Multichannel Surface-Wave-Analysis (MASW) across the Alhama de Murcia Fault Zone

Caracterización de la Falla de Alhama de Murcia mediante MASW.

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Abstract: *The deep structure of the Alhama de Murcia Fault (AMF) is characterized by means of the analysis of surface waves identified in shallow high resolution seismic reflection data. Multichannel analysis of surface waves (MASW) is used to unravel the 2-D S-wave velocity model and image the depth geometry of the fault system. The study area includes segments of the fault located in La Salud area. Two approaches have been used to achieve a well constrained velocity model in the AMF fault zone. Conventional seismic reflection processing work flow has been used to clean the seismic data and increase its S/N ratio. Occam's approach has been used to invert the digitized surface wave dispersion curves. 1D shear wave velocity-depth profiles were estimated in shot and CDP domains. Relatively well resolved 2D velocity-depth models were obtained by composite of the 1D Velocity-depth functions. These composite 2D-velocity models are able to constrain the depth geometry of the fault zone up to 100 m depth. The fault zone is indicated by a relatively broad low velocity anomaly that correlates with the fault's surface expression.*

Keywords: *Surface wave dispersion, strike-slip fault, seismic inversion, Alhama de Murcia Fault, MASW.*

Resumen: La estructura profunda de la falla de Alhama de Murcia (AMF) ha sido caracterizada mediante el análisis de ondas superficiales identificados en datos de reflexión sísmica superficial de alta resolución. El análisis multicanal de ondas de superficie (MASW) es usado para desentrañar un modelo 2D de Vs y para obtener imágenes de la geometría del sistema de fallas en profundidad. El área de estudio incluye segmentos de la AMF ubicados en el área de La Salud. Se han utilizado dos enfoques para lograr modelos de velocidad bien restringidos de la zona de falla. Por un lado, se han limpiado los datos utilizado un flujo de procesado convencional diseñado para aumentar su ratio de señal/ruido. Por el otro, se ha usado el enfoque de Occam para invertir las curvas de dispersión de ondas de superficie digitalizadas. Los perfiles 1D de profundidad de las Vs fueron estimados en los dominios de disparo y de CDP. Se obtuvieron modelos de velocidad-profundidad 2D relativamente bien resueltos mediante la interpolación de las funciones de velocidad-profundidad 1D. Estos modelos de velocidad 2D ayudan a restringir en profundidad la geometría de la zona de falla hasta los 100 m que se caracteriza por una anomalía de baja velocidad relativamente amplia que se correlaciona en la superficie con la expresión de la falla.

Palabras Clave: Dispersión ondas superficiales, falla de salto en dirección, inversión de datos sísmicos, Falla de Alhama de Murcia, MASW.

INTRODUCTION

In 2011, a 5.2 Mw earthquake took place in the vicinity of the city of Lorca, Spain. The earthquake produced remarkable damage including nine casualties, over four hundred injured and significant material damage in the area. The earthquake's hypocenter location and focal mechanism were correlated with the activation of the Alhama de Murcia Fault (AFM). This is one of the main faults of a well-known strike-slip fracture system which is one of the most active within the main Iberian Peninsula (Martínez-Díaz et al., 2012). The AFM is a strike-slip shear zone with reverse component that crosses the eastern Betic cordillera with a NE-SW direction and is one of the largest faults of the Eastern Betics Shear Zone (Silva et al., 1993).

Several studies have focused on the characterization and determination of the AMF attributes, such as its seismic potential (Ortuño et al., 2012; Martinez-Diaz et al., 2012), mainly from surface and trench studies. However, the understanding of fault properties (orientation, geometry, and configuration) requires further research as the deep geometry is not well resolved. Addressing these targets can provide understanding of the detailed structure, the distribution of its deformation and help in the assessment of seismic hazard.

Multichannel analysis of surface waves (MASW) is able to constrain a relatively wide range of subsurface features, for example delineate the shallow structure of fault zones (Ivanov et al., 2006). This approach is able to infer the

1D Vs structure of subsurface materials (Bergamo and Socco, 2016) and delineate underground structures such as voids or tunnels (Peterie and Miller, 2015). The study presented here employ MASW in one section of the AMF. The main objective is to obtain a 2D shear wave-velocity depth models and to better constrain the deep geometry of the AMF fault structure in the La Salud area.

