Detection of seismic site effects: development of experimental methods and application to the city of Nice

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ABSTRACT

Site effects represent a critical challenge in the field of earthquake prevention since these effects are capable of seriously exacerbating damage whenever an earthquake strikes. Knowledge of the soil response to seismic activity allows adapting earthquake protection regulations to better incorporate these constraints during the process of defining microzones and producing the Risk Prevention Plan. The experimental methods employed to determine site effects seek to obtain seismic amplification parameters by means of measuring earthquakes or seismic background noise. This article presents the main set of results derived through 2005 by the "Seismic risk" ERA research team during development of these techniques as well as their comparative application to Nice, a city that has constituted the main field application site thanks to its hosting of multiple seismic recording campaigns. For starters, many earthquakes have been analysed according to the transfer function method. The "Horizontal/Vertical background noise" method was in particular applied to over 600 points, with results being spatially interpolated. A geotechnical model of the subsoil then served to compare the results output with both the geology and numerical simulations of wave propagation. The complementarity of methods and their respective advantages are highlighted in this seismically-active setting.

Détection des effets de site sismiques : mise au point de méthodes expérimentales et application à Nice

RÉSUMÉ

Les effets de site représentent un enjeu important pour la prévention parasismique, puisqu'ils peuvent aggraver considérablement les dommages lors d'un séisme. La connaissance de la réponse des sols aux séismes permet d'adapter la réglementation parasismique à ces contraintes lors de l'élaboration de microzonages et de Plan de Prévention des risques. Les méthodes expérimentales de détermination des effets de site visent à obtenir les paramètres de l'amplification sismique par la mesure de séismes ou de bruit de fond sismique. Cet article présente les principaux résultats obtenus jusqu'en 2005 par l'ERA « Risque sismique » dans la mise au point de ces techniques et leur application comparée sur la ville de Nice. Cette ville a effectivement constitué le principal chantier d'application grâce à de multiples campagnes d'enregistrements sismiques. De nombreux séismes ont d'abord été analysés par la méthode des fonctions de transfert. La méthode « H/V bruit de fond » a été appliquée sur plus de 600 points et les résultats interpolés spatialement. Un modèle géotechnique du sous-sol a ensuite permis de comparer les résultats obtenus avec la géologie et des simulations numériques de la propagation des ondes. La complémentarité des méthodes et leurs atouts respectifs sont mis en valeur sur ce territoire à fort enjeu.

INTRODUCTION

Description of phenomena

The disastrous 1985 Mexico City earthquake illustrated in stark terms both the nature and impact of site effects. This earthquake, originating more than 300 km from the capital, crossed the Mexican territory while exposed to attenuation effects relative to the distance travelled. Yet upon arriving in the clayey basin where Mexico City sits, the waves were trapped and entered into resonance with the site. This phenomenon significantly amplified the seismic signal around 0.5 Hz (Singh *et al.*, 1988). Ten to thirty-storey buildings with vibrational eigenmodes corresponding to this frequency experienced the greatest damage.

Since that event, studies have shown that site effects are responsible for the rise in damage witnessed in some of the most destructive earthquakes (Northridge in 1994, Kobe in 1995, Turkey in 1999, Boumerdes in 2003).

Figure 1 illustrates the modifications caused locally by these effects. The earthquake analysed in this figure originated offshore about 20 km from Nice (4.7 magnitude); it was recorded at various stations installed in the Nice area as well as in the Isère department over 200 km to the north.

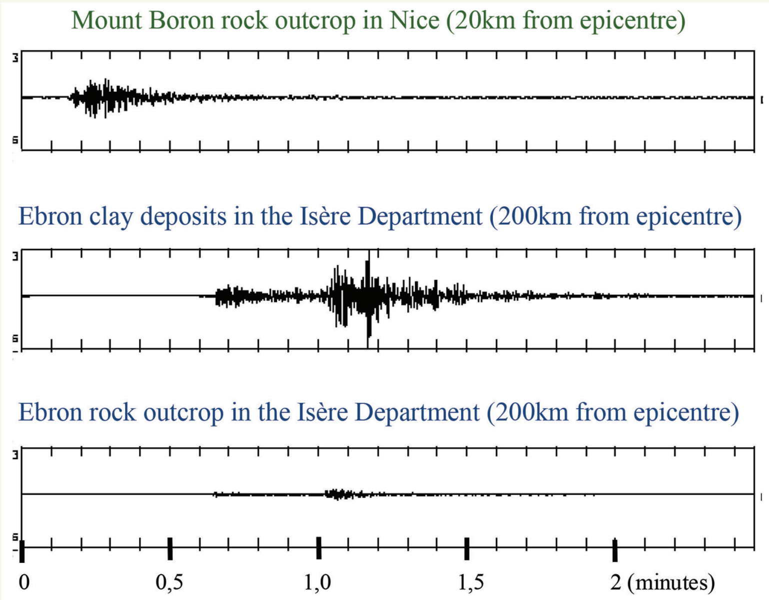


Figure 1
Records of an earthquake in the Ligurian Sea measured both in Nice (20 km away) and in the Isère Department (Ebron, 200 km away) - the same scale was used for all 3 plots

In the absence of site effects, only distance to the earthquake would influence the soil vibration amplitude. If the recordings read on rocks were compared, the waves normally arrive later in Isère and undergo attenuation due to the distance separation. In contrast, for the station installed on a clayey fill in Isère, the maximum amplitude is even higher than that measured on the rock layer in Nice. The earthquake was therefore amplified by the clay layer.

These wave amplification phenomena are very often accompanied by an extension of the strong signal phase, thus inducing fatigue of the materials composing the structures, in some cases extending beyond the resistance threshold. Seismologists and engineers have gradually focused on these hazardous and sometimes very complex phenomena (Aki, 1993). Their efforts have succeeded in distinguishing two major types of site effects, namely:

– "lithological" site effects, for which an impedance contrast between a rigid substratum and a loose cover layer causes multiple reflections followed by a trapping of waves in the surface layer. An approximation of the fundamental resonance frequency F_o is given by $F_o = V_s/(4H)$, where V_s denotes the average shear (S) wave velocity in the sedimentary cover of height H. In this case, the phenomenon is modelled by means of a simple soil column. In reality however, such phenomena are often correlated with anthropogenic or alluvial fills in valleys, which require two-dimensional field models, or even much more complex basin shapes in conjunction with 3D models;

– “topographic” site effects: the heavily pronounced shape of some topographic relief constitutes a trap for waves that concentrate in certain zones of the relief and therefore undergo amplifications along with a distinct signal extension.

Research objectives

Site effects provide a key challenge in the area of earthquake prevention: while predicting when an earthquake will strike remains out of reach, it still seems possible to predict where and how the seismic signal should be amplified. As such, the microzoning objective consists of accurately mapping zones of homogeneous risk. For each zone, the fundamental frequency (F_o) of sites must be identified, and the site spectral response (i.e. their transfer function) must be recognized. The recognition of soils and their response serves to define standard behavior and adapt the structural design spectra imposed by earthquake prevention regulations for the purpose of incorporating site effects. Such regulations however are merely able to issue simplified default values that only rarely reflect physical reality on the ground. The challenge therefore consists of understanding these phenomena and developing reliable methods to fine-tune regulations at either the national level (PS 92 rules, Eurocode 8) or local level (within the scope of Risk Prevention Plans).

Research conducted during the 1990’s served to implement and compare various site effect determination methods during multiple microzoning campaigns since 1991, both in France (Nice, Pointe-à-Pitre - Guadeloupe) and abroad (Venezuela, Tunisia, Greece, Monaco). Moreover, many localized studies were conducted in order to determine anticipated site effects: parallel to motorway projects (the 1995 Ebron Viaduct project, 1996 Tende Tunnel) or specific installations (phone switching stations, buildings, nuclear facilities).

