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2D SIMULATION IN THE GRENOBLE BASIN USING THE AKI-LARNER METHOD COMBINED WITH AN EQUIVALENT LINEAR APPROACH

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ABSTRACT - In the framework of the ground motion simulation benchmark in the Grenoble basin, the two-dimensional response of the valley to SH waves is calculated by the discrete wave-number method proposed by Aki and Larner (Aki and Larner, 1970). To overcome the frequency upper bound limitation, the Aki and Larner's method is combined with a one dimensional computation using a classical multi-layer method (Aki and Richards, 1980). The ground response is computed at ten receivers across the valley, nine at the surface, and one at depth. In the framework of the free style prediction of the benchmark, we use an original version of the method to assess the two-dimensional non-linear response of alluvial basins. The so-called "Aki-Larner extended method" is associated to an iterative algorithm, as proposed by Seed and Idriss (1969) which accounts for the modulus and damping degradation using a linear visco-elastic model. Results in the linear and the equivalent linear cases are compared for the magnitude 6.0 earthquakes proposed in the framework of the benchmark.

1. Introduction

In the framework of the ESG 2006 ground motion simulation benchmark in the Grenoble basin, the two-dimensional response of the valley is calculated by the discrete wave-number method proposed by Aki and Larner (Aki and Larner, 1970). SH wave computations are done using this 2D technique, for the 10 receivers of the provided profile.

Then, in the framework of the free-style exercises, another version of the 2D Aki-Larner code is used, in which an equivalent linear approach has been implemented, in order to account for moderate non-linear soil behaviour.

The methodology and the results are presented below, as well as a comparison between results obtained with the linear and equivalent linear approaches.

This combined approach was chose to complement other 2D modelling techniques proposed in the framework of the ESG benchmark, such as spectral element methods, finite difference methods, modal summation methods, direct boundary element methods, widely used in different contexts. For example, in the framework of the Interreg III SISMOVALP European project, a simulation benchmark has also been organised, using a generic alpine valley profile, and computations have been performed on the Grenoble basin (Causse 2004; Cotton et al., 2004; Chaljub et al., 2005).

2. Methodology

The code that is used in this study (especially the equivalent linear module) was developed at LGIT (Grenoble) by P.-Y. Bard and M. Kham and tested by Résonance SA (Carouge) in the framework of the SISMOVALP European project.

2.1. The extended Aki-Larner model

The computation of the two-dimensional response of alluvial basins is based on the discrete wavenumbers method proposed by Aki and Larner (1970). The basis of this method lies on the transposition of the direct problem in space and time domain to the horizontal wavenumber and frequency domain, achieved by a double Fourier transform. To solve the problem numerically, a discretization in both space and time, and thus in wavenumber and frequency, is operated.

Some of the simplifying hypotheses on which this method is based impose a frequency limitation which is approximately in the range between $4*f_0$ and $8*f_0$, f_0 being the resonance frequency of the considered basin. To overcome this frequency limitation, the computation is combined with a classical 1D computation, for frequencies higher than $8*f_0$. Between $4*f_0$ and $8*f_0$, an hybrid solution if linearly interpolated between the 1D and the 2D solutions, as shown on Figure 1.

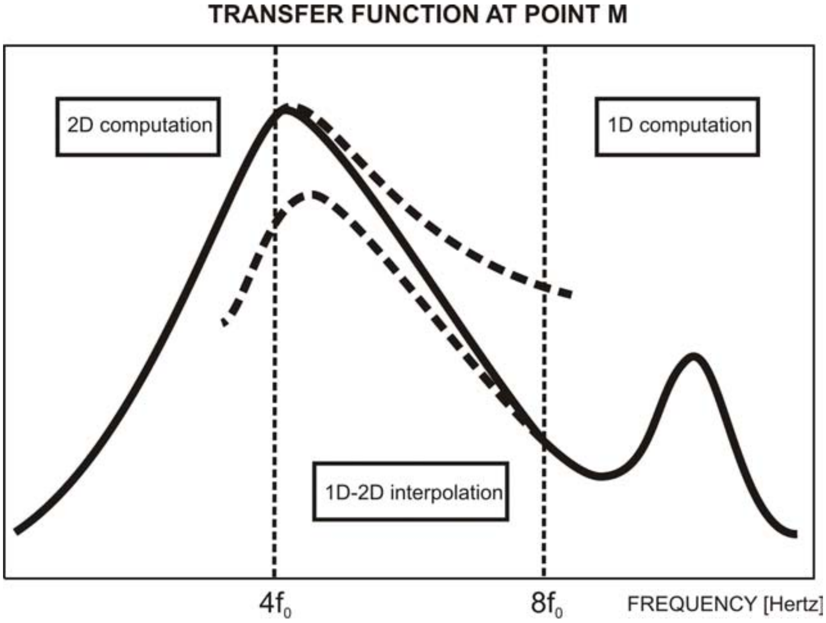

Figure 1. Approximation of the 2D basin response by the extended Aki and Larner's method.

