Numerical modeling of seismic site effects by means of modal and propagative approaches

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ABSTRACT

The amplification of seismic movement within sedimentary surface layers is a well-known phenomenon in the field of seismology. It is entirely possible to comprehend this phenomenon via a simplified approach that enables directly studying the vibrational resonance of a valley in order to estimate its "fundamental frequency". In some cases however, it becomes necessary to analyze in detail seismic wave propagation in the sedimentary surface layers. The boundary element method, for example, makes it possible to evaluate the level of amplification at any point of a valley as a function of frequency. The results obtained from both approaches are then compared with measurements derived at sites in Nice and Volvi (Greece).

Modélisation numérique des effets de site sismiques par approches modale et propagative

RÉSUME

L'amplification du mouvement sismique dans les couches sédimentaires de surface est un phénomène bien connu en sismologie. Il est possible d'appréhender ce phénomène par une approche simplifiée permettant d'étudier directement la résonance vibratoire d'une vallée afin d'estimer sa « fréquence fondamentale ». Dans certains cas, il est en revanche nécessaire d'analyser en détail la propagation des ondes sismiques dans les couches sédimentaires de surface. La méthode des éléments de frontière permet par exemple d'estimer le niveau d'amplification en tout point d'une vallée en fonction de la fréquence. Les résultats obtenus avec les deux approches sont confrontés à des mesures issues des sites de Nice et Volvi (Grèce).

MODELING THE AMPLIFICATION OF SEISMIC WAVES

The local amplification of seismic movement, or site effects, is a well-known phenomenon among seismologists: resonating the sedimentary surface layers often leads to a substantial increase in the seismic movement amplitude (Bard and Bouchon, 1985; Chávez-García *et al.*, 2000; Duval, 1996; Moeen-Vaziri and Trifunac, 1988; Sánchez-Sesma, 1983; Semblat and Pecker, 2009; Sommerville, 1998; Theodulidis and Bard, 1995). As such, these site effects could considerably exacerbate the impact of an earthquake on surface structures, even if the event is of moderate intensity or centered further away. An understanding and quantification of site effects thus prove to be critical. The required process typically calls for implementing analytical and simulation methods covering various levels of complexity: analytical approaches, semi-analytical methods, comprehensive numerical models.

This article will present and demonstrate two analytical and simulation methods: a simplified modal method, and a method intended to completely characterize seismic wave propagation (through the use of boundary integral equations).

Besides mastering the array of analytical methods (validation, accuracy, etc.), the key challenge inherent in this work pertains to the choice of method best suited to the type of problem raised. The problem solution protocol depends on both the desired level of analytical detail and the extent of available data. The influence of soil stratification on seismic wave amplification is widely recognized, but knowledge of the considered site's underlying geology tends to be imperfect.

A VIBRATIONAL ANALYSIS OF SITE EFFECTS

Various types of vibrational approaches

The use of modal approaches in the vibrational analysis of geological structures has become increasingly widespread (Paolucci, 1999; Semblat and Pecker, 2009). These approaches generally provide the fundamental frequency of geological structures by taking into account either their geometry (Bard and Bouchon, 1985; Paolucci, 1999; Semblat *et al.*, 2003) or the inhomogeneity of their mechanical characteristics (Dobry *et al.*, 1976; Hadjian, 2002). Based on a range of hypotheses, it is therefore possible to estimate the fundamental frequency of certain types of sedimentary filling. It remains difficult however to directly compare various frequencies in terms of seismic movement amplification.

› Methods adapted to one-dimensional fillings

Dobry *et al.* (1976) were the first to propose a comprehensive modal analysis of the vibrational resonance of geological layers. For a horizontal layer that is homogeneous, non-homogeneous (i.e. linear variation of the shear modulus) or a horizontal multilayer filling, their proposal called for analytically expressing the fundamental period of geological structures. For a horizontal layer of thickness H and shear modulus G varying linearly with depth z, they obtained the following expression:

$$\frac{G}{G_H} = K^2 + \frac{1-K^2}{H} z \tag{1}$$

where $K = \sqrt{G_0 / G_H}$, and G_0 and G_H represent the modulus values at the top and bottom of the layer, respectively.

In order to estimate the period T of the layer, Dobry *et al.* used the characteristics of an equivalent uniform layer by writing $T=4H/V_{eq}$, where $V_{eq} = \sqrt{G_{eq} / \rho}$ at the equivalent depth z_{eq}, given by:

$$\frac{z_{eq}}{H} = \left(\frac{a_1}{H}\right)^2 \left(1-K^2\right) - \frac{K^2}{1-K^2} \tag{2}$$

where a_1 is the 1st root of the following equation:

$$J_0(a_1)Y_1(Ka_1) - J_1(Ka_1)Y_0(a_1) = 0 \tag{3}$$

with J_i and Y_i representing the Bessel and Weber Bessel functions (respectively) of order i. Dobry *et al.* (1976) also proposed generalizing these results for two-layer or multilayer fillings. Similar cases have been studied by Hadjian (2002) by considering an iterative approach in estimating the fundamental period of multilayer fillings.

› Methods used for 2D or 3D fillings

In order to characterize the resonance of rectangular basins, Bard and Bouchon (1985) proposed a simple relationship yielding the fundamental frequency as a function of both wave velocity and a basin shape factor, i.e.:

$$f_0 = \frac{V_S}{4h}\sqrt{1+\frac{h^2}{w^2}} \tag{4}$$

where h is the basin depth and w the basin width.

The modal approach developed by Paolucci (1999) makes use of the Rayleigh method and can be applied for any type of 2D or 3D sedimentary filling; it consists of minimizing the ratio of strain energy to kinetic energy so as to estimate the fundamental frequency ω_0. This method is described in detail in Section 2.2 and allows estimating the vibrational characteristics of actual geological structures.

