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1D and 2D Seismic wave propagation modeling in the Cerdanya valley (Catalonia, Spain)

Mar TAPIA[1,2], Albert MACAU[1], Sara FIGUERAS[1], Peter FRANEK[3]
1 mtapia@icc.es, Institut Cartogràfic de Catalunya, Barcelona, Spain
2 Department of Physics of the Earth and Planets. Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia.
3 Geophysical Institute, Slovak Academy of Sciences, Bratislava, Slovakia

ABSTRACT - The Cerdanya area is located in the Eastern Pyrenees occupying both French and Spanish territory. It is a very extensive rural zone forming a valley where the population is spread over small urban nuclei. The Cerdanya valley is a very deep sedimentary Miocenic valley filled by conglomerates, sandstones and lutites, with a maximum thickness 800 meters.
The use of geological maps, the review of existing reports about geotechnical studies in the region and the performance of active seismic exploration using the Spectral Analysis of Surface Waves (SASW) technique to obtain shear velocity profiles allow to constrain realistic models. The compilation of all this information characterizes 1D soil columns and 2D structural model with realistic geological and geotechnical properties and geometry. ProShake 1D linear-equivalent method has been applied in soil columns defined along 2D valley cross-section. A finite-difference (FD) method has been applied to model the propagation of seismic waves in the 2D cross-section of the valley. The analysis of the computed ground motion in the valley is carried out by means of selected parameters in time and frequency domain. These parameters allow to find interesting conclusions in order to understand and quantify the influence of the local geology and geometry.

1. Introduction

The Cerdanya region is located in the Pyrenees, between Spain and France (Figure 1). The Cerdanya valley includes an extensive countryside where the distribution of the population is concentrated in small urban nuclei distributed between Spain and France, very crowded by the tourism of winter and summer.
The historical seismicity and recent tectonic data indicate a level of considerable seismic hazard in the Pyrenees. The highest seismic activity is located in the western part of this mountain range. In 1373 a broad zone of the Ribagorça was affected by a destructive earthquake with an epicentral intensity of VIII-IX (Olivera et al., 2006). In 1427 and 1428 Eastern Pyrenees was affected by a seismic crisis with maximum intensity of IX, and an intensity of VIII in Puigcerdà, the main town in the Cerdanya region. (Olivera et al., 2006). In 1660 the Central part of the mountain range suffered a destructive shock (I=VIII-IX). During the XXth century, important damages have been produced during the 1923 Aran Valley (I=VIII) and 1967 Arette (I=VIII) earthquakes. Recently, with the increase of population and the economic activities, some moderate magnitude earthquakes have inflict considerable economic casualties, for example the earthquakes of Saint Paul de

Fenouillet (M=5.2) in February 1996, Hautes Pyrénées (M=4.7) in May 2002 and Ripollès (M=4.0) in September 2004.

Figure 1. Situation map of Cerdanya region.

2. Geology

An asymmetric NE-SW trending intra-mountainous Tertiary basin, infill by up to 800 m of mainly unconsolidated Neogene sediments, is the most striking geologic feature of the Cerdanya valley. The basin, developed along the Tet-Conflent fault, is bounded by a basement made up by consolidated sedimentary, igneous and metamorphic Paleozoic rocks.

Figure 2 shows a representative geologic 2D cross-section of the Cerdanya valley with a maximum depth of 800 meters (Cirés et al., in edition). The bedrock is constituted by shale and limestone. The sedimentary materials of the valley are made up basically of conglomerates (32, 34 and 35), sandstone (30) and lutites (31) of Neogene age.