2.2. The equivalent linear model

Since the soil non-linear behaviour is accounted for by an equivalent linear model, it can be easily introduced in the linear method of Aki and Larner. First proposed by Seed and Idriss (1969), the original equivalent linear method states the modulus and damping degradation in the soil submitted to large strains can be modelled by the response of a linear visco-elastic model. The equivalence between linear and non-linear behaviour is ensured in terms of energy dissipation, represented by the internal area of the hysteresis loop in the stress-strain plane. As a matter of fact, the energy dissipated by the linear visco-elastic model, equal to that of a simple resonating oscillator, can be represented by an ellipse area in the stress-strain plane. Therefore, the energy dissipated by the non-linear material is adequately approximated by the linear model by fitting the ellipse area (equivalent linear) to the area of the hysteresis loop (non-linear).

This is practically achieved by fitting the modulus and damping of the linear visco-elastic model to the effective modulus and damping of the non-linear material under loading. These effective values are generally given by experimental modulus and damping degradation curves obtained by laboratory tests. In Seed and Idriss' visco-elastic model, modulus and damping values are computed from these degradation curves by an iterative algorithm, until a convergence limit is reached, between the effective strain at two consecutive iterations. Seed and Idriss' equivalent linear model, widely used in the well-known 1D SHAKE program (Schnabel et al., 1972), was implemented in the extended Aki and Larner method. In the 2D computation, it is assumed that the shear modulus and damping are constant inside each layer, with the strain amplitude being variable (2D computation). In the 2D equivalent linear frame, the mean strain amplitude, computed at several points across the valley within each layer, is used to compute the new shear modulus and damping at each iteration step.

This equivalent linear version of the Aki-Larner code is used for the free-style computations for the benchmark.

3. Valley configuration

The bedrock topography and position of the receivers were given as input to the benchmark. Figure 2 shows the shape of the 2D profile and the position of the ten receivers.

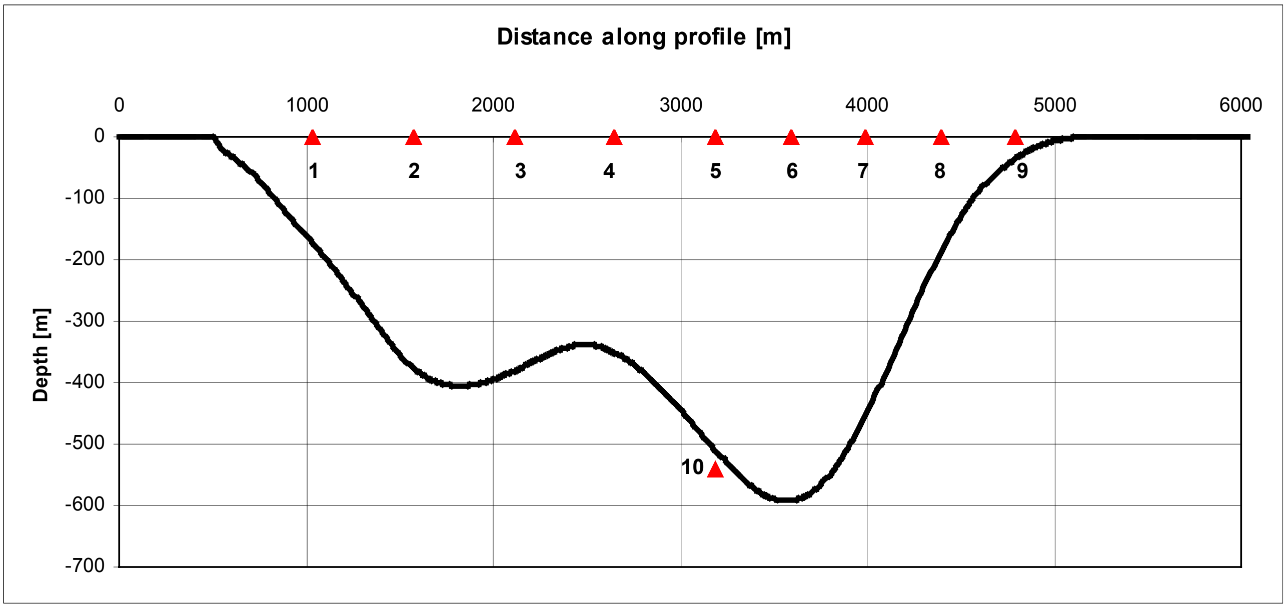

Figure 2. Bedrock geometry along the 2D profile. The red triangles indicate the position of the ten receivers used for the computation. The vertical scale exaggeration is about a factor 3.

