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SEISMIC RESPONSE OF THE GEOLOGICALLY COMPLEX ALLUVIAL VALLEY AT THE "EUROPARCO BUSINESS PARK" (ROME – ITALY) THROUGH INSTRUMENTAL RECORDS AND NUMERICAL MODELLING

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EXTENDED ABSTRACT

Questo studio ha come obiettivo l'analisi di risposta sismica locale della valle del Fosso di Vallerano, un bacino alluvionale situato a sud del centro storico città di Roma in corrispondenza del quartiere EUR-Torrino. A supporto di questa analisi è stata condotta una ricostruzione geologica ad alta risoluzione dell'area in esame, che interpreta la complessa combinazione di processi glacio-eustatici, sedimentari, tettonici e vulcanici che hanno interessato l'area dell'attuale città di Roma. La successione stratigrafica risultante dalla correlazione di 250 sondaggi geognostici comprende depositi derivanti da condizioni sedimentarie differenziate in relazione alla evoluzione paleogeografica dell'area romana dal Pliocene fino all'attuale. In particolare, sono state individuate quattro unità geologiche:

- depositi sedimentari marini plio-pleistocenici (ascrivibili alle Formazione delle Marne Vaticane, di Monte Mario e di Monte delle Piche) che rappresentano il substrato geologico dell'area;
- sedimenti alluvionali pleistocenici depositati dal Paleo Tevere 4 (ascrivibili alla Formazione di Santa Cecilia, 650-600 ka);
- depositi vulcanici eruttati dai Distretti Vulcanici dei Colli Albani e dei Monti Sabatini (561-360 ka);
- depositi alluvionali recenti che hanno riempito le incisioni vallive dalla fine della regressione Würmiana fino all'attuale (18 ka-Presente).

Le suddette unità litologiche hanno reso possibile la calibrazione di una sismo-stratigrafia tramite modellazioni numeriche 1D che si sono avvalse di: i) 55 misure di rumore (*noise*) sismico ambientale; ii) 10 registrazioni di *weak motions* ottenute tramite una rete velocimetrica attiva nell'area nel 2009 e corrispondenti alla coda della sequenza sismica de L'Aquila-Gran Sasso, iii) un'indagine *cross-hole*.

In base a tale calibrazione, il *bedrock* sismico è risultato localizzato al tetto delle ghiaie basali della Formazione di Santa Cecilia e non corrisponde al substrato geologico dell'area (depositi sedimentari marini plio-pleistocenici). La sismo-stratigrafia così ottenuta è stata estrapolata all'intera valle e sono state ottenute le funzioni di amplificazione 1D, assumendo che sia un comportamento elastico lineare che uno non lineare per i depositi trattati. A tal fine, sono state simulate tre sezioni geologiche trasversali e caratteristiche dell'assetto locale della valle in quanto contraddistinguono (spostandosi da SE verso NW): i) un sistema alluvionale caratterizzato da due valli che corrisponde a due valli dal punto di vista topografico, ii) un sistema alluvionale caratterizzato da due valli che corrisponde ad un'unica valle dal punto di vista topografico, iii) un sistema alluvionale caratterizzato da una singola valle corrispondente ad un'unica valle dal punto di vista topografico.

I risultati della modellazione numerica mostrano come il Fosso di Vallerano sia caratterizzato da un primo modo di risonanza (a circa 0.8 Hz) e da numerosi modi superiori a frequenze localmente dipendenti dell'assetto geologico del corpo alluvionale. Gli effetti non lineari sono stati modellati applicando, come sollecitazione al modello 1D, i terremoti di riferimento (*strong motion*) previsti dalla normativa regionale attualmente vigente (D.G.R. Lazio 387/09).

I risultati numerici mostrano una tendenziale riduzione sia della posizione in frequenza dei modi di risonanza (fino ad un massimo di 0.5 Hz in meno su ogni valore di picco) che dell'ampiezza dell'amplificazione a frequenze maggiori di 7 Hz.

