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Seismické lokální účinky (analýza dat a modelování)

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Charles University in Prague
Faculty of Mathematics and Physics

Seismic Site Effects (Data Analysis and Modelling)

by

Dott. in Fisica Arrigo Caserta

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Contents

1 Abstrakt/Abstract

Práce podává komplexní rozbor pohybu půdy buzeného seismickým vlnovým polem, zahrnující aspekty teoretické, geologické a geotechnické, jakož i analýzu dat a numerické simulace. Cílem je kvantifikovat hlavní parametry, umožňující odhad kmitavých pohybů v městských oblastech a případné snižování následků budoucích zemětřesení. Studie je zaměřena na Řím vzhledem k vysoké hustotě obyvatelstva a koncentraci historických památek s vysokou seismickou zranitelností. Práce zlepšuje údaje o podrobné povrchové geologii studované části Říma, vyplňuje mezeru ve znalostech geotechnických parametrů a poskytuje dosud chybějící záznamy zemětřesení na území města. Mimo jiné též umožňuje lépe pochopit prostorové rozložení škod, pozorované v Římě při dřívějších zemětřeseních. Hlavními inovacemi jsou: zřízení a dlouhodobý provoz seismické ereje, analýza seismického šumu a záznamy zemětřesné sekvence L'Aquila 2009. Trojrozměrná erej (zahrnující senzor v 70-m hlubokém vrtu) je první svého druhu v Itálii, která zaznamenala významné zemětřesení v městské oblasti. Pořízená instrumentální data jsou také porovnána s hybridní simulací pohybů půdy v údolí Tibery; jsou použity nové paralelizované programy, založené na metodě diskrétních vlnových čísel a 3D metodě konečných diferencí.

A comprehensive study of the soil shaking under the seismic wave-field excitation is presented. It includes theoretical, geological, geotechnical, data analysis and numerical simulations aspects. The aim is to quantify the main parameters allowing the estimate of the soil shaking in urban areas for better mitigating seismic risk due to future earthquakes. The city of Rome has been chosen as a case study because of its high density of population and large concentration of historical monuments with high earthquake vulnerability. This study improves significantly the knowledge concerning the detailed near-surface geology of the chosen study area of Rome, fulfills the absence both of knowledge concerning its geotechnical properties and earthquake data recordings in the city. Among others, it allows for a better explanation of the spatial damage pattern observed in the city due to earthquakes in the past. The main innovations include the construction and long-term operation a seismic array in the city, analysis of the natural seismic noise, and instrumental recordings of the 2009 L'Aquila earthquake sequence. The 3D array (including a borehole sensor at 70-m depth) is the first one in Italy planned, realized and operated within an urban area, and the first one that recorded a significant earthquake in the city. Finally, the recorded data are compared with hybrid numerical simulations of the ground motion in the Tiber valley, using new parallelized codes, based on the discrete-wave-number and 3D finite-difference methods.

2 Introduction

An earthquake can produce different damages within sites even less than hundred meters apart. Sometimes, variations of amplitude and duration of the soil shaking can be of a factor 10, or even more, in specific frequency bands. This is due to complex physical processes driving the dynamics of the interaction between seismic waves and heterogeneities of the near-surface geology. As a consequence, we observe a high level of variability in the damage distribution on the surface. In particular, such damage variability is due to the response of the uppermost layers (hundred meters beneath the surface) to the seismic wave propagation, where seismic impedance shows a strong contrast between the rock basement and the softer sedimentary deposits of natural and anthropogenic origin. In these cases, irregular geometry of the interfaces and the impedance contrast cause trapping of energy and wave interference, resulting in large spatial variations of ground shaking at the Earth surface during earthquakes. We refer to such It is easy to understand the importance to assess the strong ground motion in urban areas for mitigating the seismic risk before earthquakes occur, especially for preserving the archeological and monumental heritage.. To achieve such goals studies devoted to characterize the site effects are needed. Such studies mainly concern the assessment of the seismic response of the aforementioned uppermost layers, with particular attention at analyzing the ability of the site under study in amplifying the soil shaking in the range of frequencies of engineering interest, typically 0.2 -10 Hz, as well as ability of focusing/defocusing energy in different parts of the site.

