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Characterization of a Concealed Fault Zone Using P and S-wave Seismic Reflection Data

J. Carvalho* (Laboratório Nacional Energia e Geologia), R. Ghose (Delft University of Technology), C. Pinto (Laboratório Nacional Energia e Geologia) & J. Borges (Centro Geofísica de Évora)

SUMMARY

The Vila Franca de Xira fault zone is the central sector of the OVLS fault zone, one of the major geological structures of the Lower Tagus Valley area in Portugal. Evidences previously gathered from geological and geophysical data suggest that it is an active fault zone and is responsible for the 1531 earthquake that caused extensive damages in Lisbon and the surrounding areas. However, no clear evidence of Quaternary seismic activity has been proven until now. The characterization of the fault zone in Holocenic terrains is therefore important for seismic hazard assessment. A P-wave and an S-wave seismic reflection profiles were acquired over an existing oil-industry and high-resolution P-wave seismic lines. The processing and preliminary interpretation of our data shows that S-wave data provides a superior resolution compared to the P-wave data and is the preferred geophysical method to characterize shallow faults zones in the study area. We have confirmed that faulting affects the Holocene alluvium and a vertical offset of 1-2 m was found in the S-wave data. This finding will allow a better definition of the return periods and the maximum expected earthquake magnitude of the OVLS fault zone.

1. Introduction

The Vila Franca de Xira fault zone is part of the central sector of the OVLS fault zone, recently identified from seismic and magnetic data (Carvalho et al., 2008). It is one of the major geological structures of the Lower Tagus Valley area in Portugal. Evidences previously gathered from geological and geophysical data (Carvalho et al., 2006; 2008) suggest that it is an active fault zone and is responsible for the 1531 earthquake that caused extensive damages in Lisbon and the surrounding areas. However, no clear evidence of Quaternary seismic

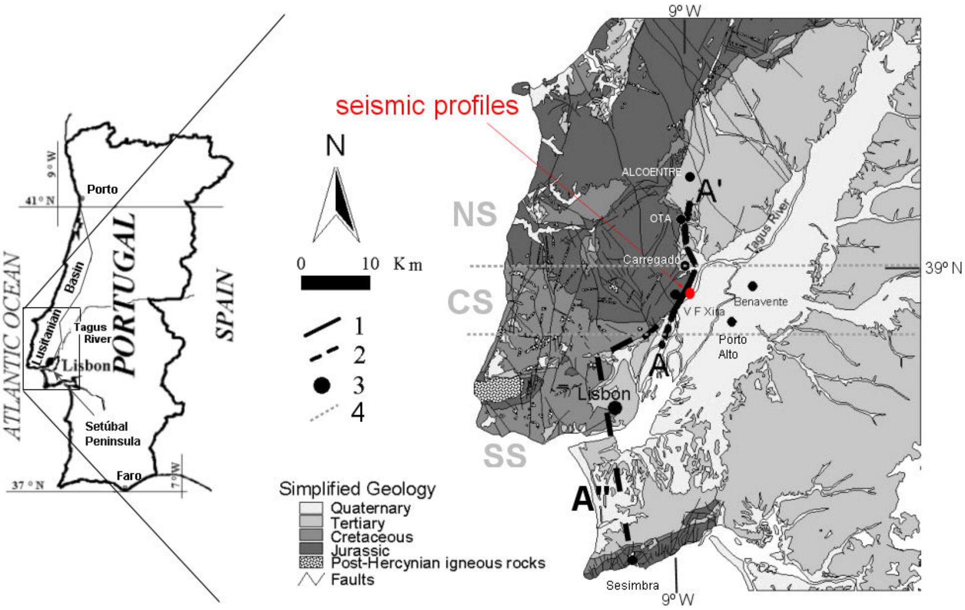

Figure 1 Location of the target of this work: the Ota-V.F. Xira-Lisboa-Sesimbra fault zone (OVLS, A'-A-A'') is shown here, together with the location of the seismic reflection profiles and the geology of the area. 1- outcrop of the fault zone in the central sector, corresponding to the Vila Franca de Xira fault; 2-fault course inferred from geophysical data. 3- localities; 4- limits of the OVLS segments. NS- Northern sector of OVLS; CS- central sector; SS- southern sector.

activity has been proven until now. It is, therefore, important for seismic hazard assessment to locate and characterize the fault zone in the Holocenic terrains that outcrop close to the surface course of the fault zone.