The layers of the deposits are considered horizontally homogeneous. The given velocity and density gradients in the sediments are:

$$Vs = 300 + 19 * \sqrt{D} \quad (1)$$

$$Rho = 2140 + 0.125 * D \quad (2)$$

where D is the depth in m, Vs is the S wave velocity in m/s and Rho is the density in kg/m^3. The S-wave velocity in the bedrock is 3200 m/s and the density is 2720 kg/m^3.

4. Input motions

In the framework of the benchmark, several earthquake sources where proposed. The Aki-Larner 2D program does not contain any source modelling. The program computes the response of the 2D deposits to an incoming plane SH wave. It is then requested to give an input motion at the base of the profile.

In order to determine the input motion, for the strong motion Mw = 6.0, S1 and S2 earthquakes, real accelerograms have been looked for in the European Strong Motion Database (Ambraseys et al., 2004). The criteria for the search where Mw close to 6.0, epicentral distance close to 7 km for S1 and close to 19 km for S2, recording in free field on rock (soil A). Only a few possible events where responding to these criteria. The finally selected input motions are the following :

- S1: Mw=5.9 earthquake, at 7 km epicentral distance, Albania, 1988.
- S2: Mw=6.5 earthquake, at 20 km epicentral distance, South Iceland, 2000.

Of course, these earthquakes are recorded in tectonic contexts which are different from the Grenoble one. Nevertheless, our goal is not to compute particular scenarios for the case of Grenoble, but to evaluate site effects and compare different methods for such evaluation. The choice of different input solicitations, with for example the S2 case which has a very large plateau on the response spectrum (see Figure 3), will participate to illustrate the importance of the choice of the input signals for the basin response analysis (Scherbaum et al., 2004).

For both cases S1 and S2, an incidence angle of 30° has been chosen to account for the fact that S1 and S2 sources are shallow sources on the lateral bank of the valley.

As said before, the Aki-Larner program computes the response to incident plane SH waves. It is thus not possible to compute 3D seismograms. Then, for each earthquake, the two horizontal components have been used, independently, to produce the resulting motion at the receivers. No vertical motion is provided using the SH Aki-Larner method.

The time series chosen from the European Strong Motion Database are recorded on soil A site, with a surface S-Wave velocity estimated at 800 m/s. The velocity of the bedrock under the Grenoble basin is given as being 3200 m/s, which makes a great difference compared to surface velocity at "rock" recording sites. In order to account for the difference in the corresponding seismic motion, a 1D deconvolution was performed, using the CyberQuake program (BRGM, 1998). A smooth decrease in velocity from 3200 m/s to 800 m/s was used in a 1D column, in order to compute the input motion for S1 and S2 at the base of the 2D profile at 3200 m/s. Figure 2 shows the resulting two horizontal components used as input motion at the bottom of the profile, for case S1 and S2. Figure 3 shows the response spectra of the earthquakes used as input for the strong motions S1 and S2, before and after the deconvolution procedure.