The various site effect approaches

Figure 2 diagrams the various site effect approaches explored over the recent past.

The use of a range of methods has enabled comparing results and gradually contributed to expanding the technical choices available depending on the study (Kudo, 1995). The characteristic site effect values to be determined consist of at least the following: site resonance frequency (F_o), and the corresponding amplification at this frequency (A_o) caused by the particular site. For greater

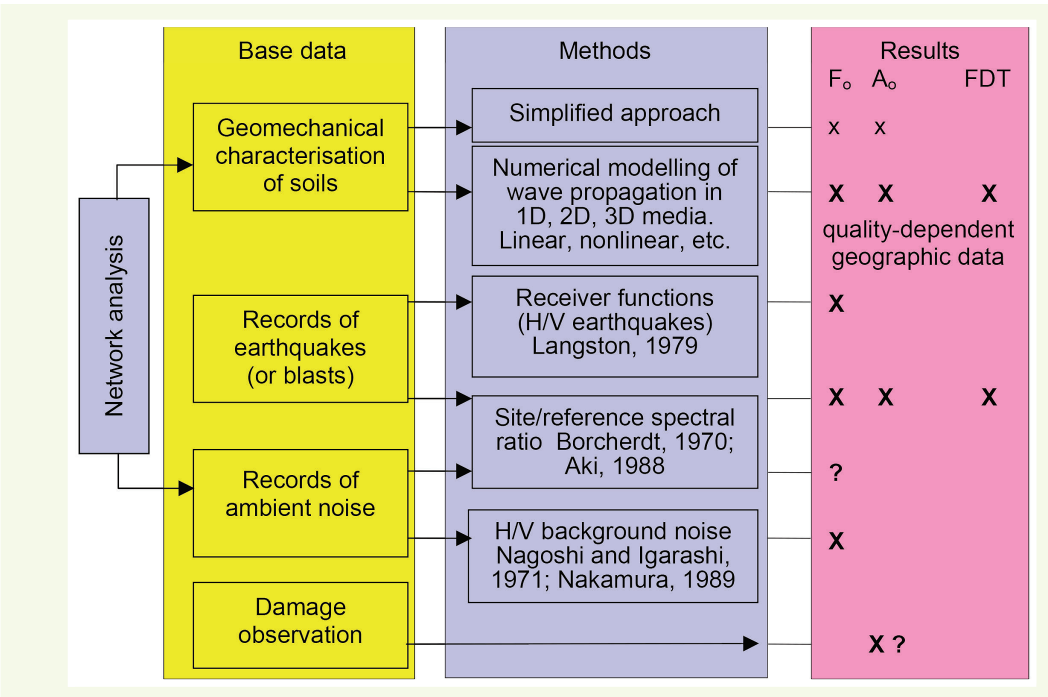


Figure 2
Various methods employed to determine site effects

precision, it is also sought to determine the site transfer function that yields the expected amplification for all frequencies (listed as FDT in **Fig. 2**).

Various wave propagation simulation modes have been proposed, in either one, two or even three dimensions, by deciding to forward the hypothesis of soil behaviour linearity. The reliability and accuracy of these methods are continuously improving, through better acknowledgment of the physical complexity of such phenomena, as indicated by Semblat *et al.* (2012). The validity of numerical results however depends in large part on the quality as well as quantity of the geophysical parameters introduced, which implies in-depth knowledge of the underground interface geometry and mechanical characteristics of each formation. The margin of uncertainty associated with these data, along with their acquisition costs, often leads to implementing experimental site effect determination methods. The dedicated "Seismic Risk" research team has become specialized in this type of approach, for the purpose of quantifying site effects on the basis of vibration measurements. The initial microzoning steps performed by this team relied on the now conventional method of site/reference spectral ratios stemming from seismicity recordings (also known as the transfer function method). The experience accumulated during the widespread application campaign allows drawing conclusions on the method's essential features and potential. These considerations will be addressed in Part 2 of this article. As of 1991, the "Seismic Risk" team has been testing another approach: the vertical/horizontal spectral ratio, applied not only on earthquake recordings (so-called receiver function method) but also, and more importantly, on ambient background noise (so-called "H/V background noise" method). The initial tests proved surprising, given the accuracy of results in many cases, especially in Nice (a section of this article will be dedicated to illustrating some of these results). Test results were then introduced into a pan-European evaluation (SESAME project), in which many expert teams pooled their efforts to generalize the method and better understand the physical mechanisms at work. SESAME also made it possible to explore another ambient noise application through network recordings aimed at characterizing geophysical soil profiles. This synthesis effort relied to a large extent on the findings produced in Nice within the framework of broader scientific projects: GEMITIS (GEMITIS, 1994; Bard *et al.*, 1995), RISK-UE (Mouroux *et al.*, 2004) and GEM-GEP (Méneroud *et al.*, 2000; Bard *et al.*, 2005).

METHOD BASED ON EARTHQUAKE RECORDINGS

Operating principle and implementation

Earthquake measurements provide a preferred approach for determining site effects. The conventional method consists of recording earthquakes occurring at various representative sites and then comparing results with a reference station (Duval, 1996; Borcherdt and Gibbs, 1970), which ideally is to be selected on the horizontal substratum. The seismic data for interpretation stem from the recording of soil vibrations; they are generated by vibration speed sensors for relatively minor movements and by acceleration sensors for greater movements.

Each site-specific seismic event recorded is the consequence of various factors. The recorded signal is processed numerically by means of Fourier transforms in order to derive its frequency spectrum. Earthquake recording *j* on site *i* can thus be depicted in the spectral domain by:

$$S_{ij}(f)= O_j(f).P_{ji}(f).H_{ij}(f).I_i(f)$$

where $O_j(f)$ denotes the effect of the seismic source itself, $P_{ji}(f)$ the effect of propagation between earthquake and study zone (at the regional scale), $H_{ij}(f)$ the targeted signal modification in the subsurface, $I_i(f)$ the instrument-related response of acquisition equipment, and f the frequency under review.

If the site-reference distance is small compared to the earthquake epicenter-reference distance, then it can be considered that source effects $O_j(f)$ and propagation effects $P_{ji}(f)$ are identical between the stations.

An instrument correction may be introduced so as to calibrate the recordings of all stations onto the same response ($I_i(f)= I_{ref}(f)$).

Performing the spectral division step on vibrations due to a single earthquake, occurring at site *i* with respect to the reference (where it is assumed that $H_i(f) = 1$ regardless of the value of *f*), yields the spectral response or site effect at site *i*, hence the following can be written:

$$S_{ij}(f) / S_{ref\,j}(f) = H_{ij}(f)$$

In practice, site (i) exhibits a non-negligible dispersion of this spectral ratio $H_{ij}(f)$ from one earthquake (j) to the next (due to an effect combining azimuth, source, distance and magnitude), thus making it necessary to obtain a large number (N) of ratios and calculate an average ratio, referred to as the site's "transfer function":

$$H_i(f) = \Sigma_j[H_{ij}(f)] / N$$

This transfer function (dimensionless) will then be applied to the reference earthquake spectrum as a means of adapting this function to local conditions.