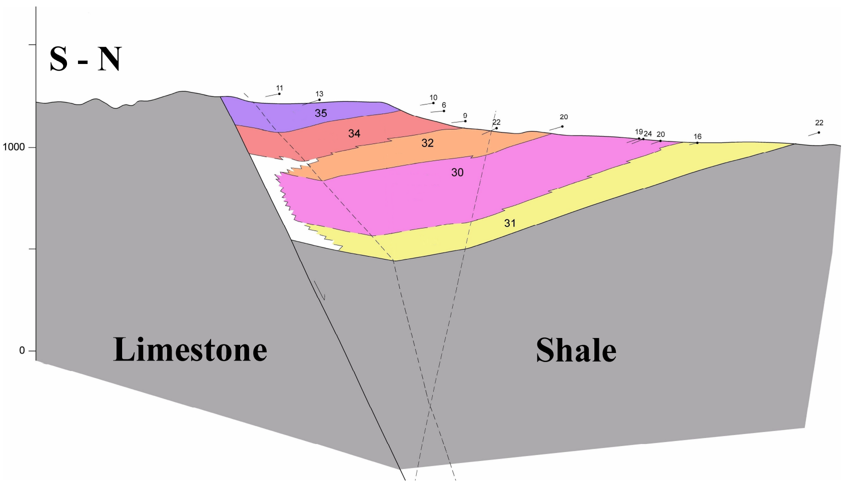

Figure 2. Geologic cross section of Cerdanya valley.

The 2D cross-section of the Cerdanya valley is characterized by a steep fault in the south and a smooth slope in the north.

3. The construction of the valley model

The wave propagation modeling requires the knowledge of some dynamic parameters and geometrical configuration of the materials that conform the area of study and its local geology that causes local effects. In particular, the dependence of the P- and S-waves, the density and the quality factors on the depth is needed for the application of 1D and 2D modeling presented here.
The available geological interpretations about the present lithologies (see section 2 in this paper), the basement valley geometry (Figure 2) and also some geophysical and geotechnical surveys (Bitri et al., 2004) allow to constrain a model of the Cerdanya valley.

3.1. Preparation of 1D columns

3.1.1. Velocity profiles
A geophysical survey carried out in the common lithologies in the Cerdanya valley area is the application of the SASW technique to characterize the velocity profiles of the shallower layers of sediments. The results for these measurements for each lithology are detailed in the Table I.

Table I. Vs profiles obtained with SASW surveys (Bitri et al., 2004) for the present lithologies in the valley avoiding the results of the first antrophic layers.

31			***30***			***32,34,35***		
Depth (m)	***Vs (m/s)***	***Averaged Vs***	***Depth (m)***	***Vs (m/s)***	***Averaged Vs***	***Depth (m)***	***Vs (m/s)***	***Averaged Vs***
13.9	458		14.4	437		15	476	
15.9	456		18.6	439		18.3	496	
17.6	450		23.6	444	455 m/s	21.3	485	497 m/s
20.3	464	456 m/s	29.3	478		25.7	496	
23.3	455		∝	575		31.3	505	
27	453					∝	572	
∝	442							

However, the results of Table I are not enough to establish Vs profiles with depth. From a geological point of view values around 800 m/s are expected for depths around 800 m that is the deepest site of the valley. Then, a curve is selected that describes velocity evolution with depth and agrees the mentioned characteristic with depth and the shallower velocity values (Table I). This is the curve proposed by Hamilton (1971) for sediment materials ($Vs=128 \cdot D^{0.28}$).
The SASW technique also provides information about Vp velocities for the shallower layers of sediments. The analysis of the values of Vp vs. Vs shows that their ratio is of a factor 2. This experimental result for materials of this type is also supported by the literature (Harris and Crede, 1976; Cotton et al, 1998). Then the velocities for Vp profiles will be obtained from Vs profile as follows: $Vp = 2 \cdot Vs$.

3.1.2. 1D columns
Some 1D soil columns are selected along the cross-section of the valley as interesting points where different local effects are expected (Figure 3).

