1D AND 2D LINEAR AND NONLINEAR SITE RESPONSE IN THE GRENOBLE AREA

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ABSTRACT - In this study we present 1D and 2D linear and nonlinear wave propagation simulations in the Grenoble basin up to 10 Hz. The numerical computations show that the strong impedance contrast between the sediments and surrounding bedrock produces a strong amplification regardless of the basin geometry. This velocity contrast also helps the development of strong surface waves at the basin edges. As a consequence, the amplification from the 2D case is higher than the 1D results. Nonlinear effects become important for an input acceleration of 0.2g and are responsible for a strong deamplification of the ground motion within the basin. Furthermore, the soil nonlinearity makes the ground motion in the basin to appear more coherent than the linear case. The computed transfer functions from nonlinear results show an evident deamplification between 1 and 5 Hz with respect to the linear ones. These results suggest that a 2D and 3D geometry should be taken into account for a more accurate estimation of the basin response.

1. Introduction

In previous years there have been numerous studies about wave propagation in complex media (i.e. Olsen and Archuleta, 1996; Satoh et al., 2001; Benites and Olsen, 2005). Most of these studies concentrate their attention on large basins, such as those in the USA, Japan, and New Zealand among others. However, other regions equally prone to earthquake hazards are located on small basins where a large number of people live and an important industrial activity may also be present. This is the case for some European cities, for example the Grenoble basin. Grenoble is located in a “Y” shaped alpine valley, on top of about 700 m (deepest part of the basin) of postglacial lacustrine sediments that cause strong amplification of ground motion. Lebrun (1997) computed site amplification in several places in the City of Grenoble using small magnitude events. He applied the standard spectral ratio technique (Borcherdt, 1970) and he found that the site response has a broadband amplification of 10, being nearly constant between 0.5 and 10 Hz. In addition, an H/V microzoning study also revealed a resonance frequency of 0.3 Hz in the deepest part of the valley and another one around 3 Hz due to the presence of a shallow layer (Lebrun et al., 2001). Further studies using antenna noise measurements showed that the ground motion within the Grenoble basin is dominated by basin edge induced waves carrying up to four times more energy than the direct wavefield, regardless of the type of event considered. In addition, the
diffraction phenomenon is mostly constrained by the 3D structure of the basin, independently of the azimuth of the incoming event (Cornou et al., 2003). These seismological observations concern small strains only. For a complete estimation of the seismic hazard, from an engineering point of view, we need to compute the basin response for large events and account for possible nonlinear effects. During the Seismic Hazard and Alpine Valley Response Analysis Project (SEISMOVALP), one item was the characterization of the dynamic properties of Grenoble sediments. Geological studies, especially at the Montbonnot site, an instrumented borehole with a surface and downhole accelerometer at GL-541m, showed that the sediments are composed mainly of clay type soils (Cornou et al., 2003). Preliminary analysis shows that these clays have a plastic index of 20% (Pierre Foray, personal communication). An interesting property of clays is that their dynamic properties depend on the plastic index. Thus, we can use the same shear modulus reduction curve at all depths within the sediments. In this study we compute 1D and 2D linear and nonlinear wave propagation at the Montbonnot site. In addition, we use a Monte Carlo technique in order to evaluate the uncertainty of the Grenoble basin response.

**Figure 1** (a) 1D velocity model for the Montbonnot borehole. (b) 2D profile containing the borehole site.

### 2. The Grenoble basin model

The ESG2006 benchmark committee proposed 1D, 2D and 3D models for the Grenoble basin. In the present study, we used the proposed 1D and 2D models concerning the density and quality factors. Within the sediments, however, we used the velocity profile described in Cornou et al. (2003). One reason to do this is because Cornou et al. (2003) model has a lower S-wave velocity in the first 40 m than the proposed model for the benchmark. This will affect the nonlinear computation. Figure 1a shows Cornou et al. (2003) velocity model in black, the gradient model in red and the smoothed version in blue, which is the model used in this study. Figure 1b shows the 2D profile. The triangles are the sites where the computed ground motion is requested. Note that receivers R5 and R10 correspond to the Montbonnot borehole.
3. Computing aleatory uncertainties