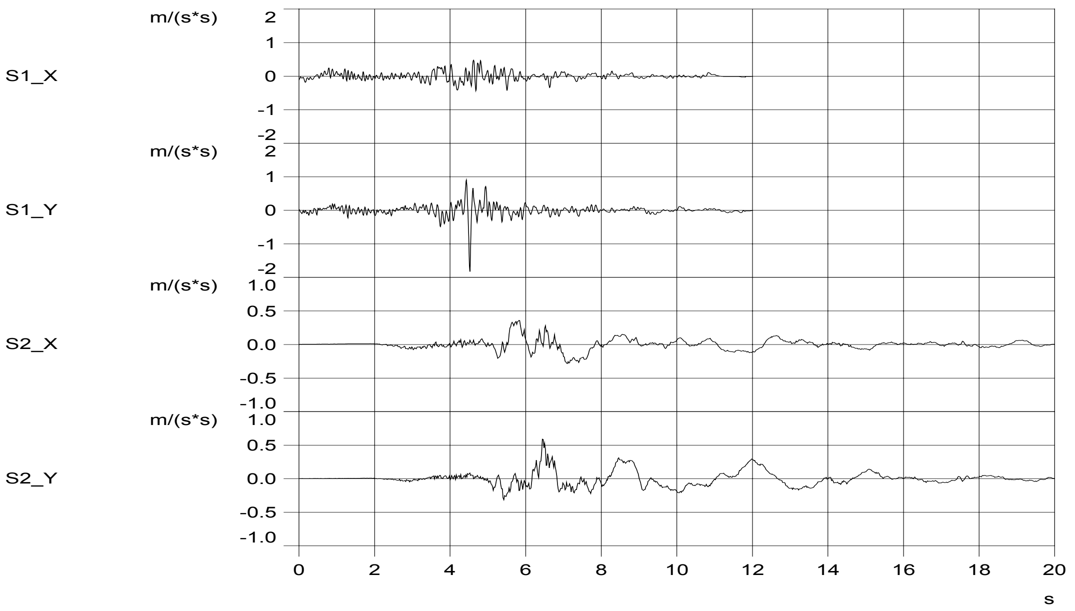

Figure 2. Horizontal acceleration time series used as input motion for S1 and S2.

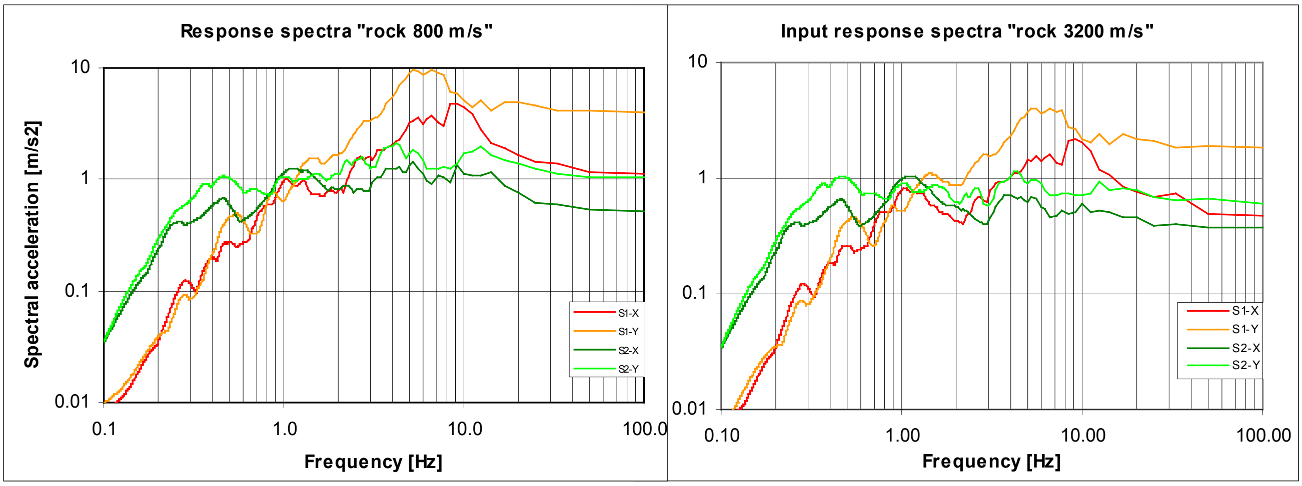

Figure 3. Response spectra of the earthquakes used as input motion for S1 and S2, before (left) and after (right) the deconvolution performed to account for the difference in rock S-wave velocity.

5. Amplification functions

The Aki-Larner code does not include any source or path modelling. Only the response of the sedimentary 2D structure is computed. For this reason, the comparison between these results and computations made by other teams in the benchmark can only be made in terms of amplification between the bottom and the top of the 2D profile.

The amplification is here regarded in terms of the so-called "amplification function", which is the ratio between the response spectrum (for 5% damping) of the resulting motion at the surface receiver and the response spectrum of the input motion at the base of the profile (twice the incoming wave field, as would occur at a free surface of the same rock).

Figure 4 shows the variation of the amplification, for the 9 surface receivers, along the 2D profile, in the case of the incident input motion S1-Y, as an example. It is possible to observe the low frequency amplification (between 0.3 and 0.4 Hz) of the central part of the basin (receivers R03 to R07), with an amplitude between 6 and 8. On the edges, receivers R01, R02 and R08, the amplification tends to be lower and to occur at higher frequencies. Receiver R09 is in a very particular situation, leading, in some cases, to strong basin edge effects, with high amplification at a frequency around 3 Hz (see Figure 5 right).