Simplified modal method

The modal method considered herein is intended to estimate the "fundamental" frequency of a geological structure. The wave propagation process typically leads to strong movement amplification at varied frequencies (Chávez-García *et al.*, 2000; Semblat *et al.*, 2005); however, for practical purposes, it is worthwhile to determine a single fundamental frequency by means of simplified approaches. As an example, the Rayleigh approximation provides a quick and reliable estimation of the resonance frequency for a geological structure (Paolucci, 1999).

This method assumes that the displacement of an elastic system in one of its eigenmodes may be approximated by the displacement of a system with one degree of freedom. We are focusing here on the first eigenmode characterized by the frequency $\omega_0 = 2\pi f_0$. Let's denote V the elastic energy of the system and T its kinetic energy, then the total energy conservation of an elastic system implies that: $V_{max} = T_{max}$. The displacement $s_k(\underline{x},t)$ corresponding to harmonic vibrations at frequency ω_0 can now be written as follows:

$$s_k(\underline{x},t) = \psi_k(\underline{x}) e^{i\omega_o t} \tag{5}$$

where $\underline{x}$ represents the space coordinate, i the imaginary number, t the time, and $\psi_k(\underline{x})$ the modal shape along the k direction. The system's kinetic energy can then be calculated as follows:

$$T(t) = \int_\Omega \frac{1}{2}\rho(\underline{x})\left(\frac{\partial s_k}{\partial t}\right)^2 d\Omega = -\omega_0^2 e^{2i\omega_0 t}\int_\Omega \frac{1}{2}\rho(\underline{x})\psi_k^2(\underline{x})d\Omega \tag{6}$$

hence:

$$T_{\max} = \max_t T(t) = -\omega_o{}^2 \int_\Omega \frac{1}{2}\rho(\underline{x})\psi_k{}^2(\underline{x})d\Omega \tag{7}$$

The elastic energy V is thus written as:

$$V(t) = \int_\Omega \frac{1}{2}\sigma_{jl}(\underline{x})\varepsilon_{jl}(\underline{x})d\Omega \tag{8}$$

where $\varepsilon_{ij} = s_{i,j} + s_{j,i}$ is the strain tensor and $\sigma_{ij} = \lambda\varepsilon_{ll}\delta_{ij} + 2\mu\varepsilon_{ij}$ the stress tensor obtained by applying Hooke's Law, with δ_{ij} the Kronecker symbol, and λ and μ the Lamé coefficients. Like for T_{max}, V reaches its maximum value when $|e^{2i\omega_o t}| = 1$. This approach allows writing:

$$\omega_o{}^2 = \frac{\int_\Omega \sigma_{jl}(\underline{x})\varepsilon_{jl}(\underline{x})d\Omega}{\int_\Omega \rho(\underline{x})\psi_k{}^2(\underline{x})d\Omega}. \tag{9}$$

Equation (9) yields the exact value of the system's fundamental frequency whenever the actual modal shape $\psi_k(\underline{x})$ is known. However, since the exact solution tends to be inaccessible, the value of ω_0 may be accurately estimated by assuming a realistic approximation of $\psi_k(\underline{x})$; this approximation must satisfy both the geometric compatibilities and boundary conditions. It has nonetheless been demonstrated (Paolucci, 1999) that the second condition might not be entirely satisfied, and moreover the modal shape may be selected from a wide range of functions that solely satisfy the geometric compatibilities.

It then becomes possible to determine the fundamental frequency using the following relation:

$$\omega_o^{\,2} \leq \min_{\psi_k} \frac{\int_\Omega \sigma_{jl}(\underline{x})\varepsilon_{jl}(\underline{x})d\Omega}{\int_\Omega \rho(\underline{x})\psi_x^{\,2}(\underline{x})d\Omega} \qquad (10)$$

Estimation of the fundamental frequency of a geological structure

In preparation of the simplified vibrational analysis, we considered a sedimentary basin located in the center of the city of Nice (southern France). This site is well known for having been the focus of many experimental campaigns as well as several numerical modeling projects (Semblat *et al.*, 2000). The basin is assumed to be homogeneous and its vibrational resonance has been analyzed for an anti-plane seismic loading in shear, as characterized by the velocity $V_S = \sqrt{\mu/\rho}$. The mechanical characteristics of both media (i.e. basin and substratum) are as follows:

– basin: ρ_1 = 2000 kg/m³, μ_1 = 180 MPa, ν = 0.2; hence, V_S = 300 m/s
– substratum: ρ_1 = 2300 kg/m³, μ_1 = 4500 MPa, ν = 0.2; hence, V_S = 1400 m/s

where ρ is the mass density, μ the shear modulus, ν Poisson's ratio, and V_S the shear wave velocity.

As shown in **Figure 1**, the interface between basin and substratum can be described using two cosine functions:

– western part of the valley: $f(x,z) = (h_1+1)\cos(2.7\cdot10^{-3}\,x + 1.55)$ (h_1 = 64 m)
– eastern part of the valley: $g(x,z) = (h_2+2)\cos(2.8\cdot10^{-3}\,x - 1.3)$ (h_2 = 32 m)

Among the allowable modal shapes, the following have been chosen (Paolucci, 1999):

$$\psi_2(x,z) = \cos^r\left(\frac{\pi}{2}(1-f(x,z))\right)\times\sin^{2s+1}\left(\frac{(n+1)\pi}{2}\left(1+\frac{x}{a}\right)\right)\times\cos^t\left(\frac{(2m+1)\pi}{2}\frac{z}{h}\right) \qquad (11)$$

where *f*(*x*,*z*) is the function given above, r ≥ 1 and t ≥ 1 are real parameters, *s* = 0.1, … is a whole number parameter, and *m* and *n* represent the mode orders along the vertical and horizontal directions (respectively).