P-wave surface seismic reflection methods have often been used for fault detection and characterization (e.g. Shtivelman et al., 1998). S-wave methods are gaining popularity in the the last decades, one of the advantages being that they provide superior resolution to P-wave methods in soft soil (e.g., Ghose et al., 1996; Brouwer et al., 1997; Ghose and Goudswaard, 2004). We have acquired a P wave and an S-wave profile over an existing oil-industry, high-resolution P-wave seismic line. The preliminary interpretation of the results has confirmed that the faulting affects the Holocene alluvium. We have found a vertical fault offset of 1-2 m in our S-wave data. This finding will allow a better definition of the return periods and the maximum expected earthquake magnitude.

2. Geological Setting

The neotectonic activity in the mainland Portugal is characterized by vertical crustal movements and reactivation of preexistent faults of different tectonic styles under a compressive regime. Average slip rates are usually <0.2 mm/yr, corresponding predominately to a low degree of activity (Cabral and Ribeiro, 1988; Cabral, 1995, Carvalho et al., 2006). As a consequence of this tectonic setting, mainland Portugal experiences a low to moderate seismicity characterized by small events (M<5.0) and occasional moderate to very large earthquakes, like the well known 1755 'Lisbon earthquake'.

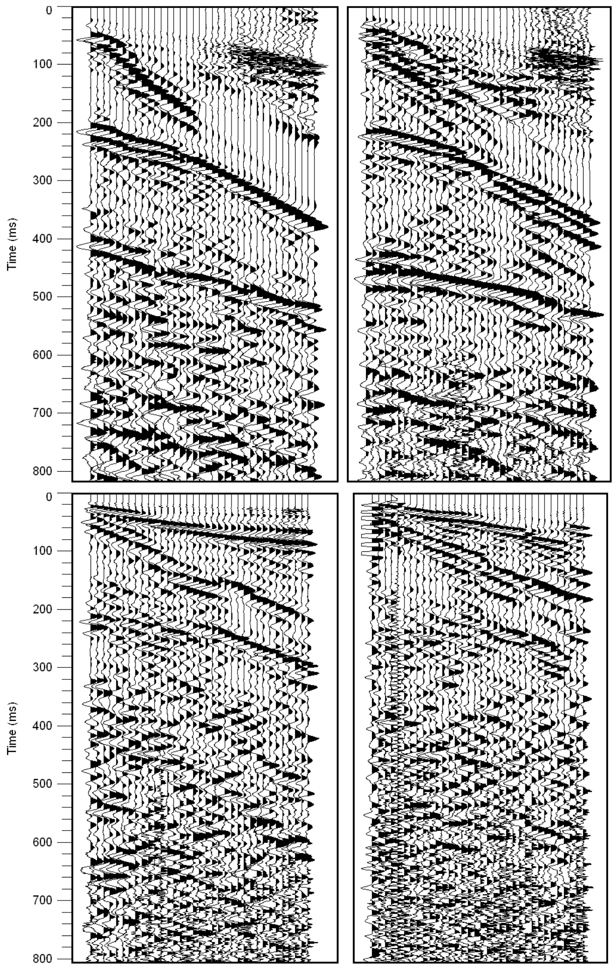

Figure 2 Example of S-wave (top) and P-wave (bottom) raw shot gathers. The shot gathers shown here are from two sides of an anticipated fault zone.

Using geophysical data, several non-outcropping fault zones were recognized and tentatively mapped in the study area (Cabral et al., 2003; Carvalho et al., 2006; 2008). For some of them, such as the Pinhal Novo fault, there are evidences of tectonic activity since the Pliocene (Cabral, 1995, Cabral et al., 2003). Other structures were very probably active in the Quaternary, such as the OVLS, the Azambuja, and the Porto Alto faults (Cabral, 2004, Carvalho et al., 2006; 2008).

