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The Signature of a Small-throw Fault Affecting Unconsolidated Sediments in S-wave Reflection Seismic Data

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SUMMARY

The definition of appropriate places for the development of paleoseismic studies is extremely important in earthquake engineering site investigations. The seismic reflection method is routinely used to locate shallow fault segments where these do not outcrop, like in low slip-rate areas where faults identified in Quaternary sediments have vertical throws less than 2 m. The Lower Tagus Valley (Portugal), covered by 50 m of alluvium sediments, is one of these areas. To find fault segments in this geological environment is a daunting task. Any displacement in the seismic data can be a velocity anomalies and/or statics effect. To illuminate the presence of a fault in Holocene sediments, we acquired an S-wave seismic reflection profile at V. F. de Xira and modelled the response of a fault segment in order to recognise it in our data. The signature of a fault segment can be a change in the shape/attitude of the reflection hyperbolae but reflections from the fault plane are rather weak. These are controlled by fault width and velocity contrast between damaged zone-adjacent sediments. The resemblance between the modelled and field data of V. F. Xira supports the conclusion that the fault affects the Holocene alluvium and is still active.

Introduction

Locating shallow fault segments using geophysical methods in areas where they do not outcrop is extremely important in earthquake engineering site investigations, to define appropriate places for trenching, and to develop paleoseismic studies. This location becomes challenging in intra-plate areas where slip-rates are low (less than 0.5 mm/year) and erosion and sedimentation erase the surface ruptures. The Lower Tagus Valley (Portugal) is one of such areas, in particular which is covered by about 50 m thick Holocene alluvium sediments. Surface ruptures identified in the Quaternary sediments usually have a vertical throw of less than 2 m (most often it is less than 1 m). To find such fault segments in soft, unconsolidated (sands and muds) sediments is a daunting task.

The superior resolution of S-wave reflection compared to P-wave has been demonstrated earlier (e.g. Ghose and Goudswaard, 2004). In this research, we have applied the S-wave seismic reflection method to fault location in the Lower Tagus Valley at V. F. de Xira. Previous studies using the oil-industry P-wave seismic reflection, geological and well data strongly suggested the presence of an important fault zone in the area, but its exact location and if it had penetrated the Holocene cover were still to be determined due to the lack of resolution and the acquisition geometry of the P-wave data.

The signature of a small vertical-throw fault segment in shallow unconsolidated sediments is difficult to recognise in the S-wave shot gathers and stacked section. Any apparent displacement in the seismic data can be an effect of velocity anomalies and/or statics. We have, therefore, modelled the response of a small-throw fault segment in order to recognise it without ambiguities in our data. We present here the comparison between modelled and field data acquired at V. F. de Xira, illuminating the probability of a fault segment in the Holocene sediments, in agreement with previous findings.

Field data

The S-wave data were acquired with an array of 36 active receiver channels and 12 roll-along channels in an inline end-on geometry, a minimum source-receiver distance of 5.0 m and a receiver interval of 0.75 m. The short receiver spacing was to ensure no spatial aliasing in the acquired data. This geometry resulted in a constant CMP fold of 18. The source used was a wooden beam, transversely oriented with respect to the line of receivers and pressed by the wheels of a jeep and hit on both sides. Data are sampled at 2 kHz Nyquist frequency, for a 800 ms trace length.

The processing sequence for this dataset was as follows: geometry installation, first arrival muting, deconvolution, velocity analysis (constant velocity panels-CVS and Horizon Velocity Analysis-HOVA), NMO correction and CMP stacking. Figure 1 shows the pre-stack time migrated stacked section obtained using a Kirchhoff algorithm, typical shot gathers and HOVA performed for the 200 ms and 400 ms reflection events. The location of one of the earlier interpreted fault segments is indicated by an arrow.

We can recognize in the shot gather indications of faulting: a change of shape and amplitude of the 400 ms reflection hyperbolae. In the stacked section we can observe discontinuities in the reflectors, local changes in velocity in the HOVA/CVS panels and scattering behavior (visible in common-offset sections) at coincident locations. All these evidences, supported by well data that show a significant change in depth of the base of Holocene at a distance of about 800 m, point to the existence of shallow fault segments at this location (Carvalho et al., 2009). However, no direct reflection from the fault zone could be noticed.

Modelling

The model used in this study is based on well data and the interpretation of the S-wave stacked section converted to approximate depth using the stacking velocities. Well data includes geological log and SPT data located about 300m from both ends of the seismic profile. This model (Figure 2) is in good agreement with the general stratigraphic model for the Holocene alluvium in the area (Vis, 2009) and can be representative for other areas in the world under a fluvial depositional regime.