The numerical approach to simulate such effects has been, and still is, very useful in urban areas (Rovelli et al. (1994); Moczo et al. (1995); Olsen et al. (2006)), where the experimental approach can not be ever used because the high level of anthropogenic noise continuously present (Boschi et al. (1995)). At the same time the experimental approach can not be neglected because it supplies not only information concerning the dynamical behavior of the near-surface geology, but also allows to tune numerical models and to validate results of such numerical simulations (Pitarka et al. (1998); Rovelli et al. (2002)). For both approaches, however, a detailed knowledge of the near-surface geology coupled with its geotechnical properties (elastic and inelastic ones) is needed. That is why the present Thesis includes studies concerning geological/geotechnical data analysis, earthquake recordings data analysis and numerical simulations aspects aimed at assessing the site effects features in urban areas. The chosen case study is the city of Rome due to its high density of buildings and large concentration of archeological and monumental heritage, both with high level of seismic vulnerability.

2.1 Motivation

During its long history, many destructive earthquakes affected the city of Rome producing moderate to significant level of damage, up to intensity VII - VIII of the Mercalli-Cancani-Sieberg (MCS) scale (Molin and Guidoboni (1989)). The large concentration of monuments and ancient buildings, and their extreme vulnerability, add to the seismic hazard for the city. A careful micro-zonation and the evaluation of the characteristics of strong ground motions in different areas of Rome are the basic tools to mitigate seismic risk.

No strong-motion recordings were available for the urban area, which made it impossible to make any estimate based on actual measurements of ground motion induced by earthquakes. Moreover, not enough knowledge of the near-surface geology concerning the part of the city under study was available. Knowledge concerning its geotechnical properties (elastic and inelastic) was fully missing, thus making very difficult even numerical simulations of the soil shaking within the city and comparisons with the observed damage distribution due to earthquakes of the past.

The present Thesis has as main objective to fulfill the aforementioned absence in knowledge. This has been done within two multidisciplinary research projects: FIRB 2002-2005 (code: RBAU01JMT3), and COFIN 2004-2005 (code: 2004041297-002). In the first one the author of the present Thesis has been the scientific responsible for the Research Unit 3, whereas in the second one he has been scientific responsible for the I.N.G.V.

Figure 1: *Top panel: epicenter of l'Aquila 6th April 2009 Mw=6.1 damaging earthquake with the epicenters of the seismic sequence. Middle panel: 3D array location, red spots represent seismic stations. The red spot outside the Tiber valley (Garbatella) is the reference station. Bottom panel: sketch of the borehole station located beneath the alluvial sediments layer. See paper* **P2** *for details.*

More in details, the projects involved the installation of a permanent seismic array and a detailed classification of the physical and mechanical properties of the rocks constituting the geological subsoil of Rome, under both static and dynamic conditions. As a consequence of the aforementioned projects, since early 2008 a small aperture four-station array has been operating on the alluvial sediments within the Tiber Valley in Valco San Paolo, in the southern part of the historical sector (Fig. 1). Inter-distance between the array stations is up to 100 m. Another station was installed, as reference station, about 2 km east of the array, above the Pleistocene pyroclastic succession and the underlying, older sedimentary deposits of the Paleo-Tiber River (Marra and Rosa (1995)).

2.2 State of the art

Even in case of a weak seismic input at the bedrock, the presence of superficial unconsolidated sediments can produce unexpected damage at the surface. These effects attract a special attention in the urban areas where a systematic tendency to a larger damage concentration has been experienced on outcrops of recent and unconsolidated terrains. In the last decades, an increasing number of seismic recordings has been available for many urban areas struck by strong earthquakes. Experimental data have allowed seismologists to understand the role of near-surface geology on the strength of shaking, explaining the mechanisms that cause the observed damage anomalies.