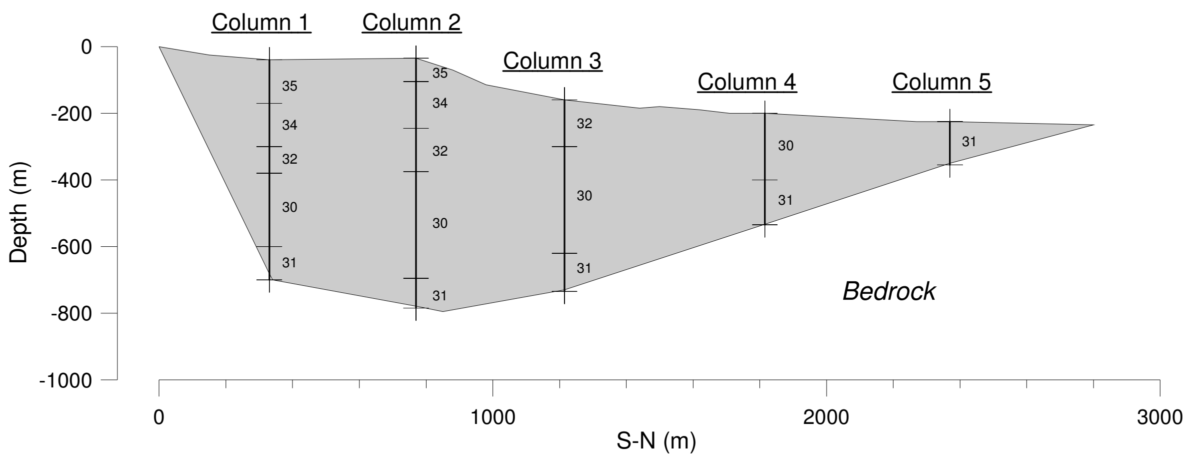

Figure 3. Geometrical interpretation of the 2D cross-section of the valley. The selected 1D columns are indicated.

Table II. Vs profiles defined for 1D modeling.

	Column 1		***Column 2***		***Column 3***		***Column 4***		***Column 5***	
Layer	***Thickness (m)***	***Vs (m/s)***	***Thickness (m)***	***Vs (m/s)***	***Thickness (m)***	***Vs (m/s)***	***Thickness (m)***	***Vs (m/s)***	***Thickness (m)***	***Vs (m/s)***
35	130	497	70	497	--	--	--	--	--	--
34	130	561	140	508	--	--	--	--	--	--
32	80	634	130	618	140	497	--	--	--	--
30	220	708	320	727	320	624	320	456	--	--
31	100	773	110	807	130	741	130	614	130	455
Bedrock	∝	1500	∝	1500	∝	1500	∝	1500	∝	1500

The densities of the different lithologies (30, 31, 32, 34 and 35) range from 1900 to 2100 kg/m^3.
The quantification of Vs profiles and density ranges demonstrates that the different sediments forming the layers do not create a big contrast between each other.

3.2. Definition of 2D cross-section

3.2.1. Vs and Vp profiles

The defined profiles for the 1D columns allow to constrain a velocity gradient for Vs that characterizes all the sediments that fill the valley. All the structure is then simplified in a realistic way due to the similarity between materials. Figure 4 shows the velocity profiles for the five columns. The curve that fits the 1D velocity dependence on depth is shown in Figure 4 and in Equation (1). Equation (2) shows the Vp velocity dependence on depth obtained from Equation (1).

3.2.2. Density profile and quality factors

An averaged density value for all the materials that fill the valley (Equation (3)) is selected to characterize the density values.

Experimental data that provides information about the values of the quality factors are not available. Therefore a set of several values was chosen (Equation (4)) to perform the modeling and to observe the consequence of the varying quality factors on the wave propagation.

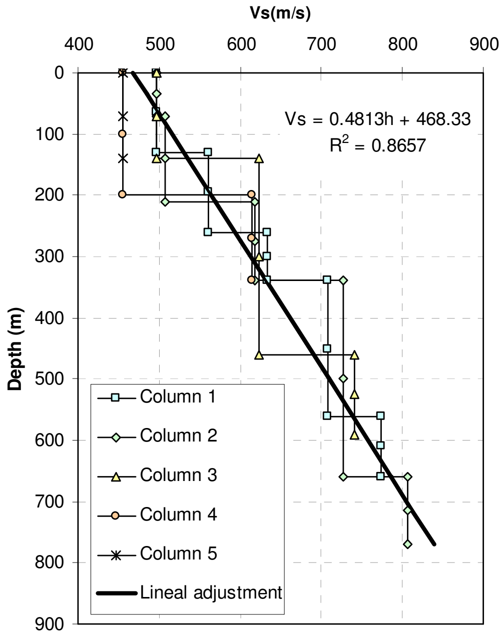

Figure 4. Dependence of the 1D Vs profiles on the depth with a linear fit that is used for 2D modeling.