Estimating the total uncertainty in site response is a complex task. Indeed, this value is a combination of different physical features. For example, the input ground motion with its inherent variability due to the seismic source. Furthermore, we lack the knowledge about the detailed velocity model of the media where seismic waves propagate. If nonlinear effects are expected, this problem worsens because the soil response depends on the input motion and the material properties at the same time. Another source of uncertainty is the partial characterization of the dynamic properties for nonlinear analysis. This is the rule rather than the exception due to the high cost of geotechnical in situ and laboratory analysis.

3.1 Input ground motion variability

![Image of acceleration response spectra](image)

**Figure 2** 5% damping acceleration response spectra for the two scenario events of magnitude 6.0 located at 8.3 and 21.5 km, respectively. The blue lines represent the median and 68% confidence limits from Berge-Thierry et al. (2003) attenuation equation.

In order to take into account the ground motion variability, 30 acceleration time histories were used to compute the 1D wave propagation. These signals were generated for two different sources of magnitude 6.0 located at 8.3 and 21.5 km hypocentral distance, respectively (ESG2006 benchmark requirements). These time histories were computed following Pousse et al. (2006) method. This technique generates non-stationary stochastic accelerograms following a statistical description of a strong motion database. For Europe, this corresponds to the data used in the computation of the attenuation equation for Europe by Berge-Thierry et al. (2003). Figure 2 shows the response spectra of these synthetics for the two scenarios mentioned above. The blue lines represent the median and the 68% confidence limits from Berge-Thierry et al. (2003) relation. Note that the variability of the ground motion is preserved, but the mean value is slightly higher than the predicted one. All these simulations are computed for rock sites.

3.2 Soil model variability

In the present work we use Monte Carlo sampling to perturb the mean value between given minimum and maximum limits. We use the coefficient of variation ($\delta$), which is the ratio between the mean and the standard deviation, to obtain the interval where
uniform sampling is performed. We chose the coefficient of variation because it is easier to have an idea of such variation rather than assigning a standard deviation directly. From its definition, the smaller \( \delta \) is, the smaller its standard deviation is. We decided to use a uniform distribution to sample, but another distribution can be used. We found that this distribution shows well the uncertainty in the velocity model as suggested from inversion results on velocity profiles (Figure 3a).

Thus, the velocity model is randomized by sampling values of the S-wave velocity, density, Qs, and thickness using a uniform distribution. Conversely, the shear modulus reduction curves \( G/G_{\text{max}} \) are sampled between clayey soils with plastic indexes between 15 and 30\% (Figure 3b). Table I shows the coefficient of variation used in the present study.

![Figure 3 (a) Monte Carlo simulation of the Grenoble velocity profile. The red line is the original model and the yellow lines are the random models. (b) Dynamic characteristics of clayey soils. The random models are bounded between soils with a plastic index (PI) of 15\% and 30\%, respectively.](image)

Table I Coefficient of variation \( \delta \) used in the generation of random models

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<th>( \delta )</th>
<th>( V_s )</th>
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<th>Density</th>
<th>Qs</th>
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<td>0.1</td>
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Finally, for each input ground motion 30 random soil models were generated and the 1D linear and nonlinear wave propagation were computed. Thus, a total of 900 random models were used.

4. Soil rheology and wave propagation

Two different nonlinear rheologies were used in this study. First, for the 1D case, the Iwan (1967) model was used. This rheology uses directly the \( G/G_{\text{max}} \) curve to approximate the nonlinear soil behavior. We followed Joyner and Chen (1975) algorithm implemented on a second order finite difference code to propagate a vertically incident SH wave.
For the 2D case, the P-SV nonlinear rheology developed by Iai et al. (1990) was used. This model follows a multimechanism description of the nonlinear soil behavior with its backbone characterized by the hyperbolic equation (Hardin and Drnevich, 1972). The hysteresis follows the Masing criteria (Masing, 1926). For more details of the model see Iai et al. (1990). This rheology was implemented into a second order staggered grid finite difference code to propagate a vertically incident P-SV wavefield.