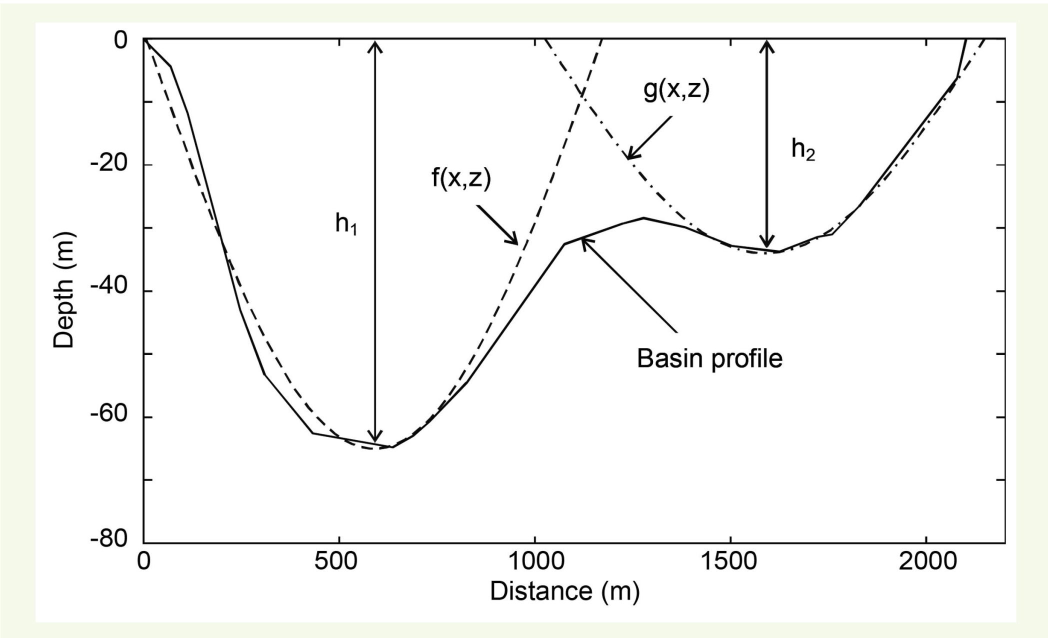

Figure 1
Description of the homogeneous geological profile for the simplified modal approach

In this case, the inequality leading to the fundamental frequency is as follows:

$$\omega_o^2 \leq \min_{r,s,t} \frac{\int_\Omega \mu\left((\frac{\partial\psi_2}{\partial x})^2 + (\frac{\partial\psi_2}{\partial z})^2 \right) dxdz}{\int_\Omega \rho\psi_2^2(x,z)dxdz} \quad (12)$$

Results are derived for the first mode by incorporating various shear modulus values: μ_1 = 180 MPa (i.e. V_S = 300 m/s), μ_2 = 120 MPa (i.e. V_S = 245 m/s), and μ_3 = 90 MPa (i.e. V_S = 212 m/s). The numerical results output by the Rayleigh method are compared with the maximum amplification frequencies given by the boundary element method via an explicit analysis of wave propagation (Semblat *et al.*, 2000).

Modal estimation of the fundamental frequency

According to these results, we can state that the fundamental frequencies output from the Rayleigh method are in good agreement with the high amplification frequencies determined by means of the propagative approach. The values listed in **Table 1** are compared for resonance in the deep basin part (west) vs. the shallow part (east), in introducing various shear modulus values. For a homogeneous basin model, the Rayleigh method thus appears to offer some very interesting results, which are in agreement not only with the values derived using other models, but also with the experimental results presented in detail by Semblat *et al.* (2000).

Comparison between the simplified modal method and amplification curves

The fundamental frequencies estimated by means of the simplified modal method have been compared with the amplification curves generated from propagative measurements and simulations using boundary integral equations (Semblat *et al.*, 2000). In **Figure 2**, the vertical lines indicate the fundamental frequency for the western and eastern parts of the basin and, moreover, have been estimated for various shear modulus values (μ_1, μ_2, μ_3). For the western part of the basin, the fundamental frequency f_3 estimated for μ_3 (solid line) is in very close agreement with the experimental amplification peaks (top) and numerical peaks (bottom). For the eastern part of the basin, the shear modulus μ_1 (dashed/dotted line) shows a very satisfactory agreement with the second amplification peak, which suggests the influence of basin shear modulus (or velocity) on the resonance process. The influence on the so-called amplification process is demonstrated by the numerical results of the propagative approach using boundary integral equations **(Fig. 2)**.

PROPAGATIVE ANALYSIS OF SITE EFFECTS

Numerical wave propagation methods

In order to numerically simulate seismic wave propagation and amplification, several numerical methods are potentially available (Semblat, 2011), namely:

– *finite difference* method, which is very accurate in elastodynamics yet typically limited to simple geometries and linear behavior (Moczo and Bard, 1993; Virieux, 1986);

Table 1
Comparisons drawn between the reference frequencies obtained from the propagative method and the fundamental frequencies stemming from the simplified modal approach

	Western part		Eastern part	
	Reference frequency EIF	Fundamental frequency	Reference frequency EIF	Fundamental frequency
μ_1	1.35 Hz	1.50 Hz	2.42 Hz	2.86 Hz
μ_2	1.30 Hz	1.23 Hz	2.13 Hz	2.34 Hz
μ_3	1.13 Hz	1.07 Hz	1.75 Hz	2.02 Hz