Sediments: $Vs = 0.4813h + 468.3$ Bedrock: $Vs = 1500$ m/s	(1)
Sediments: $Vp = 2 \cdot Vs = 2 \cdot (0.4813h + 468.3)$ Bedrock: $Vp = 3000$ m/s	(2)
Sediments: $\rho \approx 2000 kg/m^3$ Bedrock: $\rho \approx 2550 kg/m^3$	(3)
Elastic materials $Qp = Qs = 4000$	(4)
Slightly viscoelastic materials: $Qp = 400$, $Qs = 200$	
High viscoelastic materials: $Qp = 100$, $Qs = 50$	

4. The input motion

Both modeling scenarios (1D and 2D cases) use plane waves as excitation seismic waves.

A Gabor signal with fundamental frequency of f_o = 0.5 Hz and standard deviation of γ = 0.1 (Figure 5) is selected as synthetic signal to be considered as input motion in rock.

Computations will be performed also with a real signal that has an acceleration spectrum compatible with a probabilistic spectrum computed for the zone (Macau et al., 2006).

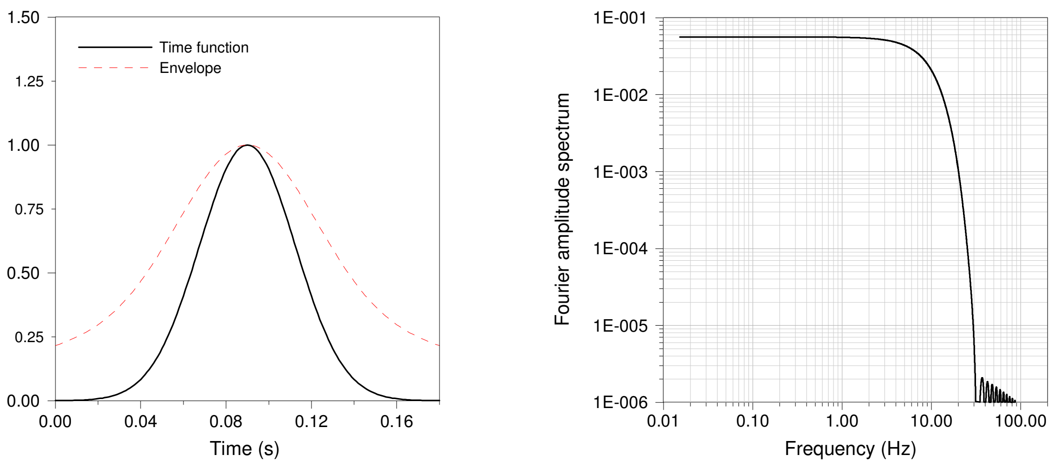

Figure 5. Gabor pulse with f_o = 0.5 Hz and γ = 0.1, time and envelope function (left) and amplitude spectrum (right).

5. The 1D modeling

ProShake program computes the response of a system of horizontal, homogenous, infinite and viscoelastic layers due to incident shear waves propagating vertically through 1D soil columns. The program is based on the continuous solution of the adopted wave equation to consider transitory movements from the Fourier transform algorithm. The shear modulus and the damping non linearity are considered using the linear equivalent properties of the soil. This is achieved by means of an iterative process to obtain values of the shear modulus and the damping compatible with the effective deformations of each layer that conforms the 1D soil column (Schnabel et al., 1972).

The method hypotheses are based on:

- Harmonic excitation: seismic waves are described in discrete form by spaced acceleration values with a temporary sampling interval.
- Propagation: it is carried out in the vertical direction considering the shear waves coming from the underlying bedrock. This implies that it only considers the soil particles motion in the horizontal direction.