In September 1985, Mexico City suffered the collapse of several tall buildings in the area of the ancient lake bed. The damage to nearby smaller buildings was minor and the earthquake was felt with light intensity in the remaining part of Mexico City, the epicenter being 300 km away. Thanks to the abundant data recorded in the city (Singh et al. (1988)) and numerical modeling of the basin response (e.g., see Kawase and Aki (1989)) the effect was interpreted as a resonance of the soft infilling of the lake bed. The spectral amplification was peaked at periods from 2 to 5 seconds and affected selectively those buildings having the same period of vibration. In Japan, during the 1995, Kobe earthquake the maximum damage was concentrated in an extended, narrow band parallel to the causative fault, but about 1 km apart. Even in this case the ground motion recordings and the numerical modeling allowed seismologists to interpret the effect as due to the local geology structure. It was found (Pitarka et al. (1998)) that the maximum damage band coincides with the zone where a constructive interference between the direct shear wave and surface waves diffracted from the basin edge causes a significant increase of the ground motion amplitude.

Also the city of Rome, our study case, during its long history suffered damage up to intensity VII-VIII of the Mercalli-Cancani-Sieberg scale due to the largest earthquakes in the Apennines (see Molin and Guidoboni (1989)).

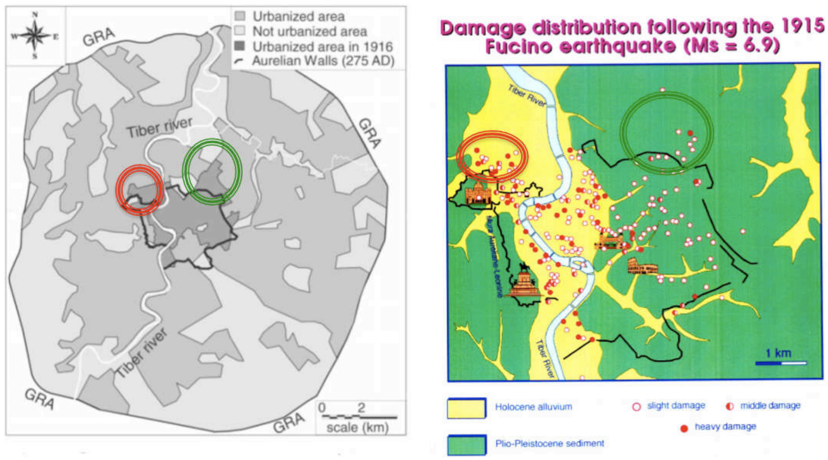

Figure 2: *Left panel: city of Rome, present urbanized area within the ring-road (GRA). The dark gray area represents the urban settings aft er the 1915 Fucino earthquake., from Cifelli et al. (2000). Right panel: sketch of the simplified near-surface geology showing the damage pattern experienced during the 1915 Fucino earthquake. The red and green circles are for comparing the damages (right panel) with the urbanized areas (left panel). From Ambrosini et al. (1986) and Cifelli et al. (2000).*

In the city, the occurrence of the strongest damage episodes seems to be restricted to the Holocene alluvial areas (Ambrosini et al. (1986); Salvi et al. (1991)), with a significant concentration close to the edges of the Tiber river valley (see Fig. 2). In absence of instrumental data, the development of techniques able to infer the spatial variability of ground motion during earthquakes is particularly important for a city like Rome as it is rich in ancient monuments and historical buildings, which are likely to be less resistant to the seismic action even in case of a moderate level of excitation. In full awareness that the computation of potential strong ground motions in the different zones of the city is a fundamental tool to mitigate seismic risk and organize the public and private intervention priorities, Rovelli et al. (1994, 1995) proposed a hybrid technique able to generate a suite of synthetic accelerograms (SH waves) along 2D profiles, whose amplitudes were modeled as a function of moment-magnitude, distance from the source, and local geology. Comparing the results of their modeling with predictions based on empirical observations in Italy (Sabetta and Pugliese (1987); Pugliese and Sabetta (1989)) and Western North America (Boore et al. (1993)), Rovelli et al. (1994) found a satisfactory agreement for seismological parameters such as peak ground acceleration and velocity as well as response spectra, which are mostly representative for earthquake engineering applications.