In both cases, elastic (transmitting) boundary conditions at the bottom edge were used. For the one-dimensional problem, all computations were carried out up to 10 Hz with a grid spacing of about 1 m and 20 points per wavelength. For the 2D problem, the time series were computed up to 10 Hz with a grid spacing of 2 m and 12 points per wavelength. All nonlinear computations are total stress analysis, which means that pore pressure effects can be neglected. This simplification seems justified given the clayey nature of the soil.

5. Results

Before computing any wave propagation, the input ground motion was first obtained by deconvolving the surface motion to outcrop motion considering a rock thickness of 541 m in the 1D case and 700 m in the 2D case. Due to the large $V_s$ of the bedrock, the deconvolved signals are practically the same as the original ones except for the effect on the travel time. Furthermore, considering that the 2D case takes much longer computation time and memory resources than the 1D case, all 900 Monte Carlo soil models were explored using the 1D code only. Then, from all these 1D results, we find the acceleration time history whose response spectrum is closer to the mean response spectrum. Its corresponding input time series and soil model is then injected into the 2D model. In this study, no vertical component was injected in the 2D modeling.

5.1 1D wave propagation

Figure 4 shows the acceleration time histories (left) and their 5% response spectra (right) for the mean scenario for the event of magnitude 6.0 located at 8.3 km. The linear case shows a strong amplification, the PGA of the surface time history is about 4 times the PGA of the input ground motion. In addition, its response spectrum also indicates a strong amplification around 3 Hz. This is probably the effect of the shallow soft soil already observed by H/V measurements (Lebrun et al., 2001). Note that at the same frequency no peak is observed in the input motion. Conversely, the nonlinear soil behavior is rather strong. The PGA of the surface accelerogram has a lower value, about 1.5 times smaller, than the one of the input motion. Moreover, the response spectrum is amplified at frequencies lower than 2 Hz. The shear strain distribution at depth, not shown here, indicates that most of the nonlinearity takes place in the first soil layer. The strain value in this layer can easily reach more than 1% deformation.

Figure 5 shows the mean amplification and its 95% confidence limits for the linear (left) and nonlinear (right) computations. These transfer functions are computed as the Fourier spectra ratio between the computed motion at the surface and the computed synthetic accelerogram on rock. This is the so-called outcrop response, and it is equivalent to the standard spectral ratio technique. As expected, the site
response for the two linear results is identical except for a small difference at low frequencies due to the energy content of the input ground motion. We observe a mean amplification of 3, which is nearly constant between 0.2 and 5 Hz. Yet, the $2\sigma$ amplification curve also suggests three distinct resonance frequencies at 0.2, 1 and 3 Hz, respectively.

Figure 4 Acceleration time histories (left) and their 5% response spectra (right) for the mean scenario for the magnitude 6.0 event located at 8.3 km.

Figure 5 Outcrop response for the Montbonnot borehole. The plots to the left show the linear response and the right hand side plots show the nonlinear response. The shaded area shows the 95% confidence limits.

The nonlinear computations show a slightly stronger deamplification for the event located at 8.3 km than the one located at 21.5 km. In both cases, the frequency band being deamplified is between 1 and 10 Hz. The resonance frequency at 0.2 Hz is not modified by the nonlinear behavior.
5.2 2D wave propagation

Figure 6 shows the acceleration time histories from the 2D linear wave propagation in the Grenoble basin. We can observe the strong amplification in both components. In particular, the strong presence of surface waves on the vertical component. These are induced basin edge surface waves, which are also affected by the basin asymmetry. For example, receiver R_9 shows a strong reverberation on the vertical component. This geometry also makes that the vertical components closer to the edges have larger amplitudes than the ones in the middle of the basin. This is reversed in the case of the horizontal components.

Figure 6 Acceleration time histories from the 2D linear wave propagation in the Grenoble basin. The triangles represent the receivers where the motion is computed.