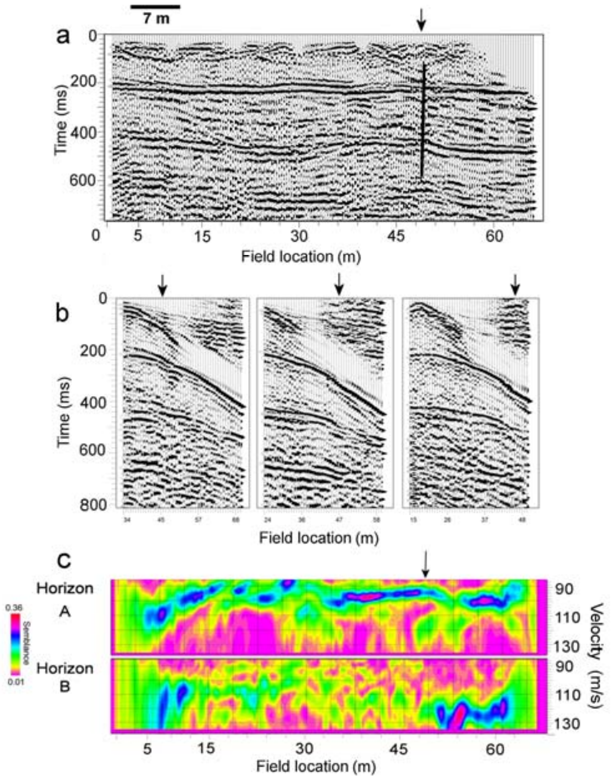

Figure 1 *a) Prestack time-migrated S-wave section acquired at Vila Franca; b) typical S-wave shot gathers; c) horizon velocity analysis performed for 200 ms (Horizon A) and 400 ms (Horizon B) reflection events. The arrow shows the location of an earlier interpreted major fault segment.*

The alluvium is composed of sands and clays with the occurrence of pebbles at the base. The maximum thickness of these soft sediments reaches about 50m. These units host a few aquifers, isolated from the water of river Tagus. These aquifers are a few meters thick. The most important aquifer, which supplies water to the city of Lisbon, is located at the base of the alluvium.

A full elastic finite difference modeling was carried out (Thorbecke and Draganov, 2011). We modeled only the SH response of the wavefield because S-wave seismic reflection method is much more suitable for our purposes than P wave, and our field data is of SH wave. The geometry of the modeled shot gathers is identical with the geometry of the field data. For the modeling we have used a dipole source oriented transversely with respect to the line of receivers, with a fundamental frequency of 40 Hz. The maximum frequency in the data is about 120 Hz, which is in agreement with the frequency range generally observed in typical S-wave seismic reflection data. To avoid numerical dispersion problem, the model grid cell size was set to 0.1 m, taking into consideration the velocities.

We started by modeling a fault segment as a rectangular (no throw) low velocity zone which is 6 m wide and has a constant velocity contrast of 15 m/s (maximum contrast suggested by our field data) with the adjacent sediments and extending from a depth of 4 m until 30 m. The synthetic seismic response of our model with the fault is shown in Figure 2, together with the input velocity model. Different seismic phases are indicated. The previously known fault location in the shot gather is indicated by an arrow. The imprint of the fault segment in the shot gather is clearly visible in Figure 2. The reflection hyperbola from the 11 m (200 ms) shows almost no distortion at the fault location.

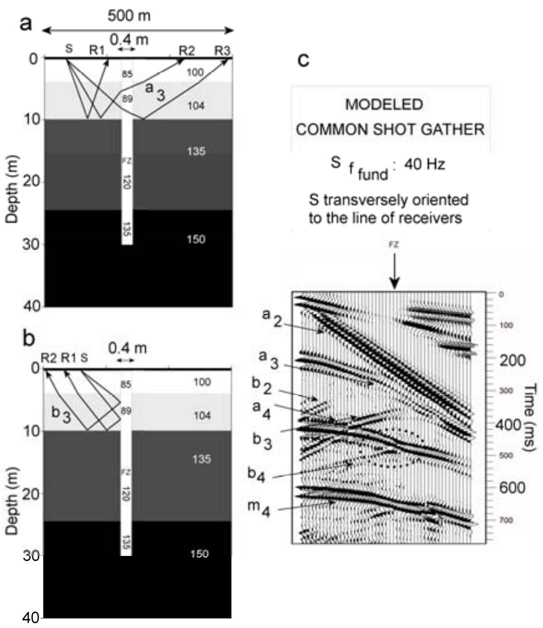

Figure 2 *a) Velocity distribution used for full elastic modeling involving a fault segment represented by a 0.4 m wide low-velocity zone with a constant velocity contrast of 15 m/s with respect to adjacent sediments. Numbers in the model represent velocities in m/s; the raypaths for the reflection event on the 10 m interface are schematically shown; b) raypaths for the expected fault plane reflections returning to the surface for the 10 m interface; c) modeled response for a 4 m fault width and 15 m/s constant velocity contrast between the damage zone and the adjacent sediments, several distinct seismic events (a_i), reflections from the top of the i th layer (b_i), reflections at the fault plane and then at the layer boundary I, and multiple of the reflection from the top of layer 4 (m4).*

