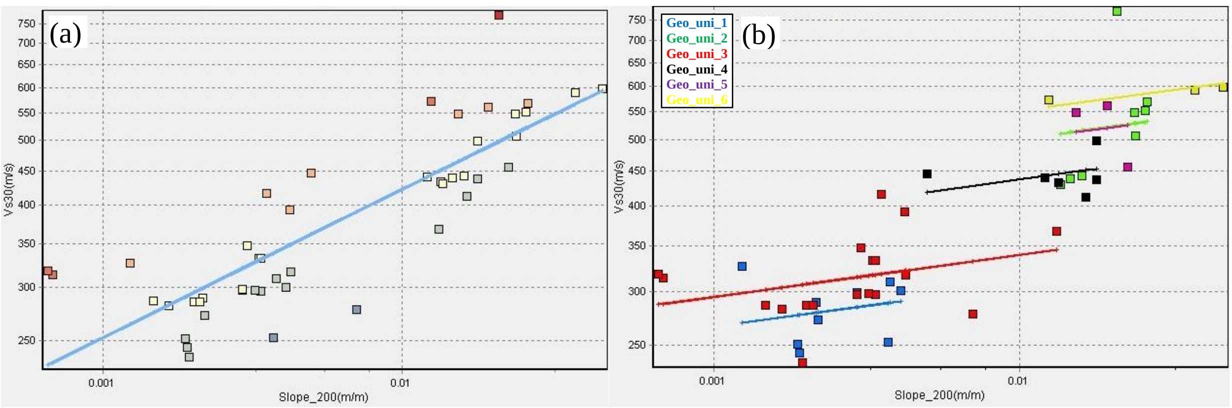

Fig. 15 – Correlation between calculated Vs30 values and slope: a) Using only those variables; b) Considering indicator variables for the geological units.

The results show mean Vs30 values for each geological unit (considering Eq.2) between 280±12 m/s for the alluvial fan_1 unit and 605±20 m/s for the unit composed by conglomerates clays and sits. These results are consistent with the average values obtained from Mini-array and MASW methods.

The average Vs30 estimated from the original topographic slope method (OTS, [6]) and from the topographic slope method including dependence on the geologic units (TSGU, Eq.2) have been compared in Table 3. The results show a mean deviation of 23.3%.

Table 3. Average Vs30 value from different relationshis between Vs30 values and slope.

Geological Unit	Lithology	Vs30 (m/s)	
		OTS	TSGU
1	Alluvial fan_1	244±29	280±12
2	Alluvial fan_2	373±59	517±43
3	Colluvial_1	251±31	313±13
4	Colluvial_2	346±55	446±20
5	Colluvial_3	418±99	532±20
6	Conglomerates, clays and silts	482±104	605±20

5. Conclusions

From the geological point view, the ground of Murcia city is composed mainly of Quaternary materials such as alluvial and colluvial deposits with different sediment thicknesses located in the south and center of the city, and conglomerates, clays and silts in the north.

The analysis of Vs30 structure by using Mini-array and MASW methods has allowed to differentiate six geological units characterized by its average Vs30 values. The mean Vs30 values range from 283±29 m/s in alluvial fan_1 deposits, located in the south of the city around Segura river, to 588±12 m/s for the conglomerates in the northern area.

The Vs30 values increase from South to North even within the same geological unit, highlighting the vertical and lateral heterogeneity due to differences in sediment thicknesses, as it is observed in the 2D cross-sections obtained from MASW profiles.

The statistical comparison of the results obtained from the different models shows the weightiness of including indicator variables for the geologic units in the correlation. The average reliability evaluated by Multiple R Squared varies between 71.8% using lineal relationship between calculated Vs30 versus topographic slope and 86% including indicator variables for the geologic units. The difference is more significant for the mean standard deviations for each geological unit analyzed, being 58.7 m/s in the first one and 18.5 m/s in the second.

Values of Vs30 estimated from the slope, including in the relationchip dependence on the geologic unit are consistent with the average values obtained from Mini-array and MASW methods. The comparison with the original topographic slope method shows a mean deviation of 23.3%.

6. Acknowledgements

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7. Copyrights

8. References

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