MASW joint analysis of Rayleigh and Love waves for site characterization

Juan José Hellín-Rodríguez[1], *Pedro* Martínez-Pagán*[2], *Ignacio* Valverde-Palacios[1], *Antonio* García-Jerez[3], *Koya* Suto[4], *Marcos Antonio* Martínez-Segura[2], *José Francisco* Orta[1], and *Julia* Álvarez-Lozano[1]

[1]*University of Granada, Andalusian Institute of Geophysics and Prevention of Seismic Disasters, C/ Profesor Clavera, 12, 18071, Granada, Spain*
[2]*Universidad Politécnica de Cartagena, Department of Mining and Civil Engineering, Pº Alfonso XIII, 52, 30203, Cartagena, Spain*
[3]*Universidad de Almería, Carretera Sacramento, s/n, 04120, Almería, Spain*
[4]*Terra Australis Geophysica Pty Ltd, 52 Nestor Avenue, Bardon, Queensland, 4065, Australia*
#*Corresponding author: p.martinez@upct.es*

ABSTRACT

The determination of reliable shear-wave velocity models using Multichannel Analysis of Surface Waves (MASW) has increased importantly for site characterisation studies due to their use in geotechnical studies and regulations. The standard MASW approach is commonly based on the analysis of vertical component of Rayleigh waves, which can result in inaccurate and potentially erroneous interpretations by personal bias. Thus, we present the joint analysis of different and independent multi-component data based on Rayleigh and Love waves to obtain 2D Vs sections for site characterization. Those seismic data were recorded using a landstreamer consisting of 8 triaxial 4.5Hz geophones. To generate Rayleigh waves, the blows were given vertically on a plate, and for the Love waves the blows were given laterally on a horizontal wooden beam. A joint analysis of Rayleigh and Love waves data was conducted on seismic data recorded from the metropolitan area of Granada city (Spain) to generate their dispersion curves. This new approach enabled a proper identification of fundamental- and higher-mode surface waves facilitating the reliable reconstruction of subsurface Vs profiles through a robust joint inversion process. The MASW 1D Vs versus depth models were corroborated at several test sites by the information obtained from boreholes. Thus, the main geological formations could be inferred from MASW 2D Vs sections down to a depth of 30 meters, as well as the Vs30 parameter to perform a reliable seismic microzonation of the study area. This methodology provides a very well constrained inversion procedure capable of providing a robust subsurface Vs model for site characterization.

Keywords: Shear-wave velocity; MASW; Rayleigh and Love waves; Site characterization.

1. Introduction

Site investigations require multidisciplinary participation by geologists, seismologists, and geotechnical and earthquake engineers. In this way, Figure 1 shows the typical workflow for geotechnical site investigation studies with the ultimate objective of a geotechnical design (Yilmaz 2015). Figure 1 points out that knowledge of the soil-column shear-wave velocity (Vs) is essential for designing civil engineering structures. In fact, the shear-wave velocity is a key parameter in dealing with mechanical properties of subsurface materials (Martínez-Pagán et al. 2018; Duan et al. 2019; Aas and Sinha 2023; Suto 2023), ground amplification, and liquefaction potential phenomena in earthquake events (Kumari et al. 2021; Hinojosa 2023; Sonmezer, Celiker, and Simsek 2024). Moreover, Vs models have been applied to seismic hazard assessment due to the fact that ground amplification often changes with shallow ground stiffness (Martínez-Pagán et al. 2018). Due to that, the Vs parameter has been adopted by international building committees such as the European Committee for Standardization, or the National Earthquake Hazards Reduction Program (USA). All of these international committees consider the average Vs in the top 30 m (usually denoted by Vs30) as the fundamental ground parameter to be considered for the structural design of buildings against earthquake occurrences (López et al. 2022).