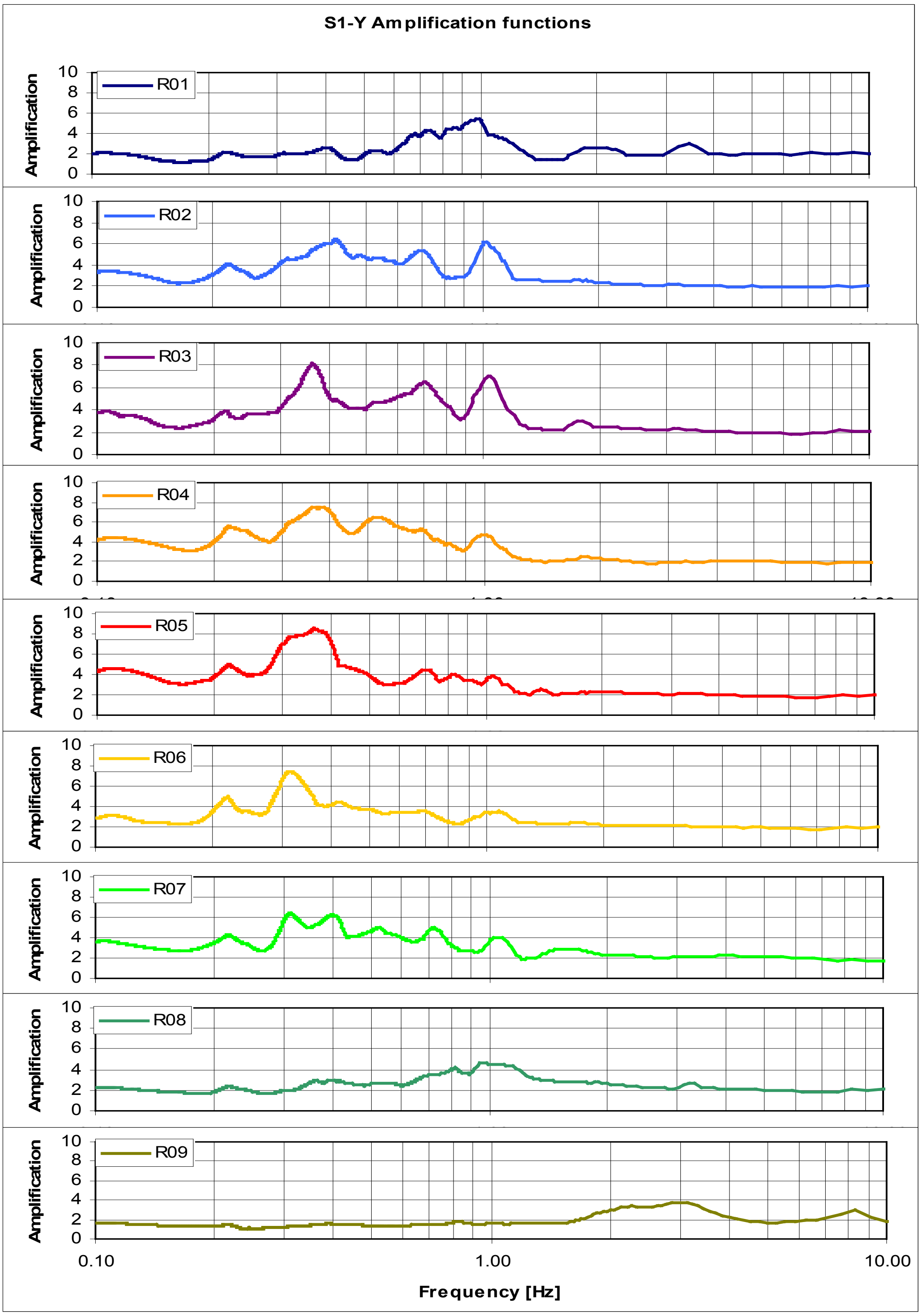

Figure 4. Amplification functions along the 2D profile for S1-Y input motion.

Figure 5 (left) also shows the strong variability of the amplification functions for the different input motions used, at receiver R06 (deepest part of the basin). This underlines the fact that, in the case of site effect or microzonation studies, it is important to consider a set of input motions, representative of the regional hazard expected for hard rock.