GEOLOGICAL SETTING

The geological architecture and the geometry of sedimentary formations in the study area are controlled by a set of faults with ENE-WSW directions (Fig. 1). These set of faults are considered to be the backbone of a strike-slip shear (fracture)- system. The Alhama de Murcia Fault System (AMF) can be considered, perhaps the main structural feature. The shear zone is a nearly 1 km wide zone of deformation that includes a set of faults with NW-SE and SW-NE directions. Along this deformation structure a number of instrumental and historical earthquakes have been identified (Fig. 1). Detailed geology and paleozeismologic studies can be found in Martínez-Díaz et al. 2012; and references therein). These studies describe the surface geology and, geomorphology of the main fault (AMF).

SEISMIC REFLECTION DATA

A seismic reflection controlled source data acquisition experiment was carried out within the framework of the INTERGEO project. The seismic profiles (Fig. 1) were located in the vicinity of the city of Lorca. The main idea was to address the subsurface structure, the shape, and the architecture depth expression of the AMF, focusing on the architectural relationship at depth between the different fault planes and the relationship with the sedimentary filling of the Guadalentín depression. Therefore, the data acquisition experiment included a series of transects across different surface expressions of the fault system. It was acquired using 240 channel system which consisted in 10 GEODE recording units with 24 channels each. The recording system was provided by the GIPP-GFZ instrumentation center. (Potsdam, Germany) The source was a 200 kg accelerated weight drop provided by the Instituto Superior Tecnico in Lisbon University, (Lisbon, Portugal). The distance from the seismic source to first receiver and the shot spacing were both set to 6 m. The sample rate was set to 1 ms and the total recording time was 4 s.

The shot records reveal prominent dispersive surface waves (Fig. 2). In order to increase the S/N ratio simple and conventional seismic processing was carried out. It mostly consisted in attenuating the high frequency and amplitude balancing. This simple and basic processing increased the lateral continuity and extent of the different phases and increased the energy of the S-wave arrivals.

Then the frequency-phase velocity diagrams also known as the wave-dispersion diagrams were obtained. These were determined by calculating the FFT of the Tau-P transformed shot gathers. The dispersion curves were then digitized. Theses frequency-velocity curved where then used in an Occam inversion scheme approach that resulted in 1D velocity-depth profiles (Park et al., 1999).

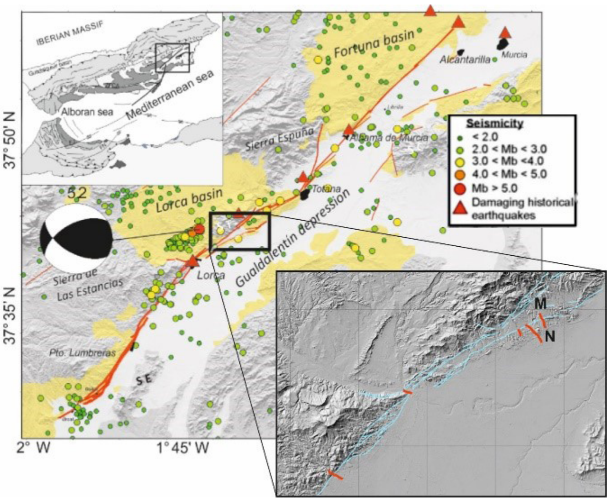

FIGURE 1. Location of the study area. The top inset indicates the overall location of the deformation zone in southeastern Iberian Peninsula. It also illustrates a simplified geology of the area. The main image reveals the trace and distribution of the identified fault traces. The coloured dots correspond to the recorded seismicity, instrumental and historical earthquakes with Mw larger than 1. The focal mechanism of the Mw 5.2 Lorca earthquake is indicated by the beach-ball. The bottom inset indicates the location and trace of the high resolution, normal incidence seismic reflection profiles acquired across the AMF. The M-N transect is used in this study.