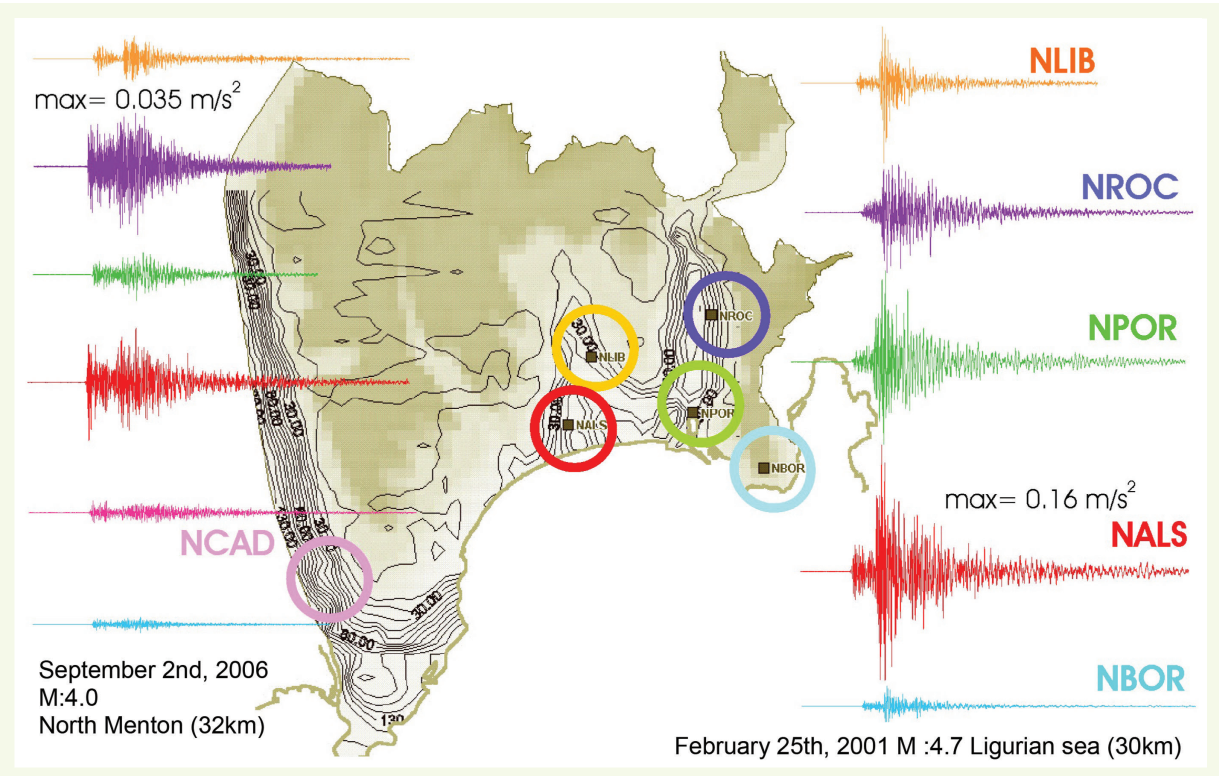
Illustration using data from Nice

For purposes of illustration, **Figure 3** displays the accelerograms output at the RAP (Permanent Accelerometric Network) sites in Nice for two earthquakes:

– the first occurring on February 25th, 2001 (whose impacts in Nice were described in the previous chapter), magnitude 4.7, originating in the Ligurian Sea about 20 km south of Nice;
– the second occurring on September 2nd, 2006, magnitude 4.0, originating in the region around Menton, some 30 km away (see **Table 1**).

The NBOR station is set as the reference for the rock measurements. The maximum acceleration (PGA) relative to NBOR is multiplied by a factor of 8 for NROC during the 2006 earthquake (yet this coefficient was only equal to 3 in 2001), by a factor of between 6 and 7 for NALS, and by 3 to 4 for NPOR and NLIB. For the September 2nd, 2006 event, the CAD site produced higher

Figure 3
City of Nice - Accelerometric recordings (east-west tracks) for 2 earthquakes at the RAP stations (the vertical scale differs for the two seismic events)



Site	February 25th, 2001 earthquake		September 2nd, 2006 earthquake	
	PGA : Valeur maximale de l'accélération (voie E-O)	Rapport PGA site/NBOR	PGA Valeur maximale de l'accélération (voie E-O)	Rapport PGA site/NBOR
NBOR	0.027		$4.4\ 10^{-3}$	
NCAD			$5.24\ 10^{-3}$	1
NALS	0.16	6	$2.94\ 10^{-2}$	7
NLIB	0.1	4	$1.14.10^{-2}$	3
NPOR	0.11	4	$1.31.10^{-2}$	3
NROC	0.07	3	$3.46.10^{-2}$	8

Table 1
Maximum acceleration values (Peak Ground Acceleration, PGA) recorded on the east-west tracks for two regional earthquakes in Nice, and comparison with the NBOR value

accelerations than NBOR despite being further from the source. This comparison would suggest the presence of a site effect, which nonetheless remains impossible to quantify with these recordings due to bias induced by the varying distance to the quake. Moreover, maximum acceleration is only read on the most highly-amplified frequencies. To specify the level of amplification from 0 to 20 Hz, the spectral ratios between the recordings at each site and the recording corresponding to the reference are shown in **Figure 4**; this display highlights the amplifications caused by all alluvial sites relative to the reference station. These amplifications are especially significant around 1 Hz for the NALS station since the spectral level exceeds 20. The NPOR site also reveals very strong amplifications.

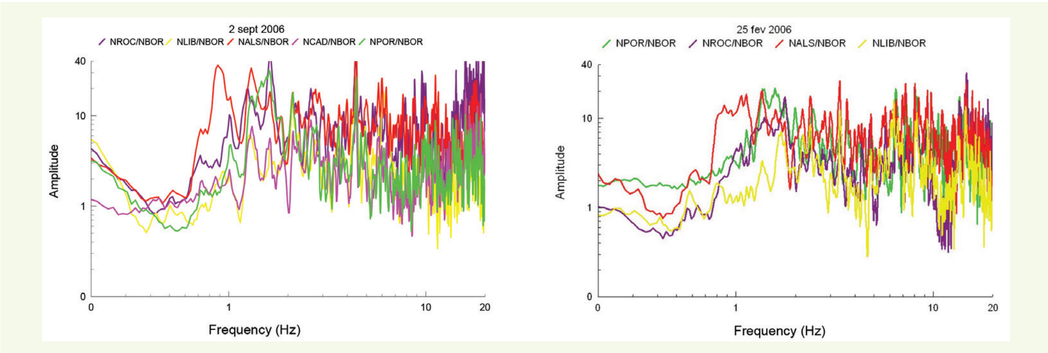


Figure 4
Nice - Site / reference (NBOR) spectral ratios for RAP stations with respect to the September 2nd, 2006 (left) and February 25th, 2001 (right) earthquakes (the colour code is the same as that used for the accelerograms in Fig. 2)

Implementation and operational constraints

This type of seismicity recording step is always considered as the most physically reliable means for determining site effects. The completion of many earthquake recording campaigns, with the intention of introducing microzoning and processing large volumes of data, now make it possible to more clearly state the constraints to be taken into account. The quality of microzoning achieved according to this method in fact depends on the equilibrium established between factors that are often contradictory. The initial factors pertain to site selection, i.e.:

• **Representativeness of the selected reference site:** A horizontal surface substratum lying near the network is not always available. Furthermore, a regional substratum may display very weak geomechanical characteristics. Even though this unit set-up is apparently capable of modifying the seismic signal, still in most cases it may be set as the reference provided that the regional hazard has been defined with respect to the unit in the form of a design accelerogram or spectrum.
• **Size of recording network:** To ensure that the propagation effect may be assumed identical at all stations, it is imposed that the earthquake-network distance be at least 5 times the distance between

network stations. Consequently, a substantial distance between the reference and a given site would prevent the inclusion of very local earthquakes.