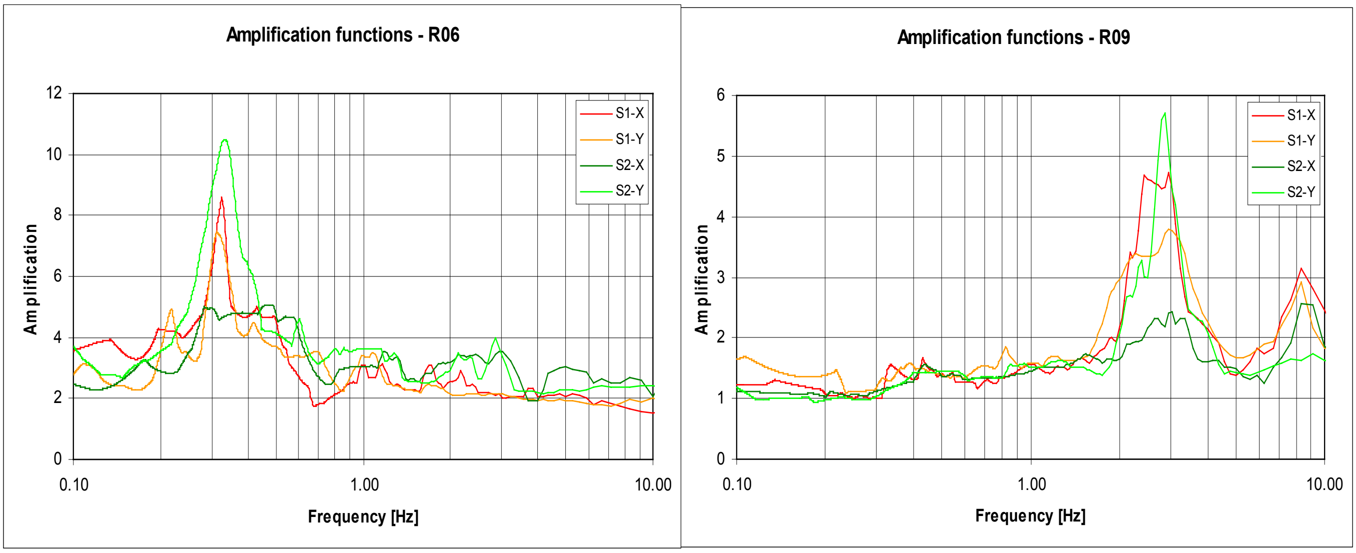

Figure 5. Amplification functions at receivers R06 (left) and R09 (right) for different input motions (different vertical scales).

6. Equivalent linear approach

6.1. Material curves

The sediments in the Grenoble basin are characterised by the presence of thick clay deposits. It is excepted that such material does not have a purely linear behaviour under strong seismic loading. For this reason, the Aki-Larner method combined with an equivalent linear model was used to perform computations on the 2D profile.

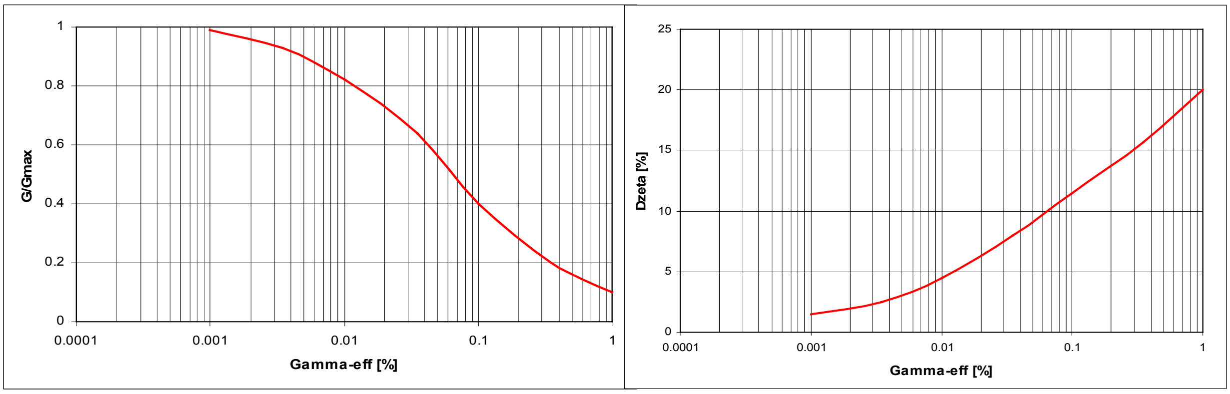

Figure 6. Material behaviour curves used for the clay deposits (Vucetic and Dobry, 1991). Left: shear modulus as a function of strain; right: damping as a function of strain.

The Grenoble clay has been studied through the samples coming from the deep Montbonnot borehole, by the laboratory 3S "Soils Solids Structures". Following these investigations, the most suitable material curves suggested for these clays (J. Jerram, pers. comm., 2006) are the one proposed by Vucetic and Dobry (1991). Figure 6 shows the shear modulus (left) and the damping (right) as a function of strain, respectively.