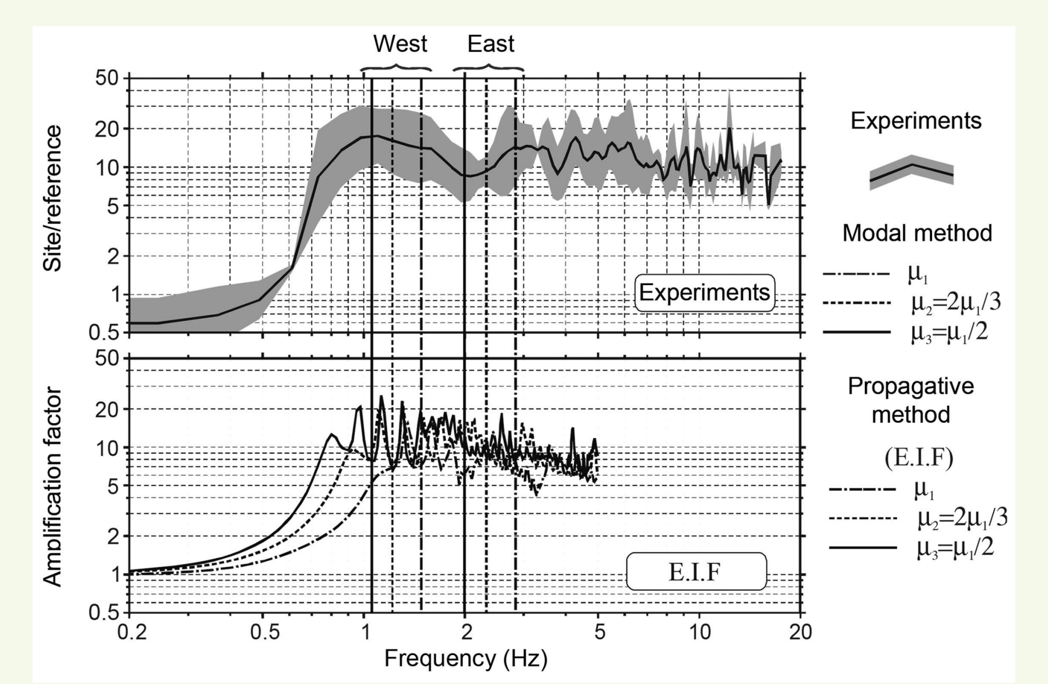

Figure 2
Fundamental frequencies estimated by the simplified modal method, and comparison with measurements (top) and simulations according to the boundary integral equation method (bottom)

– *finite element* method, used to model complex geometries and heterogeneous media (even featuring nonlinear behavior (Santisi *et al.*, 2012)), yet whose cost when applied in 3D runs very high (Bielak *et al.*, 1999; Ihlenburg and Babuška, 1995; Semblat and Brioist, 2000; Semblat *et al.*, 2011);
– *boundary element* method, which allows for an exacting description of the radiation conditions, yet remains limited to only slightly heterogeneous, linear media (Beskos, 1997; Bonnet, 1999; Chaillat *et al.*, 2009; Dangla, 1988; Dangla *et al.*, 2005; Semblat *et al.*, 2002);
– *spectral element* method, which stems from the finite element method and has become increasingly popular for analyzing propagation in 2D or 3D (Faccioli *et al.*, 1996; Komatitsch and Vilotte, 1998).

Each of these methods offers specific advantages and disadvantages and it may prove beneficial to combine them so as to harness the advantages of each one. It is now possible to couple the finite element method with the boundary element method (Dangla, 1988; Bonnet, 1999). The former can accommodate a refined description of local propagation (complex geometries, strong heterogeneities, nonlinear behavior), while the latter provides a reliable far-field (radiation) estimation.

The European test site at Volvi (Greece)

The Volvi European test site (Greece) was created thanks to European Commission financing for the purpose of analyzing site effects and the soil-structure interaction (Semblat *et al.*, 2005). The site is located in a sedimentary valley 30 km from Thessaloniki and lies within an active seismotectonic zone, which was the epicenter of a major 1978 earthquake. The basin measures 6 km long by 200 m wide.

One of the site's primary objectives is to build an in-depth knowledge base on soil stratification and draw the correlation with seismic wave amplification (Jongmans *et al.*, 1998; Riepl *et al.*, 1998). Preliminary geotechnical and geophysical analyses have yielded a comprehensive characterization of soil properties. In addition, a series of permanent and temporary networks have made it possible to measure seismic movements.

Simplified and complete models for the Volvi Basin

Numerical analysis by boundary elements

To analyze the seismic response of this sedimentary basin, a numerical model based on the boundary element method has been developed. By implementing this method, the radiation conditions at infinity are satisfied in their entirety. The solution to the integral equation is found by discretizing the interfaces into boundary elements and then by collocation (i.e. application of the integral equation at every point of the mesh). Simulations were conducted in two dimensions using the CESAR-LCPC finite element / boundary element computational code. The specific formulation employed has been presented in detail by Dangla *et al.* (2005).

Various models for the Volvi Basin

Several geotechnical models have been proposed for the Volvi site. In the present analysis, two distinct models have been introduced: a simplified model comprising just two soil layers, and a complete model described by six distinct layers. According to the refined propagation analysis, the main objective consists of characterizing the influence of local geology description on site effect simulations.

The selected geotechnical model was developed by the University of Liège (LGIH) and is described in **Figure 3**. Other geological models have been proposed by Raptakis *et al.* (2000) and used for 2D site effect simulations (Chavez-Garcia *et al.*, 2002).

In the present article, as suggested by Makra *et al.* (2005), we first considered a simplified two-layer model **(Fig. 3)**. The mechanical properties in each soil layer were estimated based on average speed values within the various layers. The complete model corresponds to the site's actual stratification and is also described in **Figure 3**. The mechanical properties of layers for both models are given in **Tables 2** and **3**. The objective of this article is to analyze seismic wave propagation using both models and then compare the quantified site effects in the two cases.