Within this framework, the contribution of the present Thesis is in improving the knowledge of the near-surface geology of Rome, its geotechnical features (elastic and inelastic ones), the vertical shear-wave velocity profile measured and extended to the whole main sedimentary body of the city - the Tiber Valley, allowing for more realistic numerical simulations of the soil shaking features in the city. But the main contribution is in allowing for data recordings through the 3D seismic array. In fact, Variations of the soil shaking observed in urban areas during strong seismic events are not different from those observed during shallow events. These features allow us to recover information about the dynamical behavior of the near-surface geology of the city regarding strong earthquakes analyzing shallow events. Such information is very important for micro-zonation purposes. Collected data are useful also to calibrate numerical simulations of dynamical behavior of the near-surface geological structures. In addition to pure research purposes, this type of studies can have important implications for the seismic risk mitigation.

2.3 Thesis overview

The present Thesis comprises of the following papers:

P1 A. Caserta and M. Di Bona (2010). Monte Carlo technique in modeling ground motion coherence in sedimentary filled valleys, *Computers & Geosciences*, **36**, 133-138.

P2 A. Caserta, G. Consolini, P. De Michelis (2007). Statistical features of the seismic noise-field, *Stud. Geophys. Geod.*, **51**, 255-266.

P3 F. Bozzano, A. Caserta, A. Govoni, F. Marra, S. Martino (2008). Static and dynamic characterization of alluvial deposits in the Tiber River Valley: new data for assessing potential ground motion in the City of Rome, *J. Gephys. Res.*, **113**, doi:10.1029/2006JB004873.

P4 A. Caserta, S. Martino, F. Bozzano, A. Govoni, F. Marra (2011). Dynamic properties of low velocity alluvial deposits influencing seismically-induced shear strains: the Grottaperfetta valley test-site (Rome-Italy). *Bull. of Earthquake Engin.*, submitted.

P5 A. Caserta, V. Ruggiero, M. P. Busico, I. Opršal (2009). Parallelisation technique for serial 3D seismic codes: SMS approach, *Annals of Geophysics*, **52**, (5), 503-514.

Chapter 4 and 5 of present Abstract (i.e. Chapers 3 and 4 of the Thesis), contain results results being prepared for the paper publication.

3 Seismic noise

3.1 Deterministic approach

Different approaches can be adopted to evaluate local site effects. Among the empirical low-cost methods involving seismic noise, the H/V spectral ratio on ambient vibrations is probably one of the most common one; the method, also called Nakamura technique (Nakamura (1989)), was first introduced by Nogoshi and Igarashi (1971) based on the initial studies of Kanay and Tanaka (1961).

The H/V method is an experimental technique to evaluate some characteristics of soft-sedimentary soils. It is based on the analysis of the spectral ratio between the Fourier amplitude spectrum of horizontal (H) components of the recorded ambient vibration, and the Fourier amplitude spectrum of the vertical component (V) of the same record.

The Nakamura technique (H/V spectral ratio) is useful for its link with the surface structure, it is given by the standard 1-layer approximation represented by the rule of the quarter of the wave-length, i.e., $f_o = \frac{Vs}{4h}$ where f_o and Vs are the resonance frequency and the velocity of the S-wave, respectively, whereas h is the thickness of the layer.

Besides the use of H/V peak for obtaining information about Vs and/or the layer thickness, it is important to note its relation with the first frequency at which earthquake ground motion is amplified. Indeed, the H/V frequency peak represents the frequency value at which the soil shaking is amplified during earthquakes. This aspect is discussed in papers **P3** and **P4**, and it is confirmed by the data analysis of L'Aquila earthquake in Chapter 4 of the Thesis.

The use of small-aperture arrays allows to derive frequency dependent estimates of the phase velocity of the noise wave field. The dispersion curve information can be used to derive velocity models for a given site in an inversion as well as in a forward procedure. The use of these methods have become wide-spread in recent times (Horike (1985, 1996); Ishida et al. (1998); Miyakoshi et al. (1998); Yamanaka et al. (1994); Sherbaum et al. (2003)), it happened particularly in Japan (Tokimatsu (1997); Chouet et al. (1998); Bettig et al. (2003); Satoh et al. (2001); Wasten and Dhu (1998)).

Major advantages of these techniques are that they can be applied in urban areas and that they are able to investigate deep soil properties, up to 1/3 of the wave-length corresponding to the fundamental resonance mode according to the low frequency content of the seismic noise (Horike (1985); Ishida et al. (1998); Miyakoshi et al. (1998); Yamamoto (2000); Sherbaum et al. (2003)). These two features are of particular interest in site effect assessment, as numerous big cities in seismic areas (Mexico City, Los Angeles, Caracas, Tokyo, etc.) are built on thick soil layers (from hundreds meters to more than 1 Km depth).