6. The 2D modeling at the Cerdanya valley

6.1. Methodology

The finite-difference (FD) method is used for the 2D numerical modeling of the seismic wave propagation in heterogeneous viscoelastic media. In particular, a staggered-grid FD displacement-velocity-stress scheme with 4th-order in space and 2nd-order in time is applied (Moczo et al., 2000; Moczo et al., 2002). The AFDA (Adjusted FD Approximations) technique (Kristek et al. 2002) was implemented to simulate planar free surface. Rheology of the Generalized Maxwell Body was applied to incorporate realistic attenuation.

6.2. Accuracy computation

A high accuracy at low frequencies is needed due to the presence of very deep parts in the valley (around 800 m). Therefore, the lower frequency limit was selected to be 0.1 Hz. To accomplish this frequency limit, the model has to be enlarged to 30000m per side.
The upper frequency limit was selected to be 10 Hz. Then, from the sampling criterion of the FD scheme results the grid spacing is 7 m.
Finally, to accomplish the stability condition of the FD scheme the time step for the 2D simulations is 0.001 s (Tapia, 2006).

6.3. Results

The simulations for three scenarios with different quality factors (Equation (4)) have been performed. The results show that variations of the quality factor affect only the level of the amplitude in the seismograms (Figure 6). In the Figure 7 the results with Qp=400 and Qs=200 (slightly viscoelasticity) are shown. The 2D effect due to the reflection of the incident plane wave front at the edges of the valley is visible.

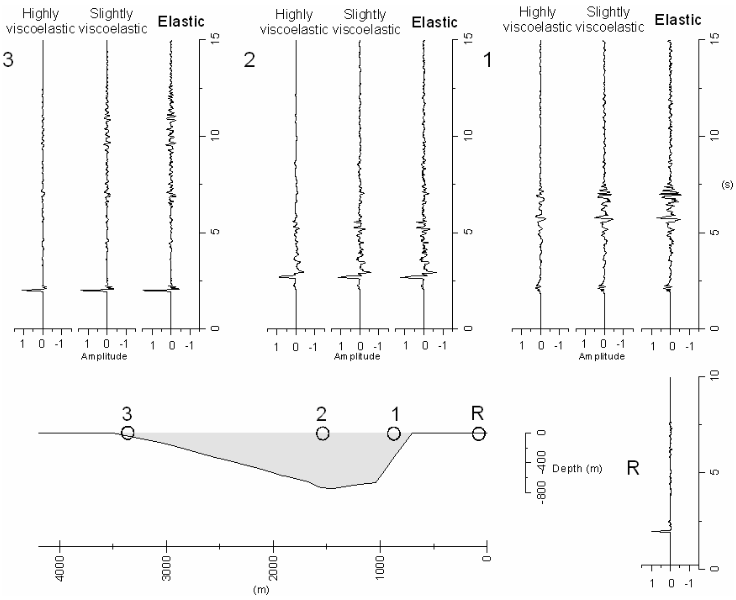

Figure 6. The results from the 2D modeling in time domain along the valley with different Q values (Tapia, 2006).