This process was applied to data from La Salud transect where the fault zone has been mapped at surface (Fig. 1). The Vs-depth profiles were then joined together to build a composite 2D velocity model of the area. The process was repeated but in this case the wave-dispersion diagrams were calculated for the CDP sorted data. Further comparisons were carried out by using the dispersion diagrams estimated by the specific surface -wave dispersion module from the Seismic Unix software: the suphasevel (Cohen and Stockwell, 2010).

The inversion scheme to compute the V_S velocity-depth profiles is an iterative inversion algorithm that requires as inputs the digitized dispersion curve and reasonable values for densities and Poisson´s ratio (Xia et al., 1999). A comparison between available commercial and academic software packages to estimate V_S profiles has also been considered in this study.

RESULTS AND DISCUSSION

The shot gather (Fig. 2) is an example to illustrate the quality and lateral continuity of the ground roll imaged within the shot records. In these records, the surface wave energy dominates the seismic data and appear moderately dispersive. This effect is recognizable as multiples from the surface waves and it is relatively coherent.

The maximum of the dispersion diagram was then digitized and a dispersion curve was extracted. The dispersion *curve shows the value of phase velocity against frequency of the surface waves (Fig. 2).*

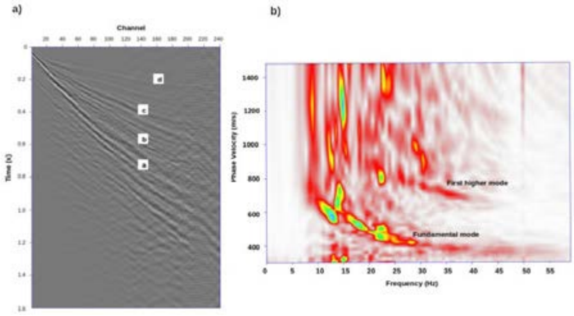

FIGURE. 2. Example of seismic shot record corresponding the Salud profile and its dispersion diagram. The labelled phases correspond to: (a) the fundamental mode of surface wave, (b) the higher modes of surface wave, (c) the reflection wave, and (d) the refraction wave. The right image corresponds to the dispersion diagram of the surface waves. The high amplitudes are indicative of the different phases (frequency and phase-velocity).

The dispersion curve generated from each shot record was assigned a location corresponding to the receiver midpoint of its receiver spread. The fundamental mode and first higher mode appear moderately clear in the resulting dispersion curve images (Fig. 2).

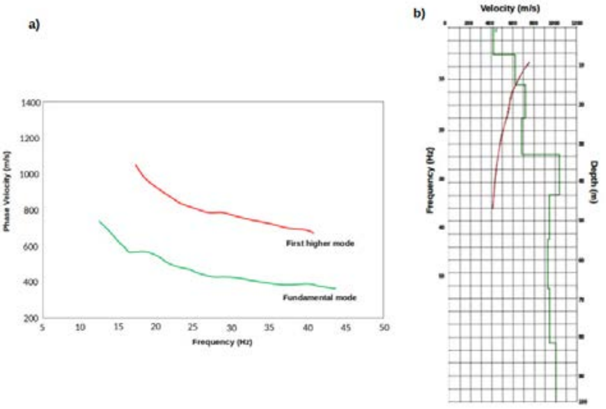

FIGURE 3. The extracted dispersion curves of the different modes calculated for every station (left). The fundamental mode is shown as a green line and, the first higher mode is represented by red line. The velocity-depth functions determined by the inversion scheme are shown in the right diagram.

The results of the dispersion curves are usually presented as two-dimensional images obtained by cross plotting the normalized frequencies and phase velocities. The high-energy bands observed display the dispersion characteristics of the recorded surface waves (Fig. 2).