In view of this, it is crucial to employ suitable approaches that provide reliable Vs models. Presently the main methodologies for the determination of the subsurface Vs profile from surface seismic data are the MASW (*Multichannel Analysis of Surface Waves*), ReMi (*Refraction Microtremor*), SPAC (*Spatial Autocorrelation*), MAAM (*Miniature Array Analysis of Microtremors*), and HVSR (*Horizontal-to-Vertical Spectral Ratio*) (Giancarlo Dal Moro 2020; Kumar, Satyannarayana, and Rajesh 2022). These methods commonly record seismic data based on a set of vertical geophones as a standard approach (Dal Moro 2020). But these standard approaches deal with just one observable as it is the dispersion of the vertical component of Rayleigh waves.

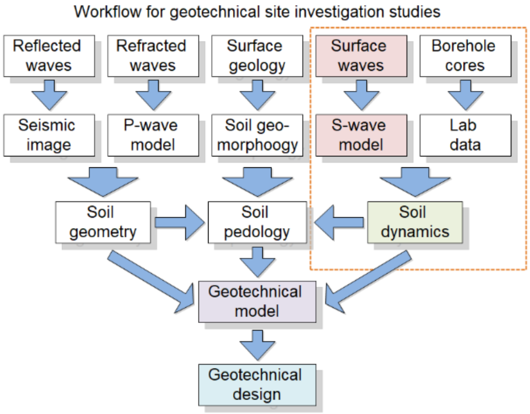

Figure 1. Workflow for a geotechnical site investigation study (modified from Yilmaz, 2015).

In this study, we examine the joint analysis of Rayleigh and Love waves by implementing the MASW method to reduce seismic data ambiguity and non-uniqueness of the subsurface shear-velocity models. More specifically, this joint analysis will provide a more robust inversion process and obtain a more reliable subsurface model for site characterization.

2. Study area

This work has been conducted in the municipalities of Fuente Vaqueros, Atarfe, and Santa Fe, which belong to the Metropolitan Area of Granada (MAG), Spain (Figure 2). These municipalities are in alluvial (quaternary) soils (clay, silt and sand with some gravel), where the depth of the water table is between 2 and 8 meters.The MAG is a predominantly Quaternary plain located in the north-eastern section of the Granada basin (Figure 2a, b). Most of the main active faults of the Granada basin are in the eastern sector between Sierra Elvira and Padul and pass through the area of Granada (Figure 2a). The MAG is acknowledged to be the most seismically active zone in Spain and seismically induced phenomena such as liquefaction and ground settlement were reported in specific zones during moderate (1806) and strong (1431) historical local earthquakes.

In fact, historical and instrumental seismic data indicate that it is the most seismically active area in Spain, and it is classified as the most hazardous seismic zone in the Spanish Building Code (Valverde-Palacios et al. 2014). A total of 47 villages and towns, including Granada city, are included on this area.