However, we can observe an important change of the shape/amplitude of the 24 m (400 ms) reflection hyperbolae (dotted ellipse in Fig. 2) and several clear fault plane reflections, as expected. In an attempt to explain the very weak fault-plane reflections that are rarely observed in our field data, we experimented next by varying several different fault parameters. These variable fault parameters were: velocity drop in the damage zone, width of the fault, and irregularity of the fault plane. Figure 3 summarises our results.

Results/Discussion

The top panel of Figure 3 shows the effects of varying fault width. The central panels demonstrate the impact of decreasing simultaneously the fault width and the velocity contrast of the damage zone with respect to the adjacent sediments. From these 2 sets of panels, we can conclude that the most important parameter for producing fault plane reflections is fault width, although the velocity contrast also has a measurable effect. The smaller the fault width and the smaller the velocity contrast the lower is the amplitude of the fault-plane reflections. The bottom panels (compare c1, c2 with b3) show that the effect of variation of the vertical spacing of the irregularities (at the side of the fault zone) is negligible at this scale. Figure c3 shows a modelled shot gather when there is no fault.

Since our data suggests that velocity contrasts between the damaged zone and the adjacent sediments is typically around 8-10 m/s and that the width of the fault segment in this type of geological setting is about 0.6 m (J. Cabral, personal communication), we conclude, by comparing Figure 3(c3) with Figure 3(b3) (and even with Figures 3(c1) and 3(a3)), that very weak fault plane reflections are expected in our data. If we consider that the actual field data is contaminated by noise, this assumption is reinforced.

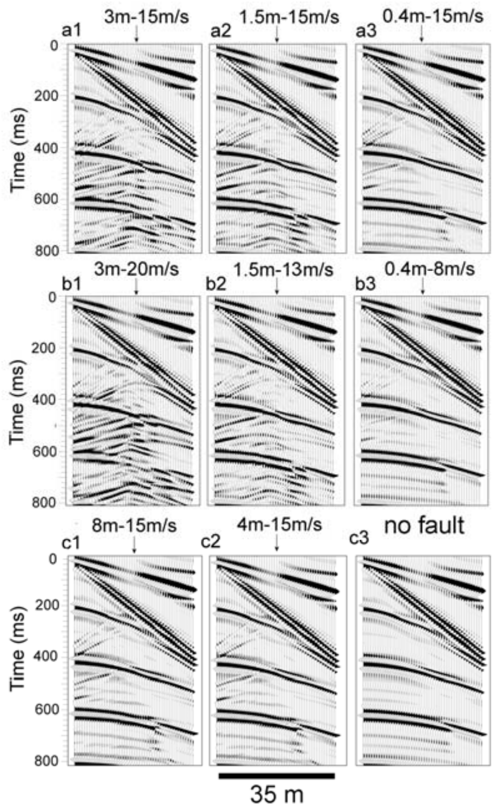

Figure 3 *Modeled response for three different fault parameters: (a1-a3) decreasing fault width and constant velocity contrast (between damaged zone and adjacent sediments); (b1-b3) decreasing fault width and also decreasing velocity contrast; (c1-c3) variable length of the irregularity at the side of the fault zone, with a constant velocity contrast and a constant fault width of 0.4 m. Exact values of fault parameters used are shown at the top of each panel. Arrow indicates location of the modeled fault segment.*

Conclusions

We have shown that the signature of a shallow fault segment, with a small vertical throw, in unconsolidated soft sediments can be recognised by a change in the shape/attitude of the reflection hyperbolae but reflections from the fault plane itself is rather weak. The fault parameters that are most influential to these weak fault-plane reflections are mainly the fault width and, to a lesser extent, the velocity contrast between the damaged zone and the adjacent sediments. We have shown that the modelled data (using reasonable fault parameters for such tectonic/geological environments) strongly resemble the field data at V. F. Xira. This supports the conclusion that the fault segments affect the entire thickness of the Holocene alluvium and that the fault zone is still active.

Acknowledgements

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