Amplification of an SH-wave in the Volvi Basin

The seismic wave is a planar SH-wave with vertical incidence. Since simulations run with the boundary element method are conducted within the frequency range, the spectral amplification of

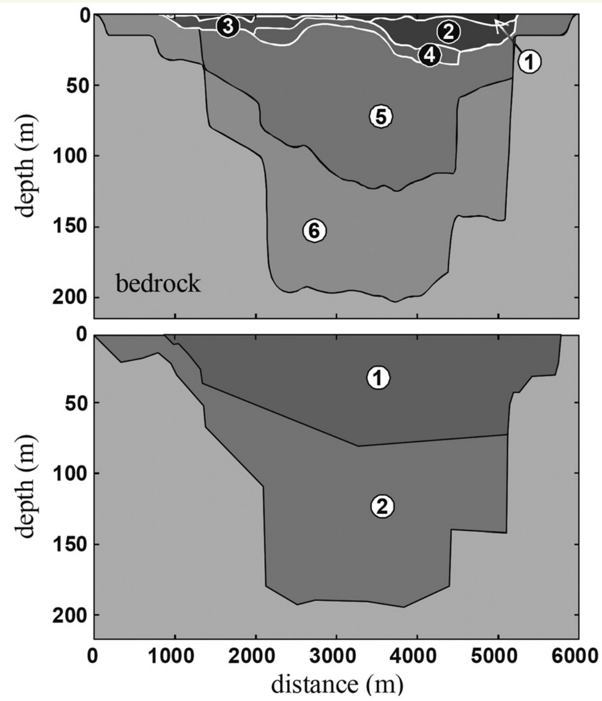

Figure 3
Geotechnical models of the Volvi Basin: complete model (top) and simplified model (bottom)

Table 2
Soil layer properties at the Volvi site for the simplified model

Soil layer	Mass density	Young's modulus	Poisson's ratio
Layer 1	2100 kg/m^3	677 MPa	0.280
Layer 2	2200 kg/m^3	3595 MPa	0.453
Rock	2600 kg/m^3	4390 MPa	0.249

Table 3
Soil layer properties at the Volvi site for the complete model

Soil layer	Mass density	Young's modulus	Poisson's ratio
Layer 1	1700 kg/m^3	180 MPa	0.33
Layer 2	1800 kg/m^3	300 MPa	0.33
Layer 3	1800 kg/m^3	300 MPa	0.33
Layer 4	2000 kg/m^3	530 MPa	0.48
Layer 5	2200 kg/m^3	1200 MPa	0.47
Layer 6	2300 kg/m^3	3300 MPa	0.49
Rock	2600 kg/m^3	4200 MPa	0.19

movement can be easily determined. For the simplified model, amplification values in the basin are given in **Figure 4** at various frequencies:

– at *0.6 Hz:* the strongest amplification appears in the deepest part of the basin and this case corresponds to the basin's fundamental mode. Maximum amplification however is relatively weak since it fails to exceed 3;
– at *0.8 Hz:* two high-amplification zones appear along the free surface over the central part of the basin and display a high amplification factor (9.5);
– at *1.0 Hz:* maximum amplification is reached on the free surface, though the maximum amplification zone (9.5) is offset to the right in the part of intermediate depth;
– at *1.2 Hz:* the left part of the basin, at intermediate depth, also exhibits significant amplification (7.5);

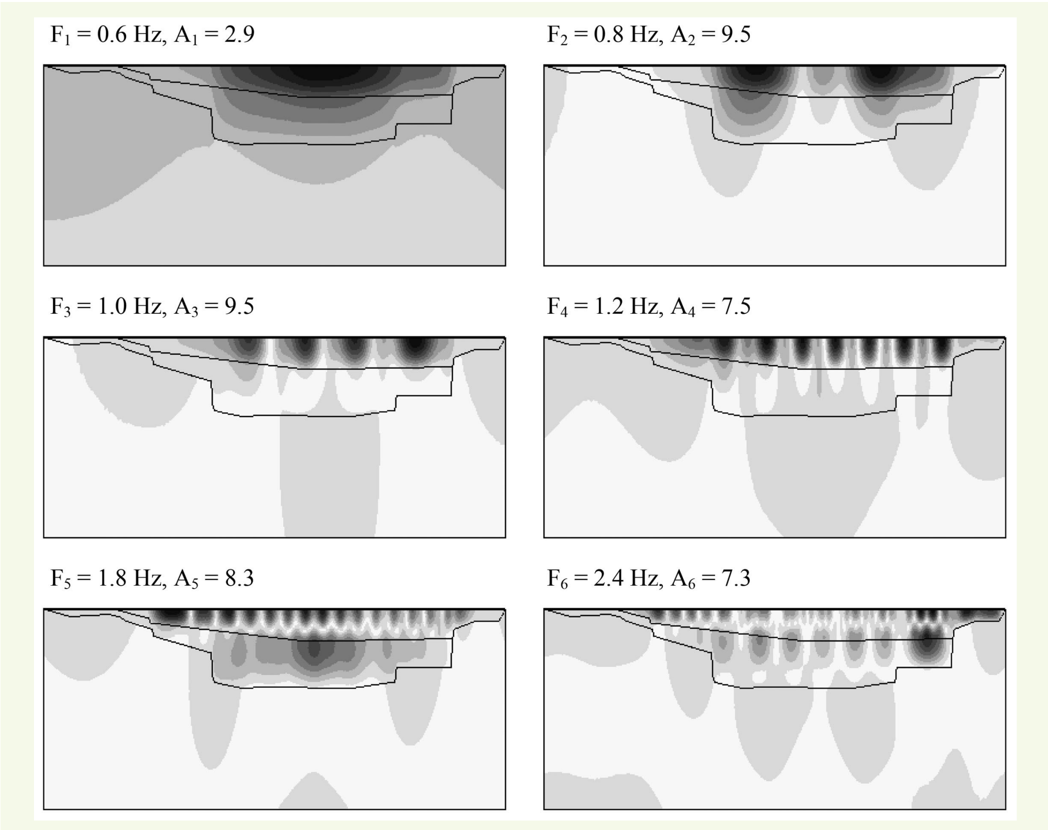

Figure 4
Amplification factor estimated numerically at several frequencies for the simplified Volvi model (frequency values and maximum amplifications)