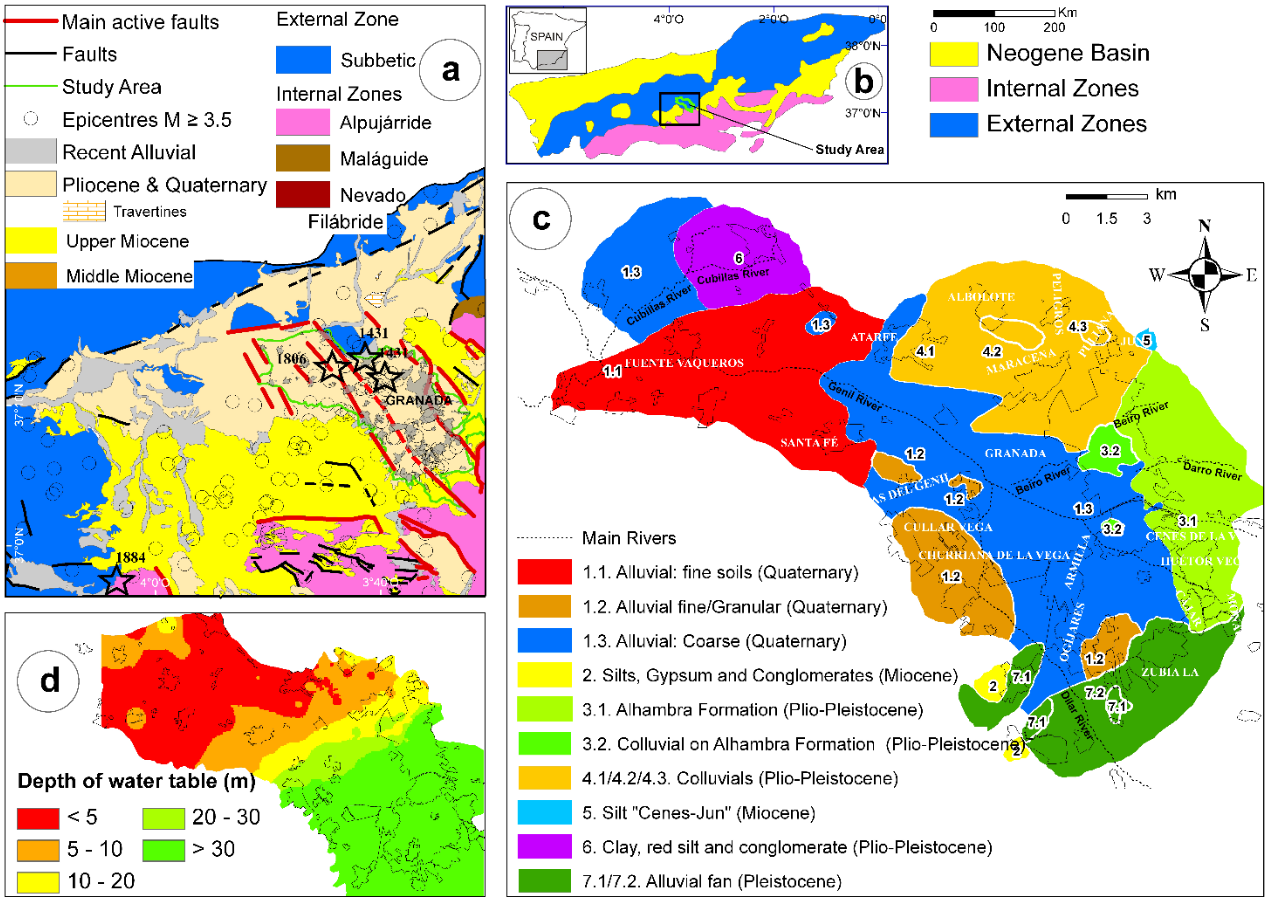

Figure 2. (a) Geological and tectonic sketch of the Granada basin showing the main active faults, geological units, and epicentres of shallow instrumental (circles) and relevant historic earthquakes (stars); (b) General tectonic sketch of the Central and Eastern Betic Cordillera; (c) Spatial location of soil units (zones and sub-zones) of the study area. Town boundaries are shown with a thin polygonal line; (d) Spatial distribution of water table depth.

The ground beneath the urbanized areas of the MAG is located on alluvial, colluvial, silt and clay deposits with different thicknesses of granular soils and varying water table depths (Figure 2c, d). In the last twenty years, the population of the MAG has doubled, and the built-up land increased a 30%, mainly on sedimentary deposits. Accordingly, the assessment of these earthquake-induced hazards is necessary.

3. Methods

We employed the multichannel analysis of surface waves (MASW) method, a technique developed and discussed by Park, Miller, and Xia (1999) to retrieve 1D S-wave velocity profiles along the depth. The MASW input data were collected using a towed land-streamer with a total of 8 4.5Hz triaxial geophones with 7 m geophone spacing (Figure 3a). This acquisition system of 49 m in length was displaced 14 m between consecutive shots (Figure 3a). The recording unit was a 24-channel SUMMIT II Compact Seismograph by DMT, Germany.