6.2. Comparison between linear and equivalent linear approaches

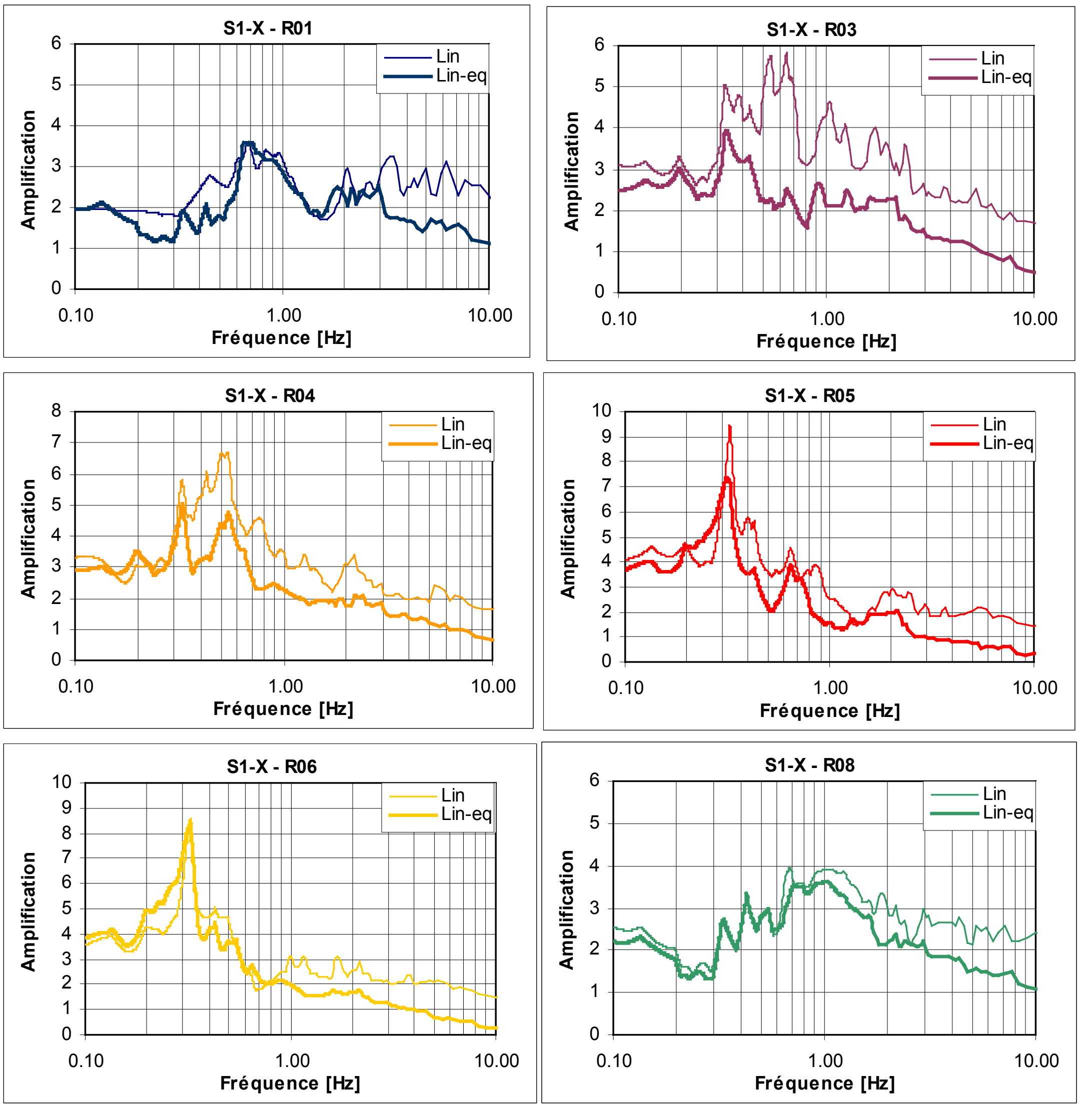

Figure 7. Amplification functions along the 2D profile (receivers R01, R03, R04, R05, R06 and R08, as examples), for S1-X input motion, for the linear and the equivalent linear computations.

The resulting motions at the ten receivers along the 2D profile where computed for the S1 input motion. Figures 7 and 8 show the amplification functions obtained both in the linear and the equivalent linear cases, at different surface receivers along the 2D profile, for input motions S1-X and S1-Y, respectively.

This comparison shows that the account for the non linear behaviour of the soil, even in an approximate way with an equivalent linear frame, significantly reduces the amplification level, especially at frequencies higher than the fundamental resonance frequency of the site. In the case of site effects or microzonation studies devoted to produce design spectra for engineering structures, this can have a major impact on the associated results and costs, depending on the frequency of interest for the considered structure.