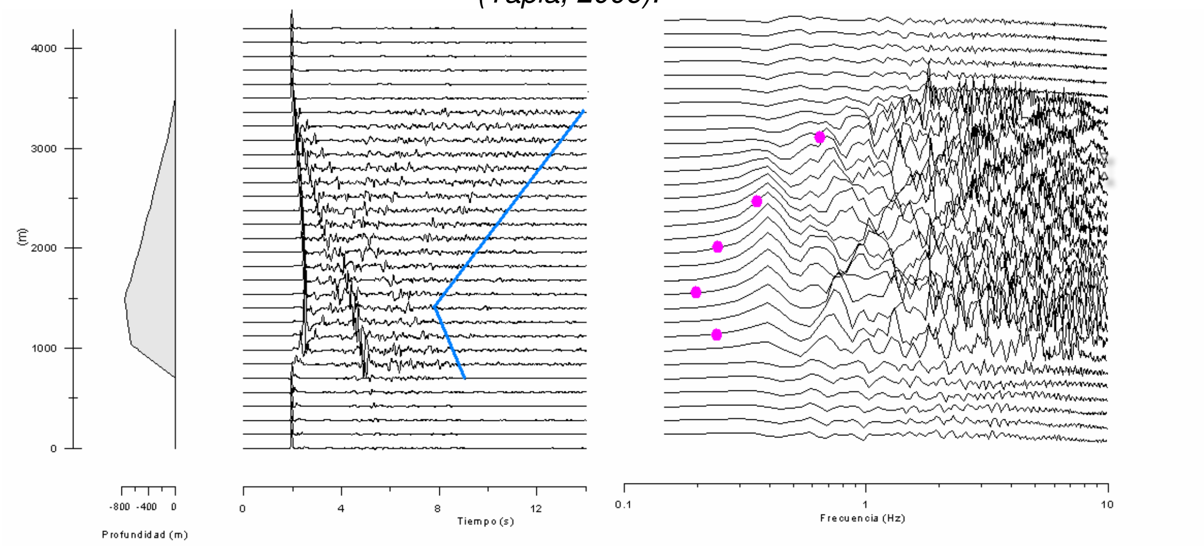

Figure 7. The results from the 2D modeling in time (left) and frequency (right) with slightly viscoelastic materials (Tapia, 2006). Points in the right plot represent the fundamental frequency obtained with the 1D modeling. Blue lines in the left plot represent the last significant wavefront.

7. Comparison between 1D and 2D results.

7.1. Arias Intensity, AI.

The Arias Intensity, AI, (Arias, 1970) is a parameter related to the energy content of the records. It is defined as the integral of the squared acceleration. Looking at this parameter it is possible to evaluate amplification effects because it is affected by amplitude, frequency content and signal duration. The comparison along the valley between 1D and 2D modeling is shown in the Figure 8 (left). Table III shows quantitatively the differences between both modeling cases. The observed increment in 2D results respect 1D is due to the 2D effect in the deepest part of the valley where wavefronts converge.

7.2. Trifunac duration

The Trifunac duration (Trifunac and Brady, 1975) is defined as the time interval in which the 5% and 95% of the energy on a ground motion has delivered. This parameter is affected by the total energy content of the record. The 1D and 2D modeling results along the valley are shown in the Figure 8 (right). The behavior between 1D and 2D cases are completely different. 1D modeling is related to the depth of the valley, it reproduces the valley shape. However, the 2D results reproduce the last significant wavefront (see blue line in the Figure 7, left).

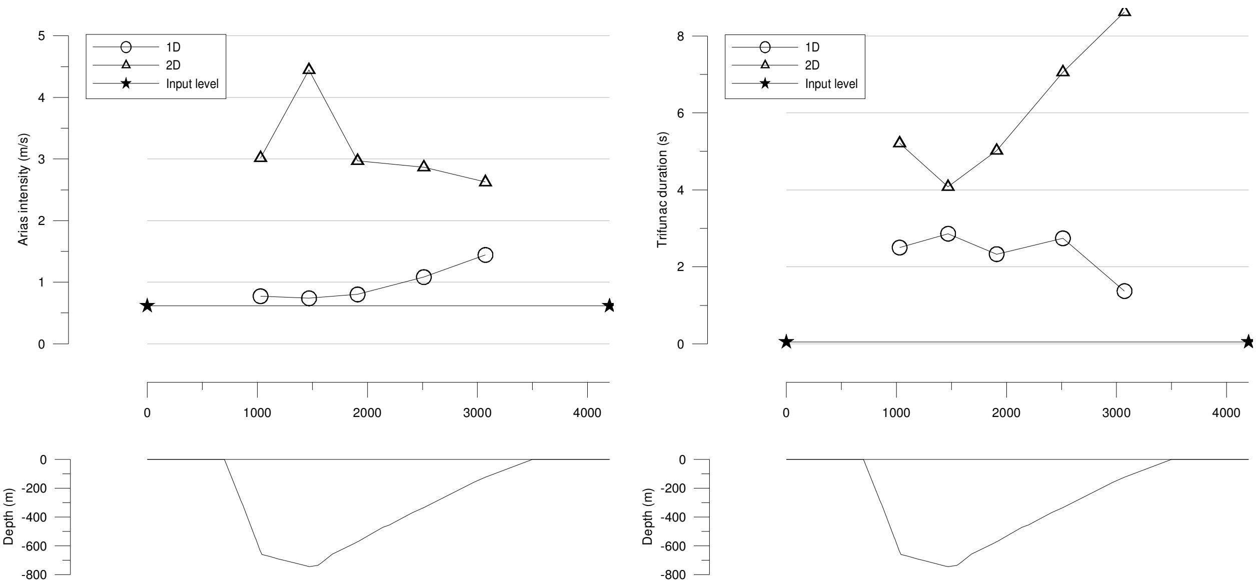

Figure 8. Arias intensity (left) and Trifunac duration (right) for 1D and 2D modeling.