Considerando i rapporti di forma (*sensu* Bard & Bouchon, 1985) ed i valori di contrasto di impedenza tra i depositi alluvionali ed il *bedrock* sismico del Fosso di Vallerano, nella valle è attesa una risposta di tipo 1D con generazione di onde laterali dai bordi (1D+*lateral waves*). Inoltre, è ragionevole assumere che la risposta sismica sia influenzata sia da effetti deformativi cosismici dovuti alla natura eterogenea del corpo alluvionale (Martino *et alii*, 2015) che da effetti legati alla presenza dell'agglomerato urbano che interagisce con il suolo (Kham *et alii*, 2006; Semblat *et alii*, 2009). Alla luce di queste considerazioni, saranno in futuro condotte simulazioni 2D al fine di valutare il ruolo delle deformazioni cosismiche del terreno e del complesso urbano su esso edificato sulla risposta sismica locale.

ABSTRACT

The analysis of the local seismic response in the "Europarco Business Park", a recently urbanized district of Rome (Italy) developed over the alluvial valley of the "Fosso di Vallerano" stream, is here presented. A high-resolution geological model, reconstructed over 250 borehole log-stratigraphies, shows a complex and heterogeneous setting of both the local Plio-Pleistocene substratum and the Holocene alluvia. The local seismo-stratigraphy is derived by a calibration process performed through 1D numerical modelling, accounting for: i) 55 noise measurements, ii) 10 weak motion records obtained through a temporary velocimetric array during the August 2009 L'Aquila-Gran Sasso seismic sequence and iii) one cross-hole test available from technical report. Based on the reconstructed seismo-stratigraphy, the local seismic bedrock is placed at the top of a gravel layer that is part of the Pleistocene deposits and it does not correspond to the local geological bedrock represented by Plio-Pleistocene marine deposits. 1D amplification functions were derived via numerical modelling along three representative sections that show how in the Fosso di Vallerano area two valleys converge into a single one moving from SE toward NW. The obtained results reveal a main resonance at low frequency (about 0.8 Hz) and several higher resonance modes, related to the local geological setting. Nonlinear effects are also modelled by using strong motion inputs from the official regional dataset and pointed out a general down-shift (up to 0.5 Hz) of the principal modes of resonance as well as an amplitude reduction of the amplification function at frequencies higher than 7 Hz.

Keywords: *local seismic response, engineering-geological model, seismic measurements, numerical modelling, recently urbanised area, Rome*

INTRODUCTION

Moderate to severe damages were historically recorded in Rome urban area (Italy) as a consequence of strong earthquakes originated in two seismogenetic zones close to the city: the Alban Hills volcanic area and the Central Apennines orogenic belt (Fig. 1) (Molin *et alii*, 1986). This was the recent case of the seismic sequence of L'Aquila (Central Apennine) that started with the 6th April 2009 Mw 6.3 main shock, about 150 km NE of Rome (Fig. 1).

Several studies have been focused so far on the local seismic response in the Rome urban area (Rovelli *et alii*, 1994, 1995; Bozzano *et alii*, 2008 ; Bozzano *et alii*, 2012; Caserta *et alii*, 2012; Martino *et alii*, 2015). These studies pointed out that the heterogeneous composition of the alluvial deposits of the Tiber River and its tributaries is responsible for both 1D amplification effects, mainly related to soil stratigraphy, and 2D amplification effects that can be related to wave refraction at the edge of the valley as well as the lateral heterogeneities (Martino *et alii*, 2015). The here considered case study is located in the Fosso di Vallerano valley, about 10 km SE of the historical centre of Rome that corresponds to a recently urbanized area which hosts the "Europarco Business Park" with the highest building-towers in the city (Fig. 2a).

The Fosso di Vallerano valley hosts two left tributaries of the Tiber River (the Vallerano and the Cecchignola creeks); it is characterized by a flat portion corresponding to flood plains (10 m a.s.l.) bordered by hills (35-50 m a.s.l) (Fig. 2b, 2c). The area shows a complex geomorphological evolution due to the Würmian glacio-eustatic cycle that led to a series of successive deviations and rearrangement of the river bed (Ascani *et alii*, 2008). A high-resolution geological model was reconstructed on the basis of several tens of borehole logs, available from site investigations. Moreover, a temporary seismometric array was installed during the summer 2009 to record the aftershocks of the L'Aquila seismic sequence. A convergence process between data from seismometric records and results of a 1D numerical modelling was performed to provide the best fit in terms of amplification functions. Such a process aimed at evaluating the influence of the subsoil composition on the local seismic response and to output the 1D seismic response along a cross section passing from the "Europarco Business Park". Due to the scarcity of seismic records in the city of Rome, the here presented