– at *1.8 Hz:* high amplifications (8.3) are observed both at the surface and in deeper reaches. The greatest amplification is obtained in the left part of the intermediate depth zone;
– at *2.4 Hz:* at such wavelengths, the shallow part of the basin located towards the right shows high amplifications. The central part of the basin presents practically no amplification at all.

Comparisons between simplified and complete models (SH-wave)

The objective behind this comparison is to evaluate the influence of the stratification description on the seismic wave amplification analysis. In order to compare the simplified and complete models, a series of frequency and time analyses were first performed.

› Comparison within the spectral domain

Figure 5 presents the spectral amplification (transfer functions) at various basin surface points for both the simplified model (top) and complete model (bottom). This figure indicates that the

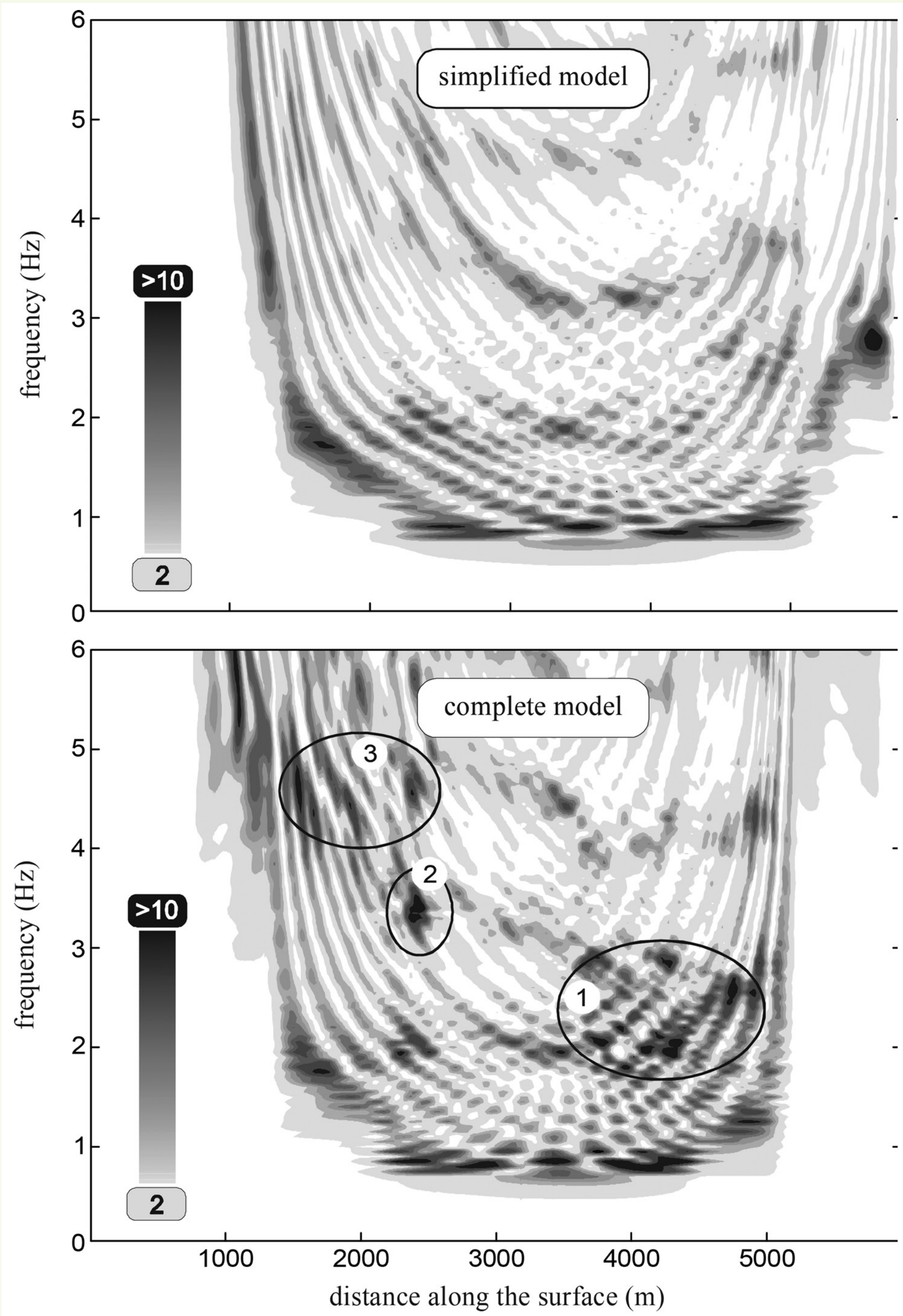

Figure 5
Amplification vs. frequency and distance for the two Volvi Basin models (boundary element method)

complete model leads to a greater number of amplification peaks, which tend to be localized in the following zones: 2 ≤ f ≤ 3 Hz and x = 4000 m; 3 ≤ f ≤ 4 Hz and x = 2500 m; and 4 ≤ f ≤ 5 Hz and x = 1500 m.