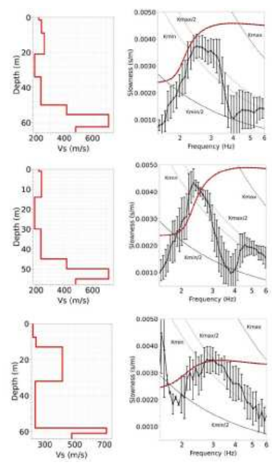

Figure 3: *Columns from the left: Vs vertical velocity profiles; theoretical dispersion curves (solid red lines) computed using Vs and experimental dispersion curves (stippled black line), the vertical bars are ±1 standard deviation. Row from top: test site, the two sites within the Tiber valley. From paper* **P3**.

The purpose is to reconstruct from array measurements of ambient vibration the dispersion curve of the Rayleigh waves. This can be done via an inverse or forward problem. In the present Thesis the forward problem has been solved. In practice, a comparison between the dispersion curve obtained by ambient vibration recordings and the dispersion curve obtained by a 1D model of stratified surface soil has been performed; the stratification represents the vertical Vs profile of the near-surface geology, i.e., our final target. Such technique has been applied first in the site where geological and geotechnical investigations were previously performed with the purpose of better tuning the technique (Fig. 3 top). Later, the same tuned procedure has been applied in other sites within the Tiber valley (Fig. 3 middle and bottom rows), in order to generalize the results concerning the Vs vertical profile to the whole sedimentary body of the city (see paper **P3**). The same procedure has been applied to a tributary lateral valley (Grottaperfetta valley) of the main sedimentary body of the city (see paper **P4**).

3.2 Stochastic approach

Starting in the 1980s, a growing number of researchers understood the importance of studies concerning the non-linearities in geophysics. So that they focused their efforts on such topic giving rise to the socalled non linear geophysics (NG). The main NG improvement, in respect of a pure deterministic description, has been to import from theoretical physics into geophysics the use of the general concept of self-organized criticality (SOC). SOC relates the statistical features that are scale invariant, having in such a way a fractal nature, to the non-linear dynamics that has generated such statistical features in the systems behavior.

To give an example, SOC models indicate that the Gutenberg-Richter frequency-magnitude statistics for earthquakes are a combined effect of the geometrical (fractal) structure of the fault network and the nonlinear dynamics of seismicity. The application of NG methods is thus indispensable for extreme phenomena and new hazard assessment techniques (Rundle et al. (2003)).

According to this relatively recent geophysical trend, an attempt to investigate the physical information on the soil shaking features hidden in the seismic noise from NG point of view, has been included in the present Thesis. Such contribution can be divided into two papers, **P1** and **P2**, corresponding to the two adopted points of view: one based on numerical simulations aimed at reproducing physical behavior of some statistical quantity such as the decay of coherence versus distance of the wave propagation, and the other one based on data analysis of the actual ambient vibration records with the aim to investigate the scale invariant statistical properties characterizing seismic noise.

Within the previous discussed site effects framework, the NG approach has been adopted with the target first to quantify the degree of heterogeneity of the analyzed soils, and later to relate such degree of heterogeneity with the soil conditions.

In paper **P1** using a Monte Carlo method based on a random walk in ad hoc N-dimensional phase space, N random time series having prescribed coherence spatial decay have been generated. The method has been applied by designing a numerical experiment to investigate how the coherence of the bedrock motion relates to the coherence of the surface ground motion in a sedimentary valley. The main features of the coherence behavior in the valley are found to tie in with data analysis and field observations.

In respect of NG point of view, the paper **P1** represents the minimum expansion toward the stochastic side of a deterministic approach. In fact, the non-deterministic part of the wave propagation process, represented by the scattering, is seen as a perturbation (stochastic noise) to the pure deterministic crustal propagation.