After same preliminary tests the following acquisition parameters were chosen: a 14-m offset (distance between the seismic source impact point and the first geophone) to minimize near-source effects, 3 shot stacking, 14-m displacement between readings, 1 ms of sampling interval, and 1 s of recording window. A 9 kg sledgehammer was used to generate both Rayleigh waves, blowing vertically on a plate; and Love waves, blowing laterally on a wooden beam (Figure 3b).

Figure 3. (a) Land-streamer, with 4.5Hz triaxial geophones, being towed through the Fuente Vaqueros streets; (b) Sledgehammer-based seismic source for generating Rayleigh (plate), and Love (wooden beam) waves.

Seismic data joint analysis was carried out with open source Geopsy software for seismic component grouping of Rayleigh waves (vertical component or ZVF, which stands for vertical component and vertical force) and Love waves (horizontal component or THF, which stands for transversal component and horizontal force) (Figure 4); and winMASW® software by Eliosoft for data processing consisting of data filtering, and computing of the phase velocity spectra (i.e. the frequency-velocity matrix computed according to the phase-shift method discussed by Park et al. 1998; Dal Moro et al. 2003)). Finally, 1D/2D shear-wave velocity (Vs) models were obtained through mathematical joint inversion of dispersion curves retrieved from phase velocity spectra by means of winMASW software.

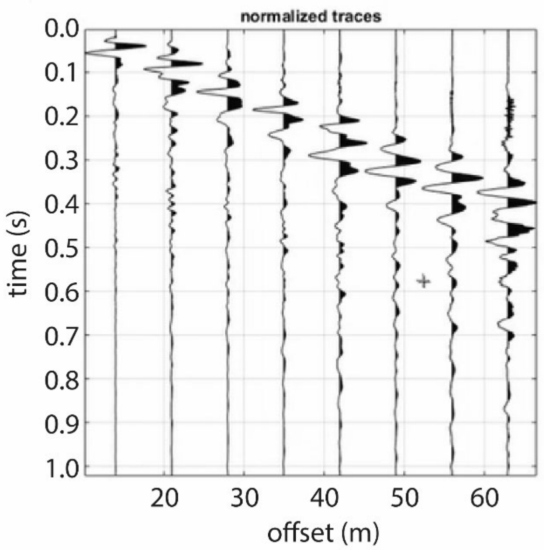

Figure 4. Example of a seismic dataset obtained at the Metropolitan area of Granada, corresponding to vertical component. Traces put in evidence the Rayleigh waves. The sampling interval was 1ms, with 1024 samples per trace, a source offset of 14 m, and 7 m of geophone spacing.

4. Results and discussion

Figure 5a depicts the phase-velocity spectrum obtained from a dataset of Rayleigh waves recorded in the vertical component of triaxial geophones and generated through vertical blows. It shows the picking undertaken (pink-colour dots) on the fundamental model, and on the first higher mode. The retrieved portion of the dispersion curve of the fundamental mode starts at the point with phase velocity of 600 m/s and frequency of 8 Hz, which provides a depth of investigation of about 30 meters (Martínez-Pagán et al. 2018), and the picking finishes at around 30 Hz, associated with a phase velocity of 200 m/s. Moreover, figure 5a provides the curve associated with the best (fittest) model shown by a blue colour line, and the curve associated with the mean model characterized by a green colour dashed line.

Figure 5b depicts the phase-velocity spectrum obtained from a dataset of Love waves recorded in the horizontal component of triaxial geophones and generated through horizontal blows. In the same way as previously discussed, it shows the picking undertaken (pink-colour dots) on the fundamental model, and on the first higher mode, which is the initial tentative dispersion curves to be used to generate the 1D shear-wave velocity for the horizontal component. The fundamental mode dispersion curve could be retrieved from the point with a phase velocity of 290 m/s and a frequency of 5 Hz, where lower frequencies are dominated by aliasing. In this example, the fundamental mode picking is extended to a frequency of 32 Hz.