The transfer functions stemming from the two basin models reveal that the greatest amplification is obtained around the same frequency $f_0 \approx 0.8$ Hz; this amplification pertains to two distinct surface zones. Such a phenomenon is not caused by soil stratification since the simplified model leads to a double fundamental mode (Makra *et al.*, 2005) as well. This observation has also been reported by Chávez-García *et al.* (2000), who emphasized the contribution of surface waves.

› Comparison within the temporal domain

In order to understand the influence of the basin description (i.e. vertical and horizontal heterogeneities), temporal responses at the surface are calculated on the basis of transfer functions. For both models (simplified and complete), we consider herein a planar SH-wave plane with vertical incidence, whereby the temporal variations are described by a Ricker signal with a spectrum centered at 1 Hz. **Figure 6** shows the surface movement vs. time plot.

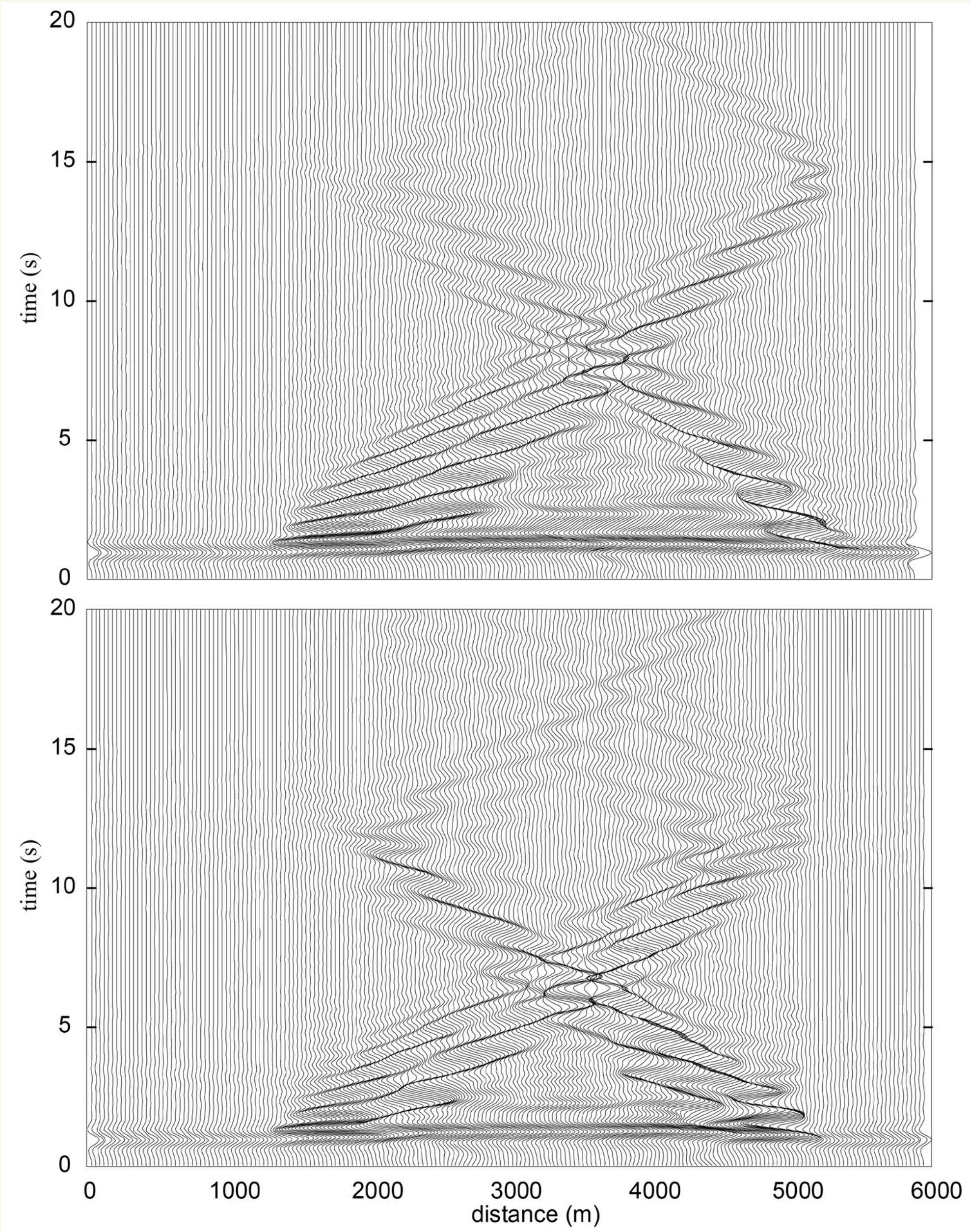

Figure 6
Temporal signals calculated for both the simplified (top) and complete (bottom) Volvi Basin models, given a Ricker signal centered at 1 Hz

The solutions derived for the simplified model (**Fig. 6**, top) clearly display the amplification process. The effects of lateral heterogeneities (i.e. basin effects) stand out through wave reflections at the basin edges. The amplification of first wave arrivals also highlights the influence of speed contrast in the deeper part of the basin. The amplification of seismic waves in the simplified Volvi Basin model is thus influenced by both vertical (stratification) and lateral (basin effects) heterogeneities.

In comparison with the solutions generated by the complete model (**Fig. 6**, bottom), the amplification of first wave arrivals is stronger than in the simplified model. With soil stratification being described more accurately, the amplification due to speed contrast is therefore higher. Moreover, the primary wave train is combined with reflected and refracted waves, leading to a more complex wave field **(Fig. 6)**. This is especially the case on the left and right edges of the deepest part of the basin, a finding most certainly due to the combined influence of vertical and lateral heterogeneities. Since speed contrasts are more accurately described in the complete model, the lateral propagation in each layer is facilitated and overall amplification is strengthened. Signal duration is also significantly extended due to the combined effect of basin edge reflections and stratification.