The OVLS fault zone shows three distinct segments (Fig.1) with different behaviour, in conformity with their various orientations relatively to the NW-SE maximum compressive stress (Carvalho et al., 2008). The northern segment splays into a series of NNE-SSW oriented, east verging, imbricate thrusts which merge to the west into a major reverse fault that resulted from the tectonic inversion of the former normal fault bordering the Mesozoic Lusitanian Basin in this area: the Ota (or Pragança) fault. The central segment corresponds to the approximately 20km long, outcropping V. F. de Xira fault, which is also a former normal structure that suffered a maximum degree of inversion. The southern segment extends for approximately 45km, crossing Lisbon and the Setúbal Península until approximately Sesimbra (probably continuing offshore) with an N-S trend and subvertical geometry. South of V. F. de Xira there are evidences for a WSW-ENE fault located underground, producing a right-lateral stepover on the major structure, and separating the central segment from the southern segment.

3. Data Acquisition and processing

The S-wave seismic reflection profiles that we shoot were located (see Figure 3) in a plain agricultural land where alluvium deposits of the Tagus river have deposited in the last 15-20 kyears. The water table could be verified in the irrigation channels at about 1-1.5m depth.

The site (Fig.1) was chosen after the identification of the OVLS fault zone in an existing oil-industry seismic reflection line which in turn was the reason for an earlier acquisition of a high-resolution P-wave seismic reflection line (Carvalho et al., 2006). Two major faults were interpreted in the latter profile and one of them came relatively close to the surface. This fault was the target of the present shear-wave studies. The goal was to verify if the Holocene alluvium was affected by the fault zone and, if so, to estimate its vertical offset.

Careful walk-away noise tests were performed before starting the CMP shooting. This ensured the best acquisition parameters for the site. A layout of 48 50Hz single component geophones with 36 active channels and 12 roll-along channels was used. From the source to the nearest geophone offset was 5m for the S-wave profile and 4 m for the P-wave profile. To

avoid spatial aliasing of the surface waves, a receiver spacing of 0.75m for the S-wave and 0.5m for the P-wave were chosen. The time sampling was 0.25ms. A vertical impact hammer and a plate were used for the P-wave source. A wooden beam pressed with the wheels of a jeep and hit from the side was the S-wave source. 4 shots were recorded independently at each source location and were later on vertically stacked, after a quality control. This prevented stacking data with trigger delay or noise contamination. Due to time constraints, the P-wave profile was shorter than the S-wave profile. Both profiles started at the same point.
An example of S-wave raw shot gathers is shown in Figure 2. Clear reflection events can be seen in the raw data; note that the two shot gathers representing two sides of the anticipated fault zone exhibit difference in the moveout velocities. The data processing flow was similar for P-wave and S-wave datasets: geometry installation, vertical stacking, trace editing, gain correction, bandpass filtering, first arrival muting, spectral whitening, velocity analysis, NMO correction and CMP stacking, 2 iterations of surface consistent static correction and velocity analysis, phase shift migration and post-stack filtering, and amplitude enhancement. P-wave data required additional FK filtering due to the presence of some linear noise on the stacked data. In absence of VSP, the time-stacked sections were depth converted using stacking velocity field. Time and depth sections are presented in Figure 3, with the interpretation overlaid in the depth sections. The interpretations were partly based on a-priori information and partly guided by the features found in our data.

4. Discussion

The S-wave stacked section (Fig. 3) shows much improved resolution compared to the P-wave section. The average vertical resolution for S-wave, using the λ/4 criteria, is about 0.6m, while for P-wave it is 2.5m. The S-wave profile shows two prominent reflectors together with many other weak, relatively discontinuous reflectors. According to the most nearby wells (there were 10 wells within 1km of the profile), located about 300m to the west of the profile, the depth to the base of the Holocene alluvium is at about 25m. The Holocene alluvium rests on the Jurassic clayey sandstones. The seismic profile shows a strong reflector at an approximate depth of 22-28m.
Another relatively shallow strong reflector in our data corresponds to a depth of 9-13m