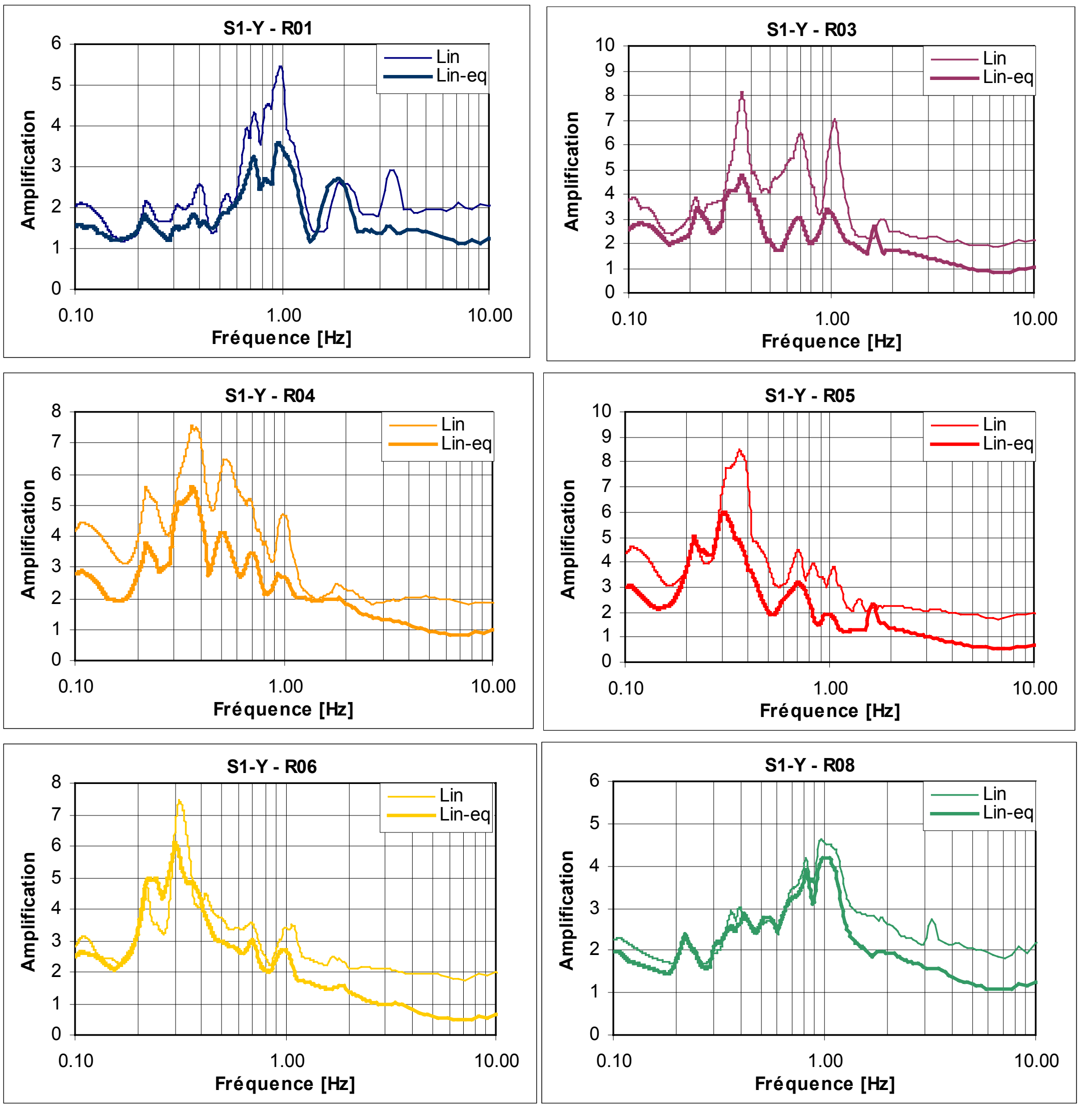

Figure 8. Amplification functions along the 2D profile (receivers R01, R03, R04, R05, R06 and R08, as examples), for S1-Y input motion, for the linear and the equivalent linear computations.

7. Conclusions

Results obtained at the receivers along the profile show the influence of the basin shape on the local site response. It is thus possible to observe a low frequency amplification (between 0.3 and 0.4 Hz) at the central part of the basin. On the edges, the amplification tends to occur at higher frequencies, with a lower amplitude. On the bevel-edged side of the basin, in some cases, strong basin edge effects can be observed, with high amplification at a frequency around 3 Hz.

As four different strong input motions are used (two horizontal components for each earthquake), it is possible to show the variation of the resulting amplification functions. This underlines the fact that, in the case of site effect or microzonation studies, it is important to consider a set of input motions, representative of the regional hazard expected for hard rock.

A comparison is done between amplification functions obtained in the linear and equivalent linear cases, for the same input motion. This comparison shows that the account for the equivalent linear behaviour of the soil significantly reduces the amplification level, especially at frequencies higher than the fundamental resonance frequency of the site. In the case of site effects or microzonation studies devoted to produce design spectra for engineering structures, this can have a major impact on the associated results and costs, depending on the frequency of interest for the considered structure.

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