Table III. 1D and 2D soil to rock Arias intensity ratios computed for the selected columns.

	Column 1	Column 2	Column 3	Column 4	Column 5
AI_{soil}/AI_{rock}1D	1.3	1.2	1.3	1.7	2.3
AI_{soil}/AI_{rock}2D	4.9	7.1	4.8	4.6	4.2

7.3. Wavelet analysis

The wavelet analysis allows to observe the evolution of the signal content simultaneously in time and the frequency domain. A Morlet mother wavelet with 6Hz of frequency is used. The results presented in the Figure 9 show the wavelet analysis for the column 1. The result corresponding to 2D modeling, clearly shows several reflections of the input motion in the smooth slope in the north of the valley. The wavefront arrives between 2-3 seconds later than the first arrival and the signal has inverted its polarity. Other significant wave front arrives between 5-6 seconds later than first arrival.

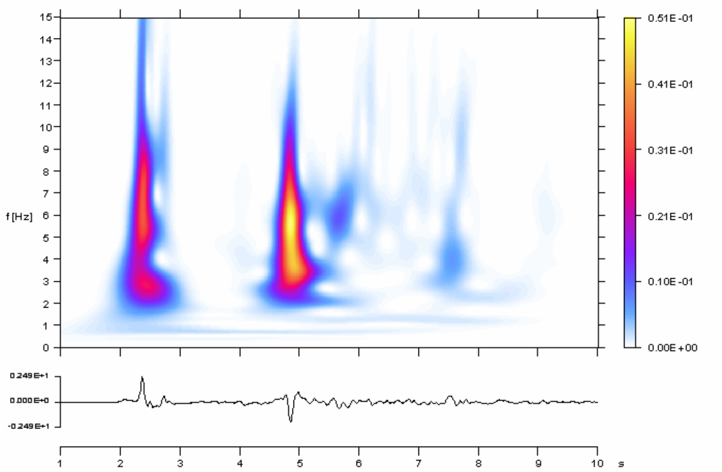

Figure 9. Time-frequency content of the record for column 1 from 2D modeling.

7.4. Time delay group, TGR

The time delay group, TGR, is a measurement of the signal phases (Beauval et al., 2003). Concretely, it is the gradient of the Fourier phase spectrum. To assess the increment in the duration of the signal knowing at which frequencies occurs is possible with this analysis.

Figure 10, shows the time delay group of the input motion that compared with Figure 11 and 12, allow to extract conclusions.

1D results (Figure 11) show a first peak between 0.2-0.3Hz and a second peak at 0.7Hz. 2D results (Figure 12) show a first peak at 0.4Hz and the second peak around 0.6Hz. Secondary peaks are present for higher frequencies in both cases having coincidences in the peaks between 1 and 2Hz.

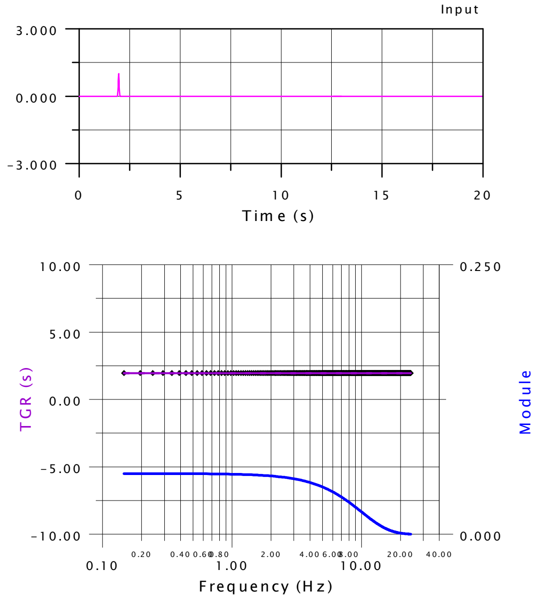

Figure 10. TGR for the input signal.