Other factors are more specifically correlated with seismic events:

• **Dispersion of spectral ratios:** To take into account differential effects as a function of the earthquake azimuth, it is necessary to generate recordings stemming from many directions. Moreover, the spectral content of earthquakes from a given source zone may vary quite a bit depending on magnitude. This dispersion leads to incorporating a large number of earthquakes when establishing an average, which explains why our measurement campaigns have often been extended from one month to the next, while assembling a base of at least 15 measurable seismic events.<i>

• **Signal-to-noise ratio:** In urban settings, the signal-to-noise ratio may be deleterious, especially at high frequency. Yet this may also be the case at an industrial site located close to a road and exposed to wind, or to swells or to any other source of vibration. In zones of moderate seismicity (such as continental France), this ambient noise could be comparable, within certain frequency bands or for the entire spectrum, to signals emitted by rare regional seismic events. Acquisition time must then be extended to multiply the number of earthquake recordings from an array of origins, thus yielding sufficient information for covering the entire spectrum. In practical terms, the amplitude of a site/reference spectral ratio will only be included in the transfer function calculation when the signal-to-noise ratio exceeds 2 at both the site and the reference for a given earthquake. In Nice or Grenoble for example, 6 months were required to obtain around 15 very weak events. **Figure 5** illustrates the consequences of these restrictions for the microzoning performed in the city of Tunis (Duval and Vidal, 1998): these remote earthquakes only surpass background noise at low frequency. The closest regional earthquakes provide results within wider frequency ranges. The explosive blasts also used as a source can only however be considered as "instructive" at high frequency. Accordingly, the resulting ratios indicate that the MEDI study site causes significant amplifications around 1 Hz, although the high-frequency information remains rather limited.

• **Soil behaviour nonlinearity:** Forecasting a major movement based on correlations established from small-scale movements introduces a hypothesis of soil behaviour linearity that is increasingly called into question. It thus appears crucial to derive transfer functions using the strongest possible movements.

The final set of factors is tied to the cost of conducting these studies:

• **Spatial extension of the results:** A geotechnical zoning step must be performed in order to delimit zones of homogeneous risk and designate the sites to be instrumented. Depending on the resources implemented, this zoning step will be based on a simple geological synthesis or else on the analysis (or execution) of geotechnical boreholes. The responses to earthquakes recorded at individual sites will then be extended to each zone (ultimately through numerical simulations), with reliability driven by the quality of geotechnical zoning.

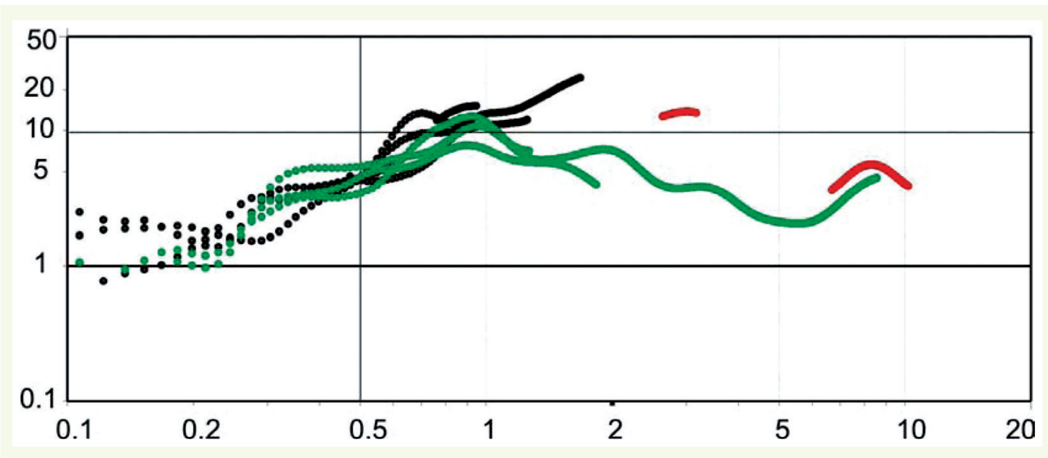


Figure 5
Microzoning of Tunis (Tunisia) - MEDI / reference spectral ratios for: regional earthquakes (green), distant earthquakes (black), and explosive blasts (red)

• **Continuous recording:** To generate a large number of recordings, a continuous regime is required (as opposed to applying threshold values to trigger a recording, as is still the case for permanent accelerometric devices). Such a continuous regime implies managing a massive and costly database.

• **Recording instrumentation:** Recording equipment has become increasingly lightweight and streamlined, but is still extremely costly. When the geotechnical study allows delimiting the zone to be instrumented, site selection conditions prove restrictive: electrical power supply (mains vs. solar panel), sensor-soil coupling, anti-theft and anti-vandalism security, noise level, uncertain weather patterns, and temperature. **Figure 6** shows the type of instrumentation deployed at a mountainous agricultural site in the middle of winter.

Figure 6
Example of a seismic recorder protection device in the Alps region

These implementation and operational constraints associated with the transfer function method have motivated us to examine other methods that rely on seismic background noise.

THE "H/V BACKGROUND NOISE" METHOD

Evolution of this method

In the 1950's, Japanese scientists first detected in seismic background noise recordings a number of indices for characterizing the behaviour of soils subjected to earthquakes (Aki, 1957, 1993). This processing mode simply consisted of studying the spectral content of an untreated recording. Afterwards, other modes of analysis (including one based on the spectral ratio of horizontal tracks overlying the vertical track) were proposed, also in a Japanese context (Nogoshi and Igarashi, 1970). However, it would take a combination of several factors for this method to attain its current level of success: awareness of the importance of site effects in earthquake prevention, development of computerized signal processing tools, and the 1989 publication by a Japanese engineer of an article in an English-language journal (Nakamura, 1989).

The attempts at justification presented in this publication first startled the scientific community, and led many seismologists to dismiss the method. Yet interest was also stirred and some of the analyses launched are still ongoing. The method's advantages became apparent quite quickly: its speed and low cost yielded certain characteristics for many points contained in the soil response to earthquakes. Our position called first for testing the method by comparing its results with other information sources and then clarifying possible explanations for the type and propagation of waves composing the seismic background noise. The extensive research underway was furthered as part of the European project SESAME, which gave rise to a method user's manual (Bard *et al.*, 2004; Duval *et al.*, 2004).

Today, the "H/V background noise" method is increasingly applied throughout the world in site or microzoning studies intended to identify sites displaying seismic amplification risks for determining resonance frequencies.

Operating principle and past results

The type of waves composing seismic background noise has been an open question for quite some time. The SESAME project has led to some breakthroughs on the issue (Bard *et al.*, 2004). The ambient seismic noise (more commonly referred to as a microtremor) is composed of both volume waves and surface waves originating:

• for long periods (i.e. up to approx. 5 seconds): from atmospheric disturbances on the oceans spreading over the surface of the Earth's crust. Other natural sources of telluric noise exist as well, such as remote earthquakes;
• for shorter periods: from human and industrial activity.

As regards experimental campaigns, the method entails placing a three-directional vibration sensor (vertical, longitudinal, transverse) on the studied soil for a 10 to 30-minute period. The ambient noise is then recorded by the numerical acquisition station **(Fig. 7)**.

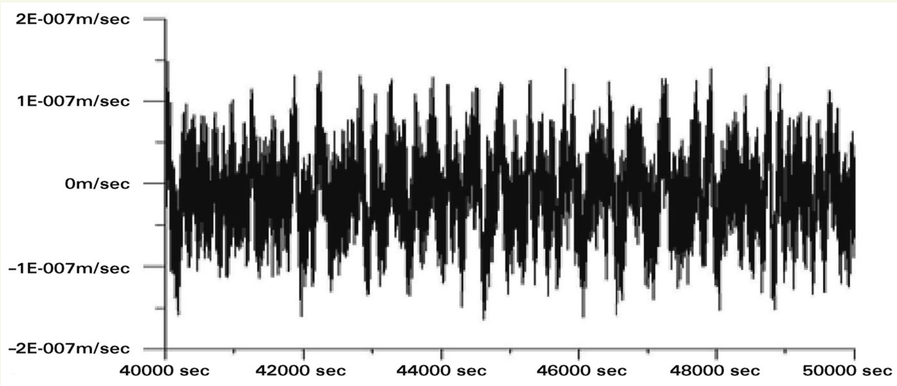


Figure 7
Example of a seismic background noise recording (soil vibration speed, in m/s)

The processing sequence for the three seismic plots obtained per recording is as follows:

• for each recording, the first search focuses on signal windows (in general on the order of 1 min), in which the signal is as stable as possible while avoiding transient signals;
• a spectral analysis by means of Fourier transform (FFT) is conducted on each of these windows. The spectrum amplitude is smoothed. Let's use H to denote the spectrum in average amplitude of the horizontal tracks and V to represent the vertical track spectrum;
• for each window, the ratio of spectrum H to spectrum V is calculated;
• an average of the ratios generated from a large number of windows leads to an "H/V" ratio that is representative of the site.