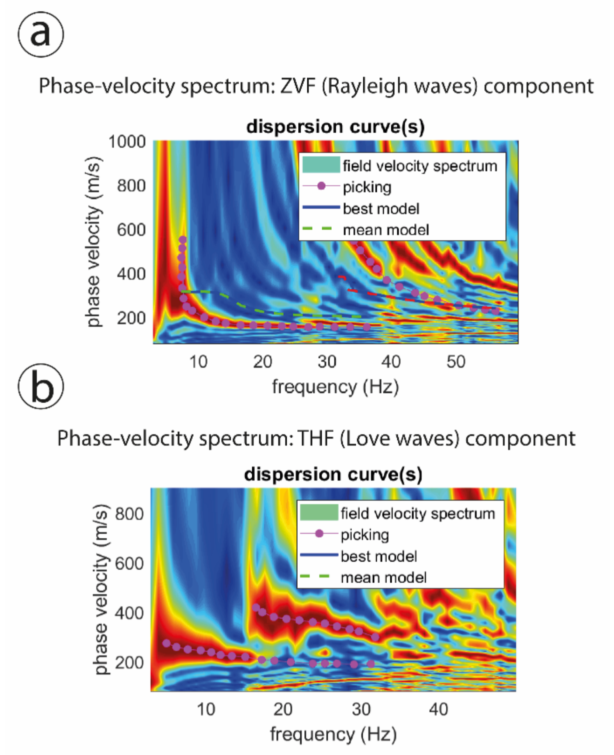

Figure 5. (a) Phase velocity spectrum of the vertical component (Rayleigh waves) with the best calculated dispersion curve; (b) Phase velocity spectrum of the horizontal component (Love waves) with the best calculated dispersion curve.

The fittest 1D shear-wave profiles were obtained, after an independent inversion process of the dispersion curves of the Rayleigh and Love waves. Both 1D shear-wave velocity profiles consist of eight layers (Figure 6), which explains pretty well the geological sequence found in the study area by means of boreholes. However, it can be appreciated that some shift occurred between them regarding the position of the different layers. For example, the 1D Vs model of Figure 6a shows an intermediate layer of lower Vs velocity of about 226 m/s detected at a depth of 15 meters, whereas the 1D Vs model of Figure 6b established the position of this layer at a depth of 12 meters depth. Similarly, differences are noticed at 30 meters depth where Figure 6a shows a Vs value above 700 m/s, whereas Figure 6b shows a Vs value below 500 m/s. It is worth noting that the 1D shear-wave profile from Rayleigh wave component is the main result retrieved from MASW survey for site characterization, however, some concerns arise when we only use that unique observable (Dal Moro and Keller 2013; Dal Moro 2020). To overcome non-uniqueness of the solution and possible interpretative issues, we also considered the 1D shear-wave velocity profile obtained from independent multi-component data: Rayleigh and Love waves joint analysis (Figure 7).

In this way, Figure 7 depicts the best model obtained using Rayleigh and Love waves, shown by blue colour line, in which a depth of investigation of 30 meters has been achieved. This joint 1D Vs model exhibits the intermediate layer of lower velocity at a depth of around 13 meters. This layer is characterized by Vs values of 267 m/s. Then, the material is characterized by an increase in the Vs value of about 411 m/s associated with a horizon of gravels and sands.

The 1D shear-wave velocity model obtained from Rayleigh waves only gave a Vs30 value of 304 m/s, whereas the 1D shear-wave velocity model from joint inversion gave a Vs30 value slightly higher, of 317 m/s. However, both procedures classify similarly the stratigraphic profile as deposits of very dense or medium-dense sand, gravel or stiff clay, according to the Eurocode 8 (Martínez-Pagán et al. 2014). The improvement of the 1D shear-wave velocity profile using joint inversion of Rayleigh and Love waves was evidence when compared to a close geological column and its associated SPT N-value (Figure 8).