After the dispersion curves were generated, the maximum spectrum trend of the dispersion curve is digitized in order to extract the best value of frequency and phase velocity. Base on the energy content of the recorded surface waves, one or multiple dispersion curves can be extracted from the phase velocity spectra. In Fig. 2, the fundamental mode is clearly identified and easy to pick. The first higher mode does not appear as clear but still it can be identified based on its similar trend compared to the fundamental mode dispersion curve. The fundamental mode dispersion characteristics are, usually, the critical and most commonly used in the inversion scheme (Xia et al., 1999). In this study, the fundamental mode and first higher mode were used in the inversion step.

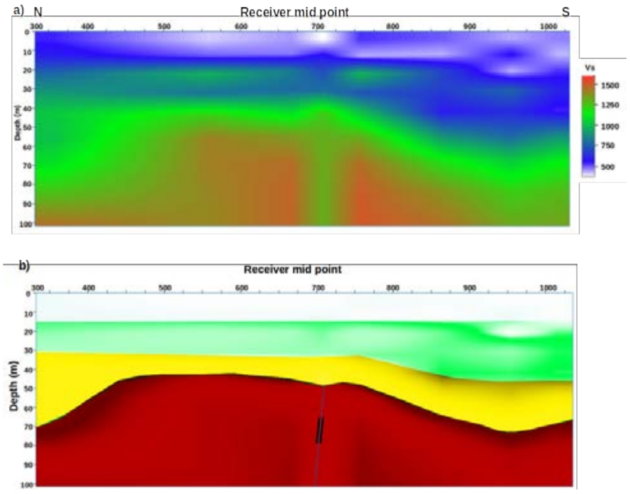

FIGURE 4.Top Shear-wave velocity field. Composite velocity cross-section obtained by pasting together the 1D velocity-depth profiles obtained by the inversion of the digitized dispersion curves. Bottom, interpreted geological model. The sedimentary cover in green and yellow, and the location of a steeply dipping feature indicated by the relatively low velocity anomaly and interpreted as the possible location of the ALMF.

The preliminary 2D S-wave velocity model is a composite of the 1D velocity-depth profiles obtained by inversion of the dispersion curve (Fig. 4). The 2D inversion covered the depth of 100 m and receiver midpoint number from 300 to 1100. The 2D composite Vs section reveals a laterally varying structural model. The shear wave velocity model presents areas of relatively low velocity values (400-900 m/s) and areas of higher velocity values (1000-1500 m/s) at a depths bellow 50 m.

Perhaps one of the most important findings of the study is the steeply dipping low velocity anomaly at receiver location 700. This relatively thin anomaly has been interpreted as the trace of the AMF fault zone (Fig 4). The geological interpretation from the MASW result is shown in Fig. 4b. Based on the 2D V_s section, the main achieved goal is the identication of the AMF. The fault zone interpreted as a parallel block of bedrock (red color) that has been identified as a strike-slip fault below receiver midpoint 700 at 50 m depth . The strike direction of the fault zone is approximately southwest to northeast (SW-NE). The other velocity values were interpreted as the sedimentary cover and bedrock (yellow, green and white color).

Similar results were obtained when using the CMP gathers to obtain the dispersion curves, but the analysis of these dataset is out of the scope of this work. In any case, and perhaps, the most important finding of the study is the interpreted fault zone of AMF at depth. According to our results (Fig. 4a) the steeply dipping lower velocity anomaly (green color) below receiver midpoint 700, extends down to depths larger than 50 m. It appears to be almost a vertical structure going across and/or splitting the relatively high velocity (red) rock into two sections. This low velocity anomaly is interpreted to represent the location of the fault zone. The low velocities would then be related to fracturing and associated local weathering that would reduce the shear modulus value.

CONCLUSION

The MASW method was used to map the geometry of the AMF strike slip fault in La Salud area. The preliminary results of the MASW analysis reveal a steeply dipping relatively low velocity anomaly that can be correlated at surface with the trace of the AMF. The procedure consists on obtaining the dispersion curves by digitizing the maximum values image by the dispersion analysis and using an inversion scheme to obtain 1D velocity depth profiles at different surface locations. These 1D functions, are then pasted together by interpolation to obtain a composite 2D velocity model. In this study, the preliminary velocity models reveal the fault zone of the AMF as a remarkable low velocity anomaly that can be traced down to 50 m depth.

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