It is now possible to confirm the inherent benefit of this method: the resultant "H/V background noise" curve displays a peak at a frequency corresponding to the fundamental resonance frequency of the sedimentary sites. **Figure 8**, derived from many recordings in France and abroad, effectively demonstrates that those sites with expected amplification phenomena display "H/V background noise" curves with peaks, whereas the same curves are flat on rocky sites (i.e. without amplification) (Duval, 2001a).

As proven by research conducted within the scope of the SESAME project (Bard *et al.*, 2004), the existence of this H/V ratio peak may be justified by various factors: Rayleigh wave ellipticity, Airy phase of the fundamental mode of Love waves, and (to a partial extent) the resonance of shearing (S) volume waves (Bonnefoy-Claudet *et al.*, 2006).

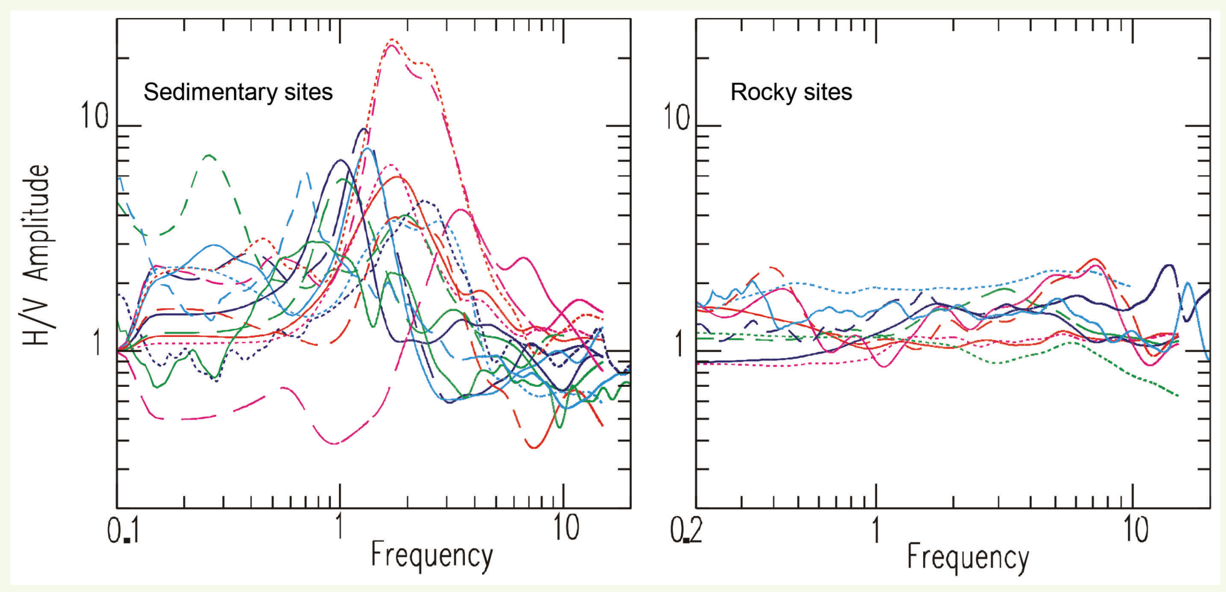


Figure 8
Examples of "H/V background noise" ratios

Prior to building a consensus on the method's possibilities and refining common operating protocols, many evaluations were carried out. The initial results acquired as of 1991, regarding stability over both time and space as well as comparisons with actual earthquake recordings or numerical simulations, have been very promising (Duval *et al.*, 1996). A synthesis of several studies performed by the ERA and LGIT research teams (Duval *et al.*, 2001a) then led to the following conclusions:

- the "H/V background noise" and "receiver function" methods (or "H/V on an earthquake") serve to quantify the fundamental frequency of sites below which all amplification ceases. The frequencies of initial transfer function peaks produced by earthquakes tend to correspond very well with the frequencies of "H/V background noise" curves **(Fig. 9)**;
- these methods provide a minimum reliable level of spectral amplification; however, they are incapable of estimating either the bandwidth involved in the amplification or the actual amplification level in the case of strong movement;
- as a general rule, these methods make it possible to verify whether a zone exhibits no site effect (a rocky zone).

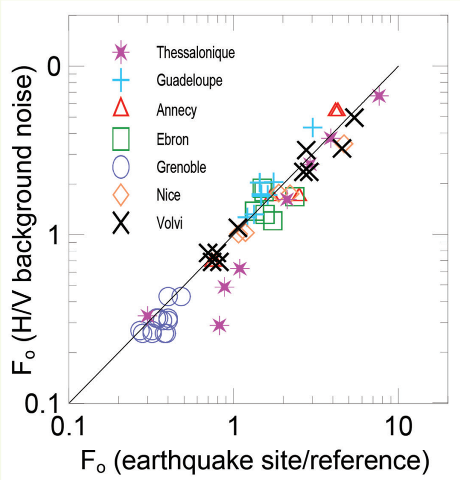


Figure 9
Frequency of both the 1st earthquake transfer function peak and the 1st "H/V earthquake" ratio peak for 44 sites studied as part of the synthesis (Duval et al., 2001a).

Application to the city of Nice

› Comparisons with earthquake recordings

Actual earthquake recordings at various points in the city have enabled establishing real transfer functions, which indicate amplifications of a factor of 10 for moderate earthquakes, in association with a signal extension.

The city of Nice is a preferred training ground for the “Seismic Risk” research team. Site effect determination methods have been applied here since 1983 (Bard *et al.*, 1983) on test sites, where RAP stations are in fact now installed. The following results serve to illustrate the broad scope of research conducted between 1991 and 2004, in the aim of evaluating the potential offered by this “H/V background noise” method.

The first result pertains to the alluvial filling of a former riverbed leading to the sea southward between two hills. This valley is filled by materials that are relatively loose and heterogeneous compared to its rocky base. Knowledge of this alluvial ground has remained imperfect up until now and has given rise to new investigations. On the basis of geological interpretations and analyses of the deepest boreholes, it can nonetheless be concluded that the thickness of this alluvium increases when heading to the sea, i.e. from approx. 15 meters at the northern RAY site to about 30 meters for the LIB site and reaching around 100 meters at the NALS site to the south (shown on the map in **Fig. 10**).

Based on this information, (1D) numerical simulations have determined the resonance frequencies associated with these three sites: 4.5 Hz, 2.5 Hz and 1 Hz respectively, from north to south (see blue curves in **Fig. 10**).

Seismic stations have recorded seismicity over a several-month period at these sites. The spectral ratios determined with a reference station positioned on a limestone rock mass (NBOR) were calculated (green curves, **Fig. 10**) and found to increase at frequencies near those identified numerically (5 Hz, 1.8 Hz and 0.8 Hz respectively, from north to south). Let’s remark that the high noise level on RAY conceals the major part of the transfer function; moreover, the amplification level is very high (reaching 20 on NALS) and remains substantial at high frequency, which should undoubtedly be correlated with the low level of seismic excitation present in the earthquakes under investigation.