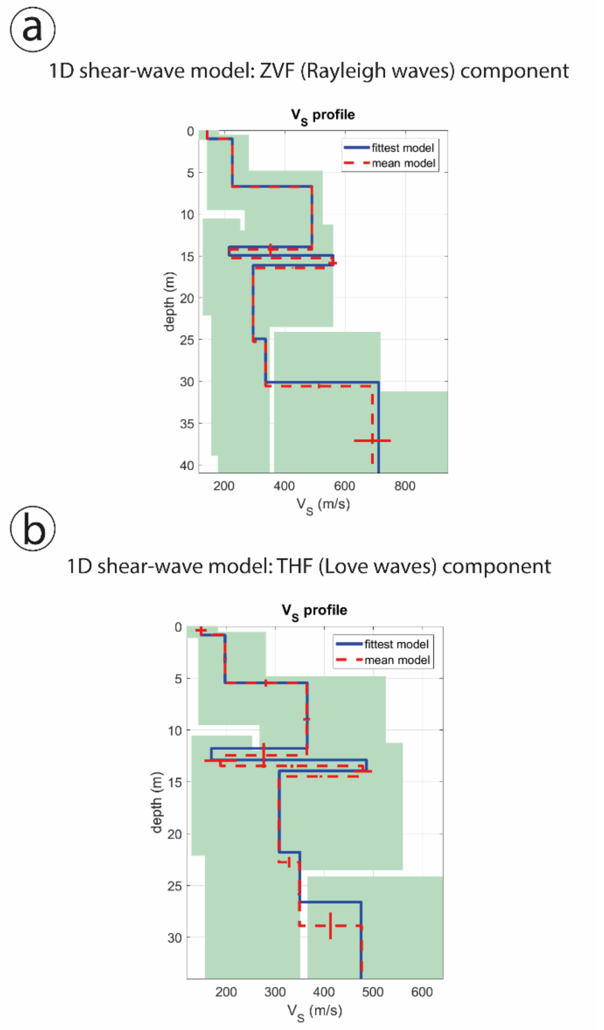

Figure 6. (a) Mean and the best 1D shear-wave velocity profile for the vertical component (Rayleigh waves); (b) Mean and the best 1D shear-wave velocity profile for the horizontal component (Love waves).

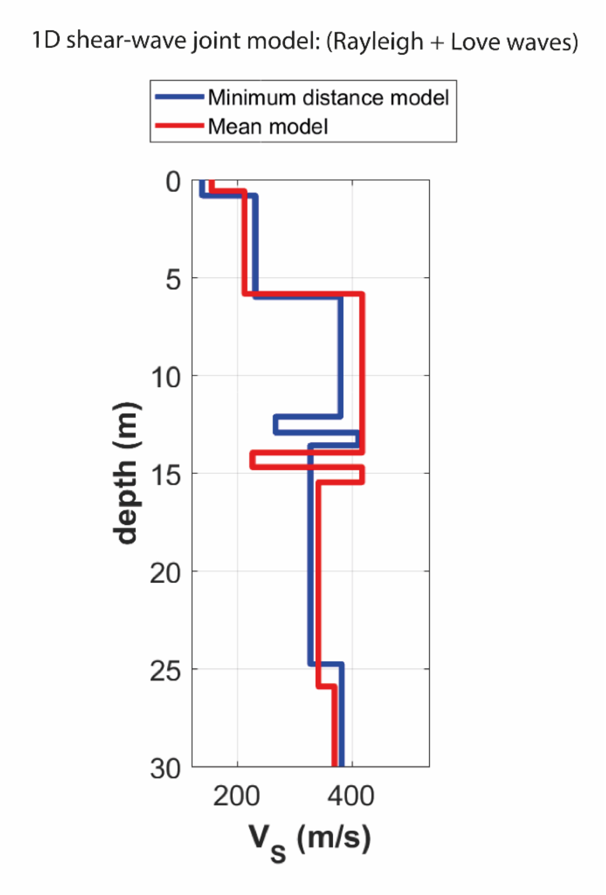

Figure 7. Minimum distance and mean 1D shear-wave velocity profile obtained from joint inversion of the two observables/objects: the ZVF (Rayleigh waves), and THF components (Love waves).