Paper **P2** goes deeper inside the stochastic nature of the ambient vibration; the aim is to study physical information hidden in the seismic noise and how such information can be related to the soil conditions. The results have been

- seismic noise is neither white noise nor Brownian stochastic process;
- it is a self-similar (or fractal) stochastic process that can be described in terms of persistent fractional Brownian motion (fBm) having the Hausdorff exponent H grater then 0.5;

- a dependence of statistical features of the soil motion on the geological nature of the site has been shown to exists.

It is worth noticing that on the contrary of the deterministic approach, such results have been reached without need of any *a priori* hypothesis neither on the noise field nor on its spectrum.

4 Experimental approach

The evaluation of the characteristics of the strongest expected ground shaking for specific areas of the site under study is a basic tool for high-priority actions aimed at mitigating the seismic risk. This is particularly true in urban areas being these latter more safety demanding. Such target can be achieved through studies concerning the site effects. In studying site effects the so called *experimental approach* can not be disregarded. This latter consists in directly measuring the response of the site under study through records of both regional as well as local earthquakes. The analysis of such records allows to investigate the soil shaking features with the aim of understanding the observed damage pattern, often unexpected, at the surface.

As already mentioned, we have chosen as case study the city of Rome where we designed, planned and realized a 5-station 3D seismic array of seismic stations (Fig. 1).

The projects involved the installation of a permanent seismic array and a detailed classification of the physical and mechanical properties of the rocks constituting the geological subsoil of Rome, under both static and dynamic conditions. 1D numerical models of local seismic response to possible strong motion (PGA of up to 0.06g) in the city of Rome were performed. These models highlight the important role that an up to 60m-thick silty-clay sedimentary pack inside the Tiber alluvia can play in terms of ground motion amplification (see **P3** and **P4**). On the 6th April 2009 a damaging earthquake hit the town of L'Aquila, central Italy. Thanks to the aforementioned array, it was recorded with its moderate-magnitude sequence of aftershocks, at 100 Km far in the city of Rome with a satisfactory signal-to-noise ratio for all events with $Mw \geq 4$ (Fig. 1). Its magnitude was Mw 6.1.

Data recorded during the April 2009 seismic sequence are the first instrumental data ever recorded in the city of Rome by an array of seismic stations, that is why they yield an unprecedented information to assess ground motion local variations allowing us to check previous theoretical and numerical estimates of the seismic response of Rome adding new quantitative information on regional and local effects with important implications for a better constrained hazard assessment of the city.

In Chapter 4 two things are discussed based on the 2009 dataset:

- spatial variations of ground motion in Rome between closely located sites on Holocene vs Pleistocene sediments;

- comparisons with ground-motion predictions equations (GMPEs) based on larger Italian and global datasets.

The instrumental data recorded indicate that the contribution to response spectra at short ($T < 0.5s$) periods is smaller than expectations (Fig. 4) . In contrast, longer period excitation is strong, especially between 0.5 and 2 s of the radial component. The causative earthquakes of the April 2009 seismic sequence were characterized by shallow ($\sim$ 10 km) depths and normal-fault mechanisms (Herrmann et al. (2011)). Both the shallow depth and effects due to the crustal structure could contribute to such strong amplification of long periods. Unfortunately these two distinctive features are also expected for the strongest potential earthquakes in central Italy, and an amplification between 1 and 1.5 s could affect a large part of Rome. The effect could be particularly dangerous for modern zones grown in sedimentary areas where tall (around 10-storey) buildings predominate.

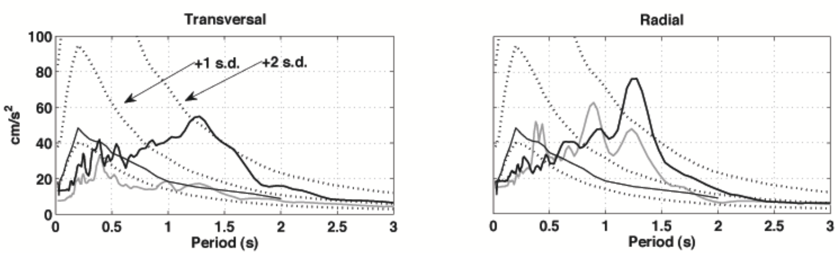

Figure 4: *Response spectra of the horizontal (radial and transversal) components: full black and gray curves are VSC and GRB, respectively. The thin black curve corresponds to the predictive equations by Bindi et al. (2009), in particular for the epicentral distance of 100 Km. The three dotted curves are predictions by Cauzzi and Faccioli (2008) for soft sites (average, average + 1 standard deviation, and average + 2 standard deviations).*

In the hazard practice, the expected spectral ordinates are conservatively incremented by + 1 standard deviation to assess hazard parameters. This increment is evidently too small: the April 2009 data show that even 2 standard deviations could be not conservative enough for Rome. A specifically determined increment is mandatory for the hazard assessment of the city.