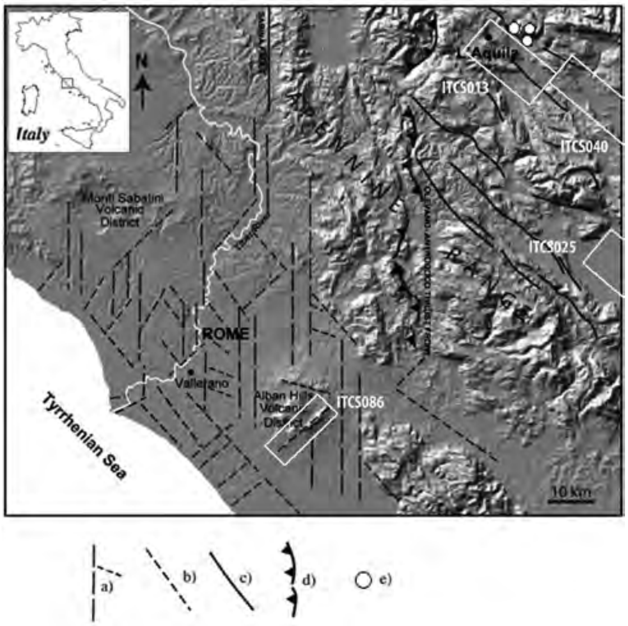

Fig. 1 - Structural map of the Central Apennines including the area of Rome. a) Main N-S faults and conjugated fault systems; b) buried faults linked to the extensional tectonic regime c) Seismogenetic faults; d) inactive thrust fronts; e) location of the 9th April 2009 L'Aquila earthquake (Mw 6.3) epicentre. The individual seismogenetic sources (white bordered rectangles) and related labels are also reported from the DISS 3.1.1. catalogue

experimental study can be regarded as a significant contribution to the local seismic response. This study lays also the foundations for future studies focusing on the "Site-City Interaction" (Kham *et alii*, 2006; Semblat *et alii*, 2009) to assess the influence of urban agglomerates on the local seismic response. In this perspective, the availability of geophysical data recorded before the strong urban development of the "Europarco Business Park", can provide an important contribution to the evaluation of the progressive influence of the buildings on the seismic response.

GEOLOGICAL SETTING

The geological bedrock of the Rome urban area is constituted of clay to sand deposits ascribable to three main sedimentary cycles corresponding to marine transgressions (Marra, 1993; Marra & Rosa, 1995) that follow the continentalization of the area, during Middle-Upper Pleistocene, and were controlled by several factors including tectonic (Faccenna *et alii*, 1994a, b; Marra, 1999, 2001; Hearty & Dai Pra, 1986; Karner *et alii*, 2001a), eustatism and fluvial evolution (e.g.: Karner & Marra 1998; Marra *et alii*, 2008). Moreover, part of the geological bedrock outcropping in the Fosso di Vallerano area (Fig. 6) is constituted by volcano deposits ascribable to the activity of the Volcanic Districts surrounding the city (Karner *et alii*, 2001b; Giordano *et alii*, 2006; Marra *et alii*, 2009; 2014; Sottili *et alii*, 2010, Marra *et alii*, 2014). As it regards the sedimentary deposition, a first cycle is associated to the Marne Vaticane Formation (Pliocene-Early Pleistocene, Marra *et alii*, 1995) which constitutes the geological bedrock of the Tiber alluvia body. Nonetheless, previous studies referred to the historical centre of Rome (Bozzano *et alii*, 2008; Caserta *et alii*, 2013) demonstrated that it does not generally correspond to the seismic bedrock, as it results at the top of the coarse grained deposits at the basis of the most recent Tiber River alluvial deposits.

The second and third marine cycles correspond to the deposition of the marine to continental sediments outcropping in the north-western area of Rome (Monte Mario hill) and include the Limi di Farneto unit, the Monte Mario, Monte delle Piche, Monte Ciocci Formations (Bonadonna, 1968; Cosentino *et alii*, 2008; Marra, 1993; Bergamin *et alii*, 2000).