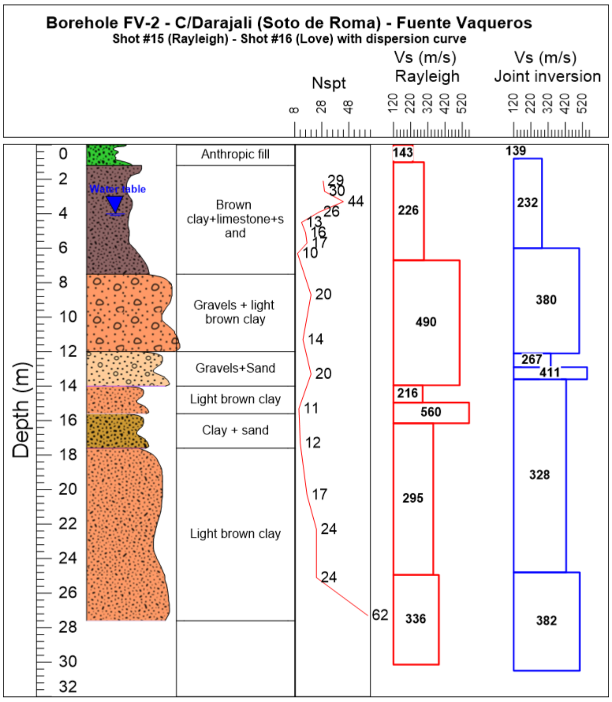

Figure 8. Comparative of 1D shear-wave velocity models with joint inversion (Rayleigh + Love waves), and without joint inversion (only Rayleigh waves) to the stratigraphic column from borehole FV-2, and its SPT N values.

Figure 8 shows a comparison between both 1D shear-wave velocity models and a stratigraphic column obtained from a near borehole, named borehole FV-2, and its associated SPT-N values. It shows that the 1D Vs model from joint inversion correlates quite well with the N-values, since where N-values increase the shear-wave velocity values follow the same trend, being the contrary true. In this way, the intermediate hard layer of gravels and sands that exhibits a SPT-N of 20 blows correlates with the increase of Vs up to 411 m/s. On the other hand, the adjacent layers of light brown clay with/without gravels which show a decreasing SPT-N value to 11 and 14, respectively, correlate well with a decrease in the Vs to 328 m/s and 267 m/s, respectively.

5. Conclusions

The comparison between the stratigraphic column and SPT-N values and the results obtained from surface waves analysis of multicomponent data (Rayleigh and Love waves) shows an improvement in the correlation when the velocity profile is obtained by means of joint inversion.

These results suggest that the extended practice of conducting MASW surveys with the only use of the Rayleigh vertical component should be revised to reduce potential ambiguities derived from the non-uniqueness of the final solution.

From these findings, we have established the procedure of obtaining the 1D shear-wave velocity profiles using joint inversion for the whole project, which is still under development, to obtain a more reliable site characterization of the Metropolitan area of Granada city (Spain).

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References

Aas, A., and S. K. Sinha. 2023. "Seismic site characterization using MASW and correlation study between shear wave velocity and SPTN." *Journal of Applied Geophysics* 215: 105131. https://doi.org/https://doi.org/10.1016/j.jappgeo.2023.105131.

Dal Moro, G., and L. Keller. 2013. "Unambiguous Determination of the Vs Profile via Joint Analysis of Multi-component Active and Passive Seismic Data." https://doi.org/https://doi.org/10.3997/2214-4609.20131376.