5 Numerical simulation approach

Site effects can be studied using the data recorded during an earthquake but because it would be useful to know the site characteristics of ground motion before an earthquake occurs, numerical modelling seems to be a useful method. This is particularly true in urban areas for planning actions aimed, among others, at mitigating the seismic risk.

All numerical simulations concerning the city of Rome are lacking of knowledge concerning both the detailed near-surface geology and its geotechnical properties. Moreover, neither regional nor local events were recorded by seismic stations within Rome. Thanks to the already mentioned two multidisciplinary research projects (FIRB 2002-2005 and COFIN 2004-2005), data recorded in the city (l'Aquila 6th April 2009 sequence) are now available as well as detailed near-surface geology coupled with its geotechnical properties (see **P3** and **P4**). Such knowledge allows us not only to make more realistic numerical simulations using both detailed surface geology and actual elastic and inelastic parameters, but also to tune simulations of the soil shaking in order to better assess strong ground motion features through the whole city as well as estimating parameters of engineering interest such as peak ground acceleration and velocity, Arias Intensity, response spectra, etc.

Our first aim is to numerically reproduce the main features of the the spectral ratio content of soft/stiff, soft/bedrock and stiff/bedrock soils, i.e., VSC/GRB, VSC/BHR and GRB/BHR, respectively. For such purpose we do not need a subsurface model of the whole city, a model of near-surface geology of Valco S. Paolo zone (Fig. 5), where the array is located, is enough.

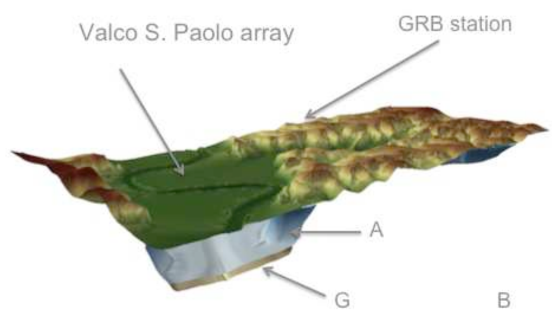

Figure 5: *Near-surface geological structure of Valco S. Paolo site used in numerical simulations. G is gravel layer, A is alluvium layer, B is bedrock (semi-space). Topography is from satellite Digital Elevation Model (DEM). Position of seismic array where both BHR and VSC stations are located, is shown. BHR is the borehole sensor below VCS the surface one. GRB reference seismic station position is shown as well.*

For the purpose of our study, we adopted the serial code of Opršal et al. (2005). Even though it is based on a hybrid technique saving a big amount of computational time and memory, it is not enough to simulate big size domains and high frequencies (3-4 Hz). Indeed, the great drawback when modeling more realistic site dynamics is the impressive computational requirements needed for numerical simulations; gigabytes of memory and gigaflop performance rates, combined with days of computational time to simulate a minute of soil shaking etc. Seismologists are being addressing these issues since nineteens (see Olsen and Archuleta (1996); Bao et al. (1996) among others), through the use of parallel computers.

That is why we require to adopt the parallel computing in which more multiprocessors machines work at the same time and on the same program to both increase the amount of memory available and speed-up the results. To use parallel computing a parallel code is needed. Paper **P5** is devoted to the parallelisation of the Opršal et al. (2005) code. Moreover, it is explained why we have chosen to parallelise a serial code in place of writing another one parallel in a *native form,* and are also discussed limitations that are ever present whatever will be the approach chosen for parallelising a serial code.

Using the parallel code illustrated in paper **P5**, numerically simulated the soil shaking of the Valco San Paolo portion of the Tiber valley, shown in Fig. 5, where the 3D seismic array is located. Synthetic seismograms were extracted for the grid points corresponding to the VSC, BHR and GRB stations.