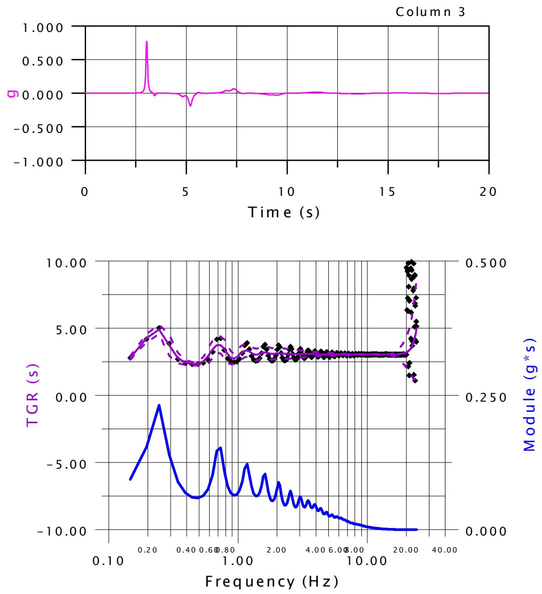

Figure 11. TGR for the 1D results for column 3.

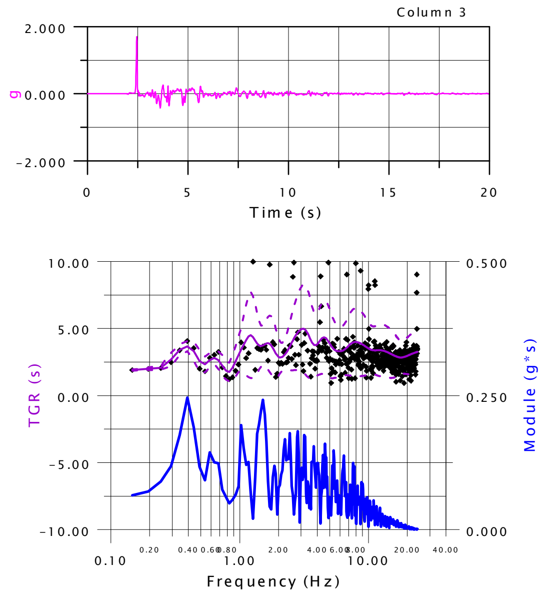

Figure 12. TGR for the 2D results for column 3.

7.5. Transfer functions.

Figure 7 (right) shows the frequency content of the 2D modeling computations and the fundamental frequencies that are found with 1D modeling computations (pink points). The fundamental frequencies of 1D modeling are in agreement with the depths of the valley. However, the first significant frequency in 2D modeling is almost constant and is between 0.3 and 0.4Hz for the center of the valley. Secondary frequencies for 2D modeling follow the 1D fundamental frequencies behavior.

8. Conclusions

The analysis of the selected parameters (Arias intensity, Trifunac duration, Time delay group, wavelet analysis and transfer functions) shows differences between 1D and 2D mainly due to the fact of taking or not into account the geometry of the valley.

Energy content is higher in 2D modeling computations that in 1D modeling computations (Arias intensity). Increments in duration (Trifunac duration) offer different behaviours due to the geometry of the valley.
Wavelet analysis allows to observe the mechanism of the wave reflections in the 2D structure. It is possible to recognize the reflected wavefront looking at the frequency content. The Time Delay Group shows that for low frequencies the results are in agreement and the main differences are present at frequencies higher than 1Hz.
In general, in 2D modeling the effects due to the thickness of the sediments and the effects due to the 2D geometry are present. The 1D effects detected in the 2D computations are in agreement with the 1D results when we observe parameters that are able to distinguish between these two type of effects (Time delay group).
From the analysis of synthetic results using real signal as input, it is expected to extract more conclusions.

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