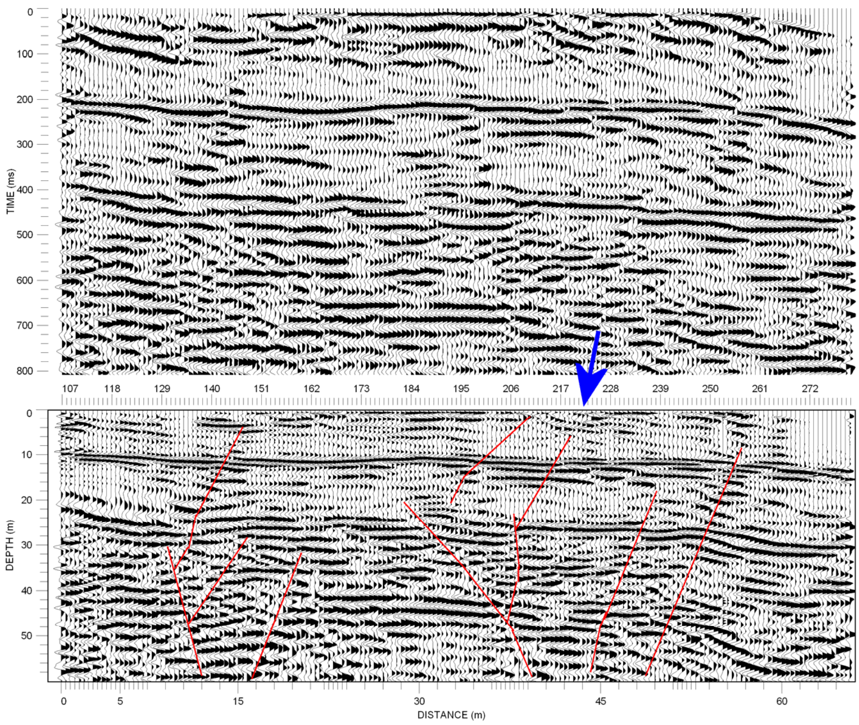

Figure 3 S-wave time stacked section (top) and depth converted section using stacking velocities (bottom). The location of an expected fault zone, based on previous studies, is indicated by the blue arrow.

(200ms two-way-time); this is most probably the boundary between clayey alluvium to sandy alluvium zones observed in the wells at depths 3.5 to 7m. Because the two-way-times of these two strong reflectors in our data give an impression of multiple events, we were careful before interpreting them as primary reflection event. The moveout velocity of the deeper is much faster, and their trends are different.

The P-wave profile also shows very similar depths for a package of strong, continuous reflectors that we conclude to be the base of the Holocene alluvium. Below these events in the P-wave data and the deepest prominent reflector in the S-wave data, a seismic pattern of discontinuous and variously dipping reflectors is visible in both datasets. This seems to correspond to the highly fractured rocks. This interpretation agrees with the well information that show a Jurassic basement presenting variable depths and probably displaced.

From the stratigraphic interpretation, we conclude that several faults affect the alluvium top soil in this area. This is more clearly visible in the S-wave profile than in the P-wave profile. Our expected fault location, based on our previous work, is indicated in Figure 3. We can see that besides a fault zone in this position another fault zone is present further west on the profile. The vertical offset observed in the intra-alluvium horizon is relatively small (about 1-2m). This value is consistent with the inferred activity of this fault zone. Earlier, Carvalho et al. (2006) estimated a slip-rate of 0.30mm/year and a maximum bound of approximately 5000 years for the return period of the co-seismic ruptures.

5 Conclusions

We can draw 2 important conclusions base don these results. First, the S-wave seismic reflection data provides much superior resolution than the P-wave data. Therefore, the preferred geophysical method to characterize shallow faults zones in low slip-rate areas underlying soft sediments and with shallow water table should be the S-wave reflection method. Secondly, our newly acquired data shows, for the first time, that the OVLS fault zone is an active Quaternary structure with measurable vertical offsets of 1-2m across the fault. This data, together with the information from trenching, will allow better estimates for the slip-rates and return periods for the fault ruptures, and provide an improved seismic hazard assessment of the area.

6 Acknowledgements

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