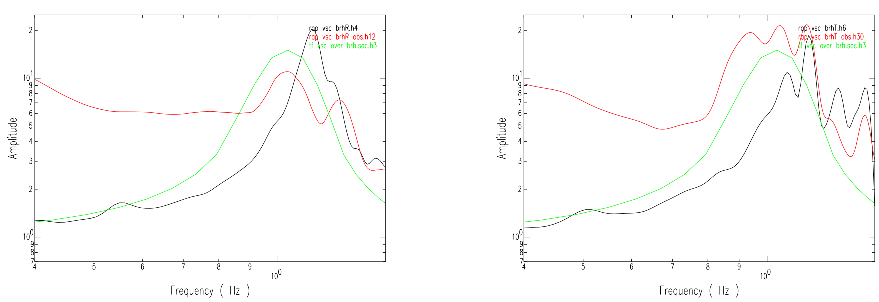

Figure 6: *Observed (red curves) and simulated (black curves) VSC/BRH ratios of FAS for the R component (left panel) and T component (right panel). The green curve represents the theoretical ratio for 1D model and the plane-wave excitation. The part of red curve between 0.4 and 0.7 Hz is not usable being the borehole sensor the 1Hz one.*

In Fig. 6 the observed and 3D simulated VSC/BRH spectral ratios of FAS are shown for both radial (R) and transversal (T) component. The theoretical ratio for the 1D model of the plane-wave excitation is shown as well. A good agreement at high frequencies ($> 1Hz$) between the simulated and observed ratios for the T and R component can be recognized. The agreement between 0.8 Hz and 1.Hz is worse, and at frequencies f $<$ 0.8 Hz the comparison cannot be performed because the BRH record seems not reliable due to instrumental reasons (the observed ratio does not approach value of 1 as frequency decreases). he fact that around 1 Hz the VSC/BRH

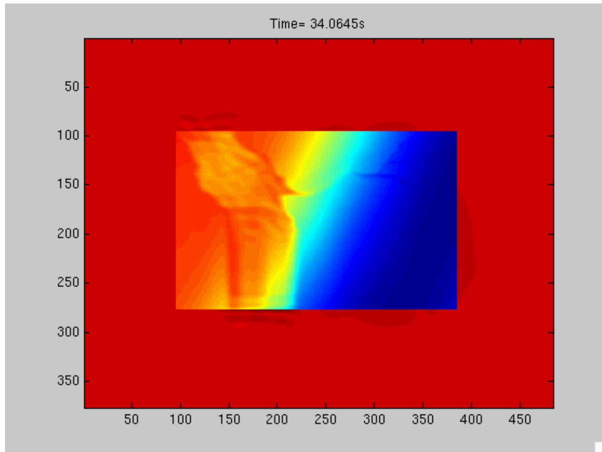

Figure 7: *Snapshot, from movie in the attached CD, of the soil displacement on the Tiber valley's surface. The darker is the red color and the higher is the displacement amplitude. The darker red is mainly localized at the edges of the basin. Note that the vertical axis is reversed.*

ratio is fitted for both R and T, while VSC/GRB only for the T component seems to be due to the fact that the observed difference between VSC and BRH is mainly due to 1D local structure, i.e. possible 3D effects are almost the same at both the surface and the borehole station. When comparing VSC and GRB, the true 3D structure and our ability/inability to model it plays a more significant role. While the amplification around 1 Hz is mostly due to 1D structure, above 1Hz the 3D effect become probably more important, mainly at the edges of the valley.

This is better visualized by the snapshot in Fig. 7 where is clearly seen the role played by lateral heterogeneities of the Tiber basin edges in amplifying the soil shaking. For more details see in the attached CD the full animation of the soil shaking in the Tiber valley. The calculations will be extended to 3Hz and realist time function, thus allowing a more detailed discussion.

Such a simulation has to be seen as a preliminary example of the first results of the 3D soil shaking simulations analysis. In fact, test calculations of Chapter 4 arrive up to 1.5 Hz. Extension to 3 Hz and a paper concerning the comparison between the L'Aquila data and simulations is under preparation.

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