Lastly, ambient background noise was recorded at these sites. The average “H/V background noise” ratios of each site yield characteristic peaks at frequencies that are entirely compatible with the

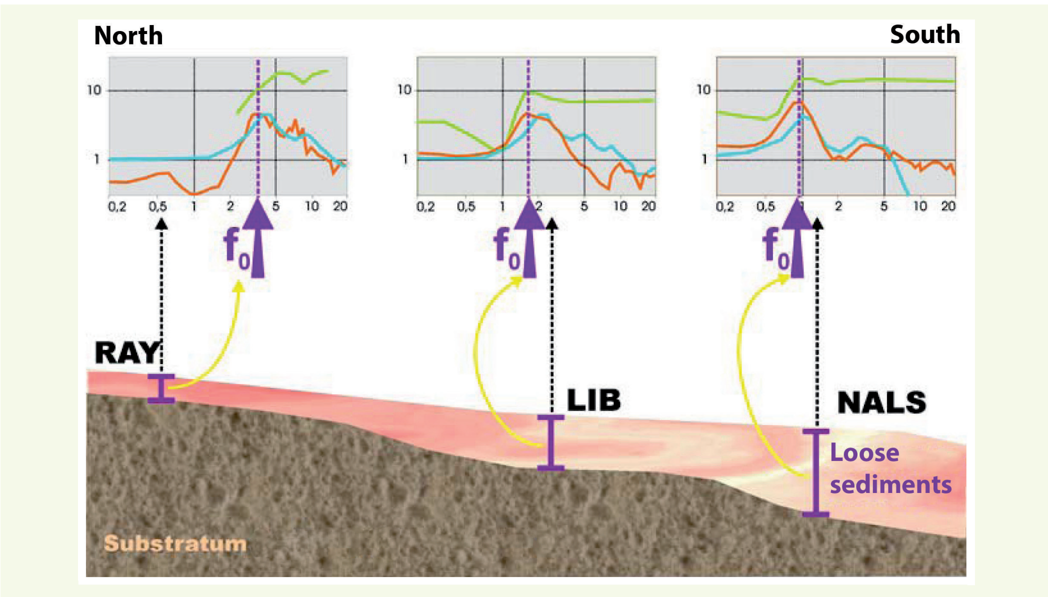


Figure 10

Nice - central valley (in green): site/reference earthquake spectral ratios; in orange: H/V background noise spectral ratios; in blue: (1D) numerical transfer function.

expected resonance effects: from a value of 3.5 Hz to the north (RAY), frequency decreases at the centre (LIB) to between 1 and 2 Hz, winding up in the south with the highest peak at the lowest frequency: 0.8 Hz (NALS). These encouraging results have motivated us to pursue application of this method on a larger territory.

› Spatial distribution of background noise measurements

The large number of background noise measurement campaigns in Nice has resulted in a total of 687 points localized both on the zone's relief and the alluvial deposits in **Figure 11**, and on the

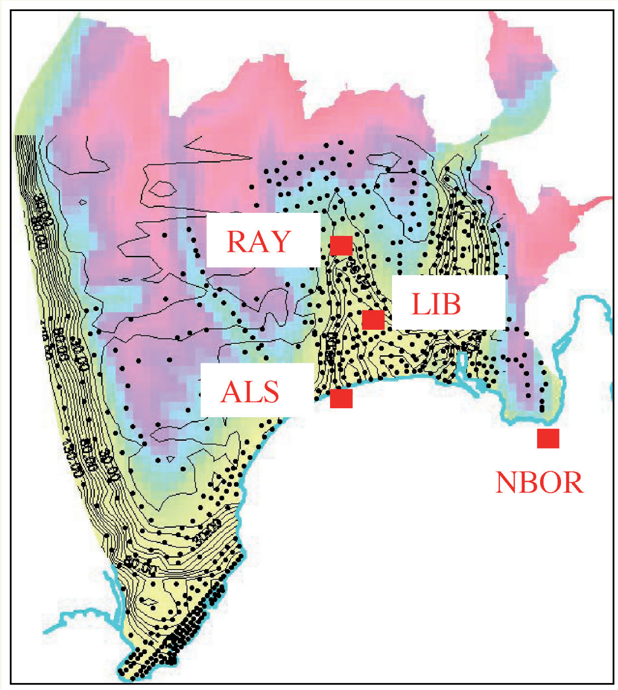


Figure 11
Localization of background noise measurement points (shown in black) on the (colored) relief, and sedimentary filling (thickness contour lines)

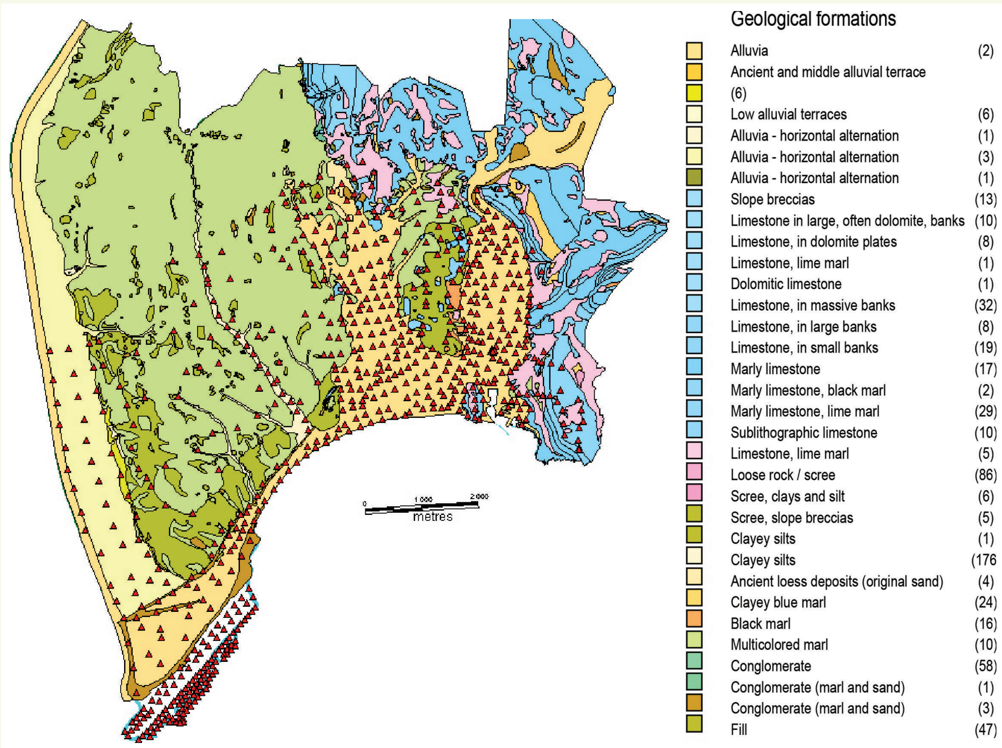


Figure 12
Nice - Localization of background noise measurement points from 1991 to 2005 (triangles) on the given geological units

geology in **Figure 12** (Duval and Vidal, 2003). The density of these points is greater in the alluvial zones than on the limestone or conglomerate hillsides.

› Interpolation of soil resonance frequencies

The “H/V background noise” method was applied to these recordings. The frequency F_o of the primary peak from each H/V curve (between 0.5 and 15 Hz) was interpolated so as to produce **Figure 13**.