The influence of basin stratification on both the amplification process and signal duration requires detailed knowledge on soil properties as well as layer geometry.

› Comparison for an actual accelerogram

Let's now consider an actual accelerogram and calculate the temporal response at the surface for both our basin models. Only the June 1994 earthquake (M = 3) is presented herein, yet other simulations using the Arnaia quake (May 1995) have been performed (Kham, 2004). The incident seismic movement is defined relative to the PRO (North) reference station. As shown in **Figure 7**, signals are calculated for all other station positions along the surface. Chávez-García *et al.* (2002) have already discussed in detail the influence of reference station quality. **Figure 7** shows the measurements conducted at various stations (top) for the purpose of drawing comparisons. The signals are filtered above *6 Hz*. Slight differences can be observed between signals measured and recalculated at the PRO station given the presence of a thin sedimentary layer (Chavez-Garcia *et al.*, 2002).

According to **Figure 7**, the two models lead to a strong amplification and duration increase over the central part of the basin. This trend is in close agreement with measurement results, which is suggestive of high amplification in the deep part of the basin.

In general, the complete model leads to greater amplifications (closer to measurement values) since it offers a more accurate description of stratification near the surface. Such is particularly true at the GRE station, where the influence of subsurface geology seems to be significant.

As indicated by Kham (2004), noteworthy differences appear when considering the two earthquakes (i.e. June 1994 and May 1995) since the first has a higher frequency content than the second. Basin model accuracy is key to simulating high-frequency seismic movement.

CONCLUSION

The amplification of seismic movement may be modeled using various methods. Several alternative approaches have been proposed in this article and lead to results closely resembling *in situ* observations. Analytical or semi-analytical approaches offer considerable versatility yet often rely on simplistic hypotheses that are not always justified in real-world cases. Analytical methods based on numerical approaches accommodate more realistic hypotheses, yet they raise the important issue of method accuracy and validation (Semblat, 2011).

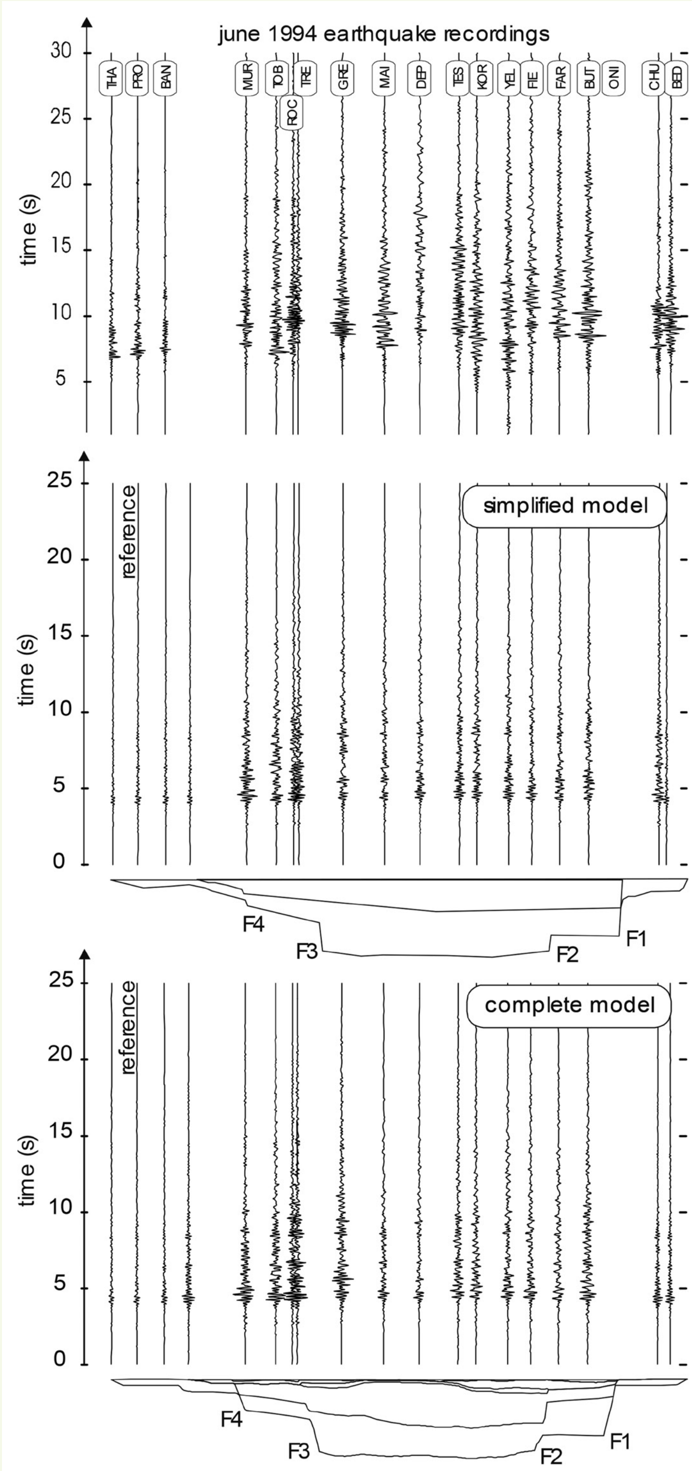

Figure 7
Accelerograms at the Volvi Basin surface for the June 1994 earthquake: Comparison of measurements (top) and simulations for the simplified model (middle) and the complete model (bottom)

Depending on the desired level of analytical detail and the extent of available field data, the various approaches presented herein appear to offer complementarity, as do the associated experimental methods (background noise measurements, earthquake recordings, etc.). A pertinent step would therefore consist of overlapping the complexity of intended simulations with both the targeted objectives and available data.

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