Figure 7 shows the accelerograms from the 2D nonlinear wave propagation. In this case, we observe a deamplification of the ground motion in both components compared to the linear case. Nonetheless, the presence of surface waves on the vertical components is still important. Another interesting result is the longer duration of the ground motion observed on the horizontal components compared to the linear computations. Indeed, since there is a shift of energy toward lower frequencies, the waves arrive later in time producing an increase on the ground motion duration. This phenomenon is also exacerbated with the combined effect of the induced basin edge waves. In this particular simulation, receiver R_{10} (downhole sensor) shows that the
computed ground motion for both linear and nonlinear cases is quite similar. A possible explanation is the strong impedance contrast between the basin the bedrock, which traps most of the reflected energy from the shallow layers. In this way, the receiver located in the bedrock is only slightly affected by the reflected waves coming from either the linear or nonlinear sediments.

Figure 7 Acceleration time histories from the 2D nonlinear wave propagation in the Grenoble basin. The triangles represent the receivers where the motion is computed.

Figure 8 shows velocity snapshots of the linear (lower subplots) and nonlinear (upper subplots) 2D wave propagation. The first interesting observation is the fact that the nonlinear computation shows a stronger coherent wavefield in the basin than the linear one. The linear case shows a more complex wavefield, with large amplitude surface waves induced in the basin edges. The snapshot at 2.15 s also shows that these surface waves are produced in the shallow layers and are highly attenuated in the nonlinear case. The next snapshot, at 3.9 s, also shows that reflected waves are highly attenuated due to nonlinear soil behavior around the first 300 m depth.

Figure 9 shows the outcrop response for the horizontal components. The solid line represents the linear computation and the dashed line represents the nonlinear one. As in the 1D case, the reference site is the computed synthetic accelerogram on rock. The basin response is complex. The amplification functions change at the different receivers. The sites located toward the center of the basin can see the basin response at 0.3 Hz. The sites located close to the basin edges are mainly affected at frequencies higher than 1 Hz. In addition, the broadband response of the basin is more pronounced in the sites closer to the center of the valley. Site R5, the
Montbonnot borehole, presents a similar linear transfer function as the 1D case, but its amplitude and resonance peaks are more pronounced in the 2D computation due to the presence of surface waves. The nonlinear computation shows deamplification and a slight shift of the resonance peaks to lower frequencies. The deamplification is more evident between 1 and 5 Hz. This suggests that nonlinear effects under a 2D geometry are far more complex than what is expected from 1D nonlinear computations.

Figure 8 Velocity snapshots of the 2D wave propagation in the Grenoble basin at 2.15 (left) and 3.9 (right) seconds. The upper subplots show the nonlinear computation and the lower ones the linear results.

Figure 9 Outcrop response for horizontal components computed at the receiver stations. Solid line represents the linear computation and the dashed line represents the nonlinear one.

6. Conclusions

1D and 2D wave propagation within the Grenoble basin were carried out. This propagation considered linear and nonlinear soil behavior of the Grenoble sediments. The strong impedance contrast between the sediments and surrounding bedrock
produces a strong amplification regardless of the basin geometry. This velocity contrast also helps the development of strong surface waves at the basin edges. As a consequence, the amplification from the 2D case is higher than the 1D result. This suggests that 3D basin geometry should be taken into account for a more accurate estimation of the response of the Grenoble valley. Nonlinear effects are rather important and are responsible for a strong deamplification of the ground motion. These results are, however, preliminary given the uncertainty on the material dynamic properties and the soil rheology. Nonetheless, it appears that nonlinearity helps to control the basin motion in a more coherent way than its linear counterpart. Finally, amplification functions nonlinear results show an evident deamplification between 1 and 5 Hz with respect to the linear ones. For larger frequencies the difference in amplification values is not significative. This implies that the combination of 2D or 3D basin geometry with nonlinear soil behavior produces a complex basin response, which cannot be predicted by 1D nonlinear studies.

7. References