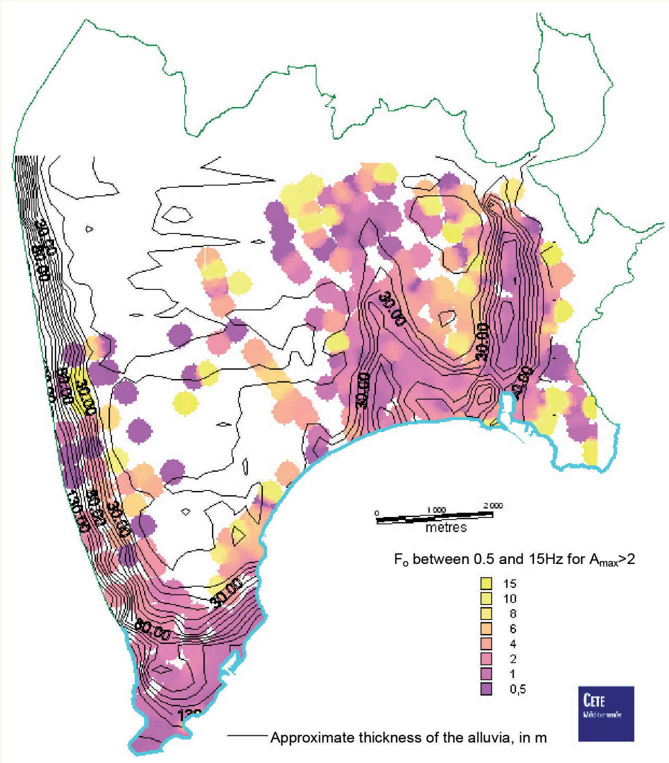


Figure 13
Nice - Frequencies F_o of the maximum peak between 0.5 and 15 Hz on the “H/V background noise” ratios (in Hz)

An analysis of this figure leads to the following remarks:

✓ The highest values of F_o (above 10 Hz) generally lie outside the sedimentary zones;
✓ The alluvial fill zones display F_o values of less than 2 Hz;
✓ Many points on the rock (as readily found on western hillside conglomerate as on Cimiez hill gypsum or eastern Nice limestone) also show F_o readings below 0.5 Hz.

The maximum A_o level of the “H/V background noise” ratios has been interpolated across the entire territory **(Fig. 14)**. None of the numerical studies or theoretical interpretations on such phenomena has until now been able to ascribe a physical meaning to this A_o value. It is noteworthy however to observe that H/V ratios are only intended to reveal a site effect once they exceed a threshold value (equal to 2 as a general rule). A few examples would suggest that when a given site causes seismic amplifications to be sharply higher than another site in the same territory, its H/V background noise curve is also higher. Yet this suggestion still needs to be proven by means of new microzoning syntheses.

A study conducted on the Palos Grandes district in Caracas has allowed establishing a correlation between the distribution of damage from the 1967 earthquake, soil resonance frequencies (by numerical simulation) and frequencies F_o of maximum H/V background noise ratios. This study has confirmed the possibility of an overlap in resonance frequencies between the soil in certain zones and some destroyed buildings. In addition, heavy damage is concentrated in a zone where

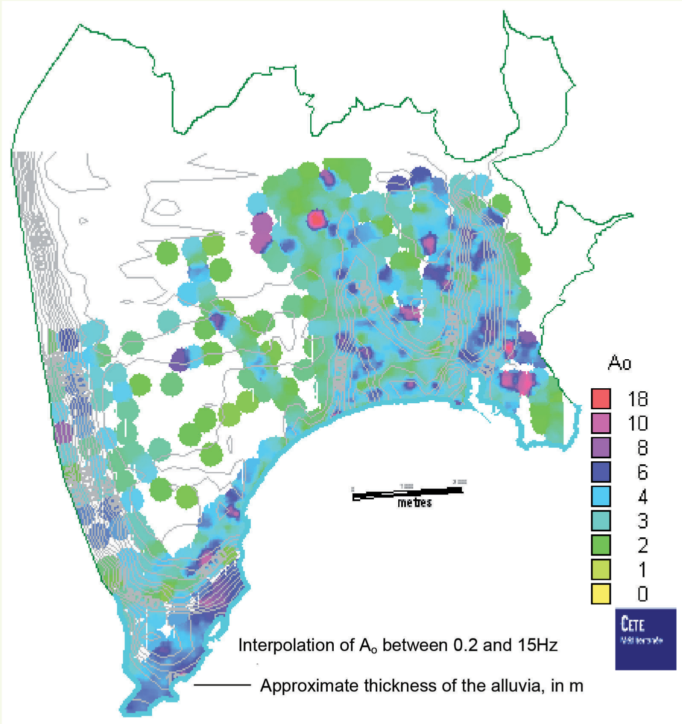


Figure 14
Nice - Amplitude A_o of the maximum peak between 0.5 and 15 Hz on the "H/V background noise" ratios (in Hz).

amplitudes A_o of the H/V curves were among the highest, as indicated in the numerical simulations (Duval *et al.*, 2001b; Semblat *et al.*, 2002). As such, the contribution of **Figure 14** is not necessarily negligible. The maximum A_o values are somewhat higher at the airport (loose anthropogenic fill) and at the centre and periphery of some basins, thus closely corresponding to zones where amplifications have been numerically forecasted (Semblat *et al.*, 2000).

› Comparison with numerical simulations using a 3D geotechnical subsoil model

The 3D geotechnical model developed for the whole city during the GEM-GEP study has been implemented in order to associate each background noise measurement point with a sedimentary cover thickness (Méneroud *et al.*, 2000). This model was produced by collecting and analysing all available geotechnical boreholes, in the aim of characterizing the nine geotechnical layers making up Nice sedimentary deposits. The spatial extension of these layers was then performed by taking into account the geological and topographic surface elements and introducing expert supervision. Let's recall that even though the overall trend and maximum thicknesses seem to be consistent with current knowledge, the accuracy of this model is definitely limited: of the 436 initial boreholes, 155 reached the substratum (obviously a rare occurrence in deep fill zones). The model developed encompasses a vast territory, composed of complex Alpine geology at the seaside. Sand lenses, for example, have not been included in the representation. In the deepest zones (e.g. around the NALS site), knowledge remains very limited and any attempt at interpolation is thus risky since no borehole has reached the substratum. While the depth ultimately adopted in the current model is apparently plausible to experts, the model is undergoing improvements, thanks in particular to the so-called "network background noise" technique described further below.

Figure 15 contrasts the maximum peak frequency of the H/V background noise curves (when the A_o level exceeds 2) with fill thicknesses deduced from the model by summing the various sedimentary layer thicknesses. This figure provides an overview and indicates the expected decrease in frequencies as fill thickness increases. Attention must however be drawn to the rather wide dispersion on display.

Numerical simulations were run using the Shake software (Schnabel, 1972) on soil columns resulting from the 3D geotechnical model. The propagation of a seismic signal (California earthquake)

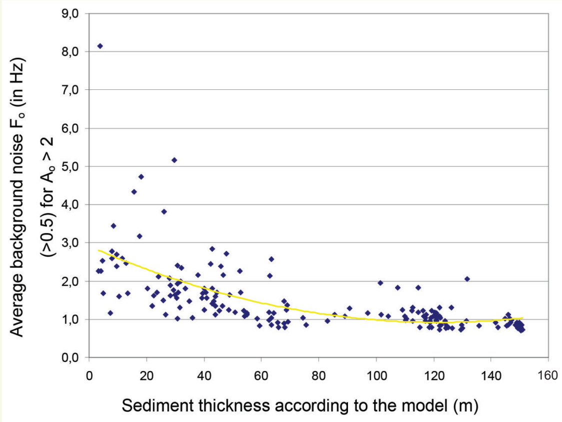


Figure 15
Nice - Frequency F_o corresponding to the maximum "H/V background noise" curves, between 0.5 and 15 Hz (when this maximum A_o > 2), vs. fill thickness (in m) according to the 3D geotechnical model.

through sedimentary fill zones was simulated for 1,992 points identified in **Figure 16**; these points are listed on the calculation grid of the geotechnical model.

The transfer functions of each point with respect to the rock (reference) are saved; these curves showcase the seismic signal modification (in frequency terms) caused by each site. The maximum amplification values (F_o and A_o), between 0.2 and 15 Hz, were calculated in the same manner as for background noise.