More in particular, the Monte Ciocci Formation is ascribable to paleo-river deposits (Paleo-Tiber 1 in Fig. 3) and it is followed by three other Paleo-Tiber depositional units (Paleo-Tiber 2-4), among which the Paleo-Tiber 4 only is recognizable in the Fosso di Vallerano valley. These deposits are strictly related to the glacial-eustatic sea oscillations (Karner & Marra, 1998; Marra *et alii*, 1998; Karner *et alii*, 2001a; Florindo *et alii*, 2007; Marra *et alii*, 2008; Marra & Florindo, 2014; Marra *et alii*, 2015) as shown by several studies carried out by integrating stratigraphical, geochronological and paleomagnetical data. These studies led to the identification of 10 aggradational successions which correspond to as many glacial terminations, encompassing Marine Isotopic Stage (MIS) 22/21 through 2/1 (Fig. 3).

Fig. 2 - a) Photo view of the two "Europarco Business Park" towers during their construction in 2012 from the Laurentina Vetus archaeological site, located immediately SW of the Fosso di Vallerano river valley (left) and actual view of the towers from the terrace of Euroma2 shopping centre (right); b) satellite views of the "Fosso di Vallerano" area from SE (left) and E (right); c) panoramic photo-view of the Torrino hill

These successions are generally fining-upward (Karner & Marra, 1998), with coarse-grained gravel and sand, up to 10 m in thickness, at the base of each section. The basal coarse-grained deposits are followed by a relatively thin sand horizon, which grades upward into a several meter thick pack of silt and clay. In the older deposits, related to the Marine Isotopic Stages (MIS) 21 through 15, clays reached a moderate thickness (<10 m), probably as a consequence of the smaller sea level oscillations associated to these early glacial cycles (Karner *et alii*, 2001a). On the contrary, a significant increase of clay thickness is observed in the later successions, up to that of the modern Tiber River, which reaches 70 m within the present-day coastal plain (Marra *et alii*, 2008, 2013).

AVAILABLE DATA

To construct a high resolution engineering-geological model of the Fosso di Vallerano valley borehole log stratigraphies as well as data from geophysical investigations were taken into account. More in particular, 250 boreholes (Fig. 4) distributed over an area of about 25 km^2, one cross-hole test, log-stratigraphies and expeditious geomechanical on-site investigations (Pocket-Penetrometer and Pocket Vane-test) were available from technical reports and official archieves of the study area (Bozzano *et alii*, 2000; Ventriglia, 2002). Moreover, specific seismometric records were collected from 2009 until 2014 consisting in seismic noise measurements. A velocimetric temporary array was also installed in summer 2009 to record weak-motion events during the tail of L'Aquila seismic sequence.

Borehole data

The aggradational successions deposited by the Paleo-Tiber River and its tributaries in the area of Rome result in the filling of a complex, laterally discontinuous network of paleo-river valleys incised in the marine deposits. Each succession is substantially characterized by a lateral homogeneity, with a coarse gravel horizon at its base, grading upward into sand, silt and clay layers. However, this upper, finer portion of the sedimentary pack is characterized by diffused lateral variation of the lithological features, due to the fluvial sedimentary conditions that cause the juxtaposition of lenticular bodies of sand, clay and peat.

A high-resolution geological model was requested to represent such a complex geological framework.

At the time of this study, no more reliable geophysical investigations or boreholes could be performed except for single-station noise measurements because of the intense urbanisation of the area and consequent disturbance.

Seismometric measurements

From 2009 until 2014 five ambient noise surveys were carried out in the Fosso di Vallerano valley, using three different triaxial velocimetric stations, for a total of 56 measurements. The first survey was performed by a 4Hz digital tromometer TROMINO (Micromed) set to a 128 Hz sampling frequency that acquired noise samples 20 minutes long in different hours of the day. Since 2012 four further surveys were realized by a 1.4 Hz SL06 acquisition system (SARA Instruments) set to a 200 Hz sampling frequency and a LENNARTZ LE3D/5s sensor coupled with a REFTEK 130 digitizer set to a 250 Hz sampling frequency. Noise samples from 45 minutes to 2 hours long were acquired in different hours of the day; given the short distance among the measure sites (less than 500 m), repeated recordings in the same site were performed only in case of ambiguous data or results inconsistent with the one obtained in the neighbouring sites.

The records, sampled with a 40 s moving time window, were de-trended, tapered, converted to the frequency domain and smoothed by a Konno-Ohmachi function (b=40) to get average HVSR (Horizontal to Vertical Spectral Ratio) according to Nakamura (1989). Especially in 1D condition, HVSR peaks of significant level (>2 according to SESAME, 2004) can point out frequencies which are amplified by the local geological condition.

The ambient noise analysis (Fig. 5) shows a homogeneous