Dal Moro, G.. 2020. "Introduction: A Miscellanea." In *Efficient Joint Analysis of Surface Waves and Introduction to Vibration Analysis: Beyond the Clichés*, edited by Giancarlo Dal Moro, 1-53. Cham: Springer International Publishing.

Duan, W., G. Cai, S. Liu, and A. J. Puppala. 2019. "Correlations between Shear Wave Velocity and Geotechnical Parameters for Jiangsu Clays of China." *Pure and Applied Geophysics* 176 (2): 669-684. https://doi.org/10.1007/s00024-018-2011-x.

Hinojosa, H. R. 2023. "The Importance of Assessing the Geological Site Effects of Ancient Earthquakes from the Archaeoseismological Point of View." *Eng* 4 (1): 719-737. https://doi.org/10.3390/eng4010043.

Kumar, A., R. Satyannarayana, and B. Giridhar Rajesh. 2022. "Correlation between SPT-N and shear wave velocity (VS) and seismic site classification for Amaravati city, India." *Journal of Applied Geophysics* 205: 104757. https://doi.org/10.1016/j.jappgeo.2022.104757.

Kumari, R., P. Kumar, N. Kumar, and Sandeep. 2021. "Implications of Site Effects and Attenuation Properties for Estimation of Earthquake Source Characteristics in Kinnaur Himalaya, India." *Pure and Applied Geophysics* 178 (11): 4345-4366. https://doi.org/10.1007/s00024-021-02872-2.

López, F., M. Navarro, P. Martínez-Pagán, A. García-Jerez, J. Pérez-Cuevas, and T. Enomoto. 2022. Vs30 Structure of Almeria City (SE Spain) Using SPAC and MASW Methods and Proxy Correlations. *Geosciences* 12 (11). https://doi.org/10.3390/geosciences12110403.

Martínez-Pagán, P., M. Navarro, J. Pérez-Cuevas, F. J. Alcalá, A. García-Jerez, and S. Sandoval-Castaño. 2014. "Shear-wave velocity based seismic microzonation of Lorca city (SE Spain) from MASW analysis." *Near Surface Geophysics* 12 (6): 739-750. https://doi.org/10.3997/1873-0604.2014032.

Martínez-Pagán, P., M. Navarro, J. Pérez-Cuevas, F. J. Alcalá, A. García-Jerez, and F. Vidal. 2018. "Shear-wave velocity structure from MASW and SPAC methods: The case of Adra town, SE Spain." *Near Surface Geophysics* 16 (3): 356-371. https://doi.org/10.3997/1873-0604.2018012.

Park, Choon B., Richard D. Miller, and Jianghai Xia. 1999. "Multichannel analysis of surface waves." *GEOPHYSICS* 64 (3): 800-808. https://doi.org/10.1190/1.1444590.

Sonmezer, Y. B., M. Celiker, and H. Simsek. 2024. "Evaluation of the seismic site characterization of Kovancilar (Elazig), Turkey." *Bulletin of Engineering Geology and the Environment* 83 (1): 42. https://doi.org/10.1007/s10064-023-03509-5.

Suto, K. 2023. "Pseudo-N-value: From Geophysicists to Engineers." 2023 (1): 1-5. https://doi.org/https://doi.org/10.3997/2214-4609.202378062.

Valverde-Palacios, I., F. Vidal, I. Valverde-Espinosa, and M. Martín-Morales. 2014. "Simplified empirical method for predicting earthquake-induced settlements and its application to a large area in Spain." *Engineering Geology* 181: 58-70. https://doi.org/https://doi.org/10.1016/j.enggeo.2014.08.009.

Yilmaz, O. 2015. "Site Characterization." In *Engineering Seismology with Applications to Geotechnical Engineering*, In Investigations in Geophysics, 371-512. Society of Exploration Geophysicists.