Frequencies F_o are minimized at the basin centre (1 Hz in the central city, less than 1 Hz for the Var Plain); they increase when moving away from the centre and are maximized (above 5 Hz) at the basin periphery **(Fig. 17)**. Similarly, **Figure 18** accurately illustrates the fact that the resonance frequencies stemming from these 1D numerical transfer functions are indeed correlated with fill thickness.

Conversely, as opposed to results generated from the background noise, the numerical transfer function amplification level A_o increases systematically from the fill centre towards the exterior (from A_o = 3 to 6.9), as shown in **Figure 19**. The calculations executed by taking into account not just a single soil column but instead (2D) profiles seem to better reflect actual amplification levels (Semblat *et al.*, 2002).

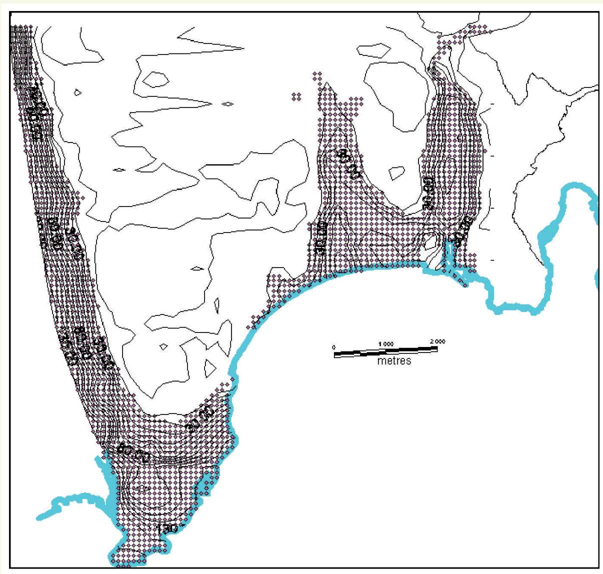


Figure 16
Localization of the 1D simulation points (purple squares) - Contour lines represent the approximate thickness of the alluvial fill (see also figure 17)

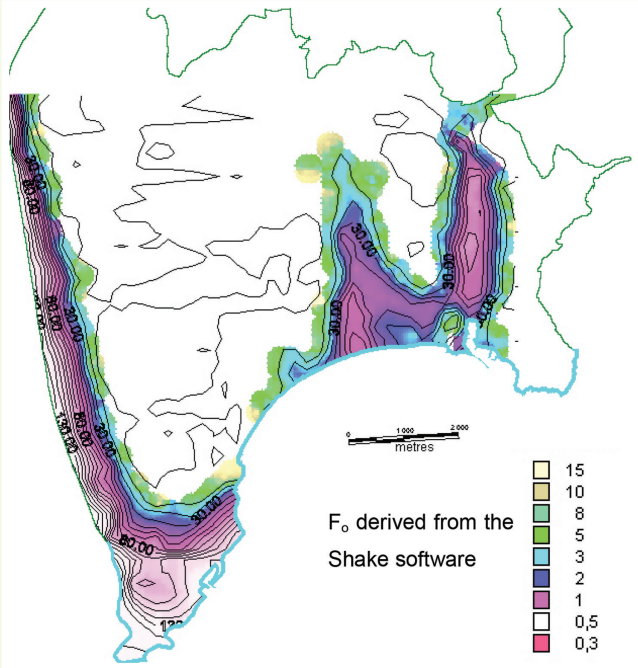


Figure 17

Nice - Interpolation of transfer function frequencies F_o (1D numerical simulations) between 0.2 and 15 Hz. Contour lines represent the approximate fill thickness.

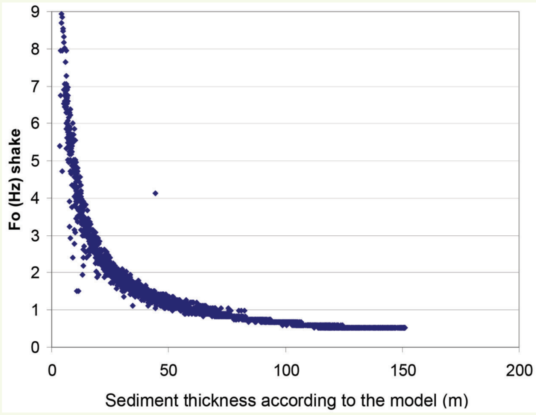


Figure 18

Nice - Frequency F_o corresponding to the transfer function maximum (1D simulation) vs. fill thickness (in m) in the 3D geotechnical model

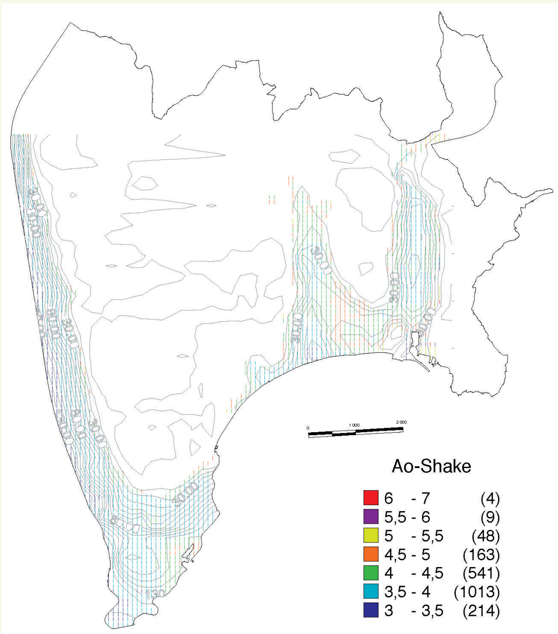


Figure 19

Nice - Interpolation of transfer function maximum amplitudes A_o (1D numerical simulations) between 0.2 and 15 Hz. Contour lines represent the approximate fill thickness.

CONCLUSION

The application to the city of Nice of several techniques for detecting site effects has enabled verifying the existence of amplification phenomena, in addition to comparing the results of various techniques and verifying their complementarity within the scope of a microzoning procedure:

– The great number of seismic recording campaigns we undertook over the past years have indeed confirmed the existence of site effects in Nice city centre. These phenomena are manifested by the amplification of seismic movements at what are often fundamental frequencies for the buildings and correlated with the type and thickness of the sedimentary fill. An enhanced knowledge of the so-called "earthquake reference site" method and its limitations was acquired. Five of the sites studied in Nice by the CETE Research Centre have become permanent stations within the French Permanent Accelerometric Network;
– The "H/V background noise" method was applied at nearly 700 points over a vast and contrasted territory. The results yield a soil resonance frequency mapping, which corresponds to the frequencies deduced from the "earthquake reference site" method, with the particularity of a resonance frequency on the order of 1 Hz around the NALS site;
– The three-dimensional geotechnical model, devised using both a borehole database and a fine-tuned map of surface geology, is the first of its kind at this scale within a microzoning context. The numerical model has revealed its full advantages for this type of study by proceeding with the assignment of a soil column at each point of the alluvial fill. The propagation of accelerograms through the thousands of columns could thus be simulated. Moreover, resonance frequencies could be mapped based on these results.

2D numerical simulations were also performed as part of this work program.

The results of these three techniques ("earthquake reference site", "H/V background noise" and "numerical simulation") have substantiated the hypothesis of worrisome site effects in the centre of alluvial valleys. Several avenues for research are currently being explored in order to further improve the understanding and prediction of seismic amplifications. Among the points that require clarification, let's cite: topographic site effects (caused by abrupt relief), which remain largely unknown; the effects of basins that complicate site response; and the transposition of transfer functions generated from weak earthquakes into strong movements (problem of soil behaviour nonlinearity).

From the standpoint of risk prevention, the reality of site effects in Nice, combined with the extent of structural vulnerability and the importance of potential damages, has been clearly demonstrated for risk managers via the GEM-GEP project in particular. This scientific approach allows to assess risk in the most appropriate terms, and to adapt national regulations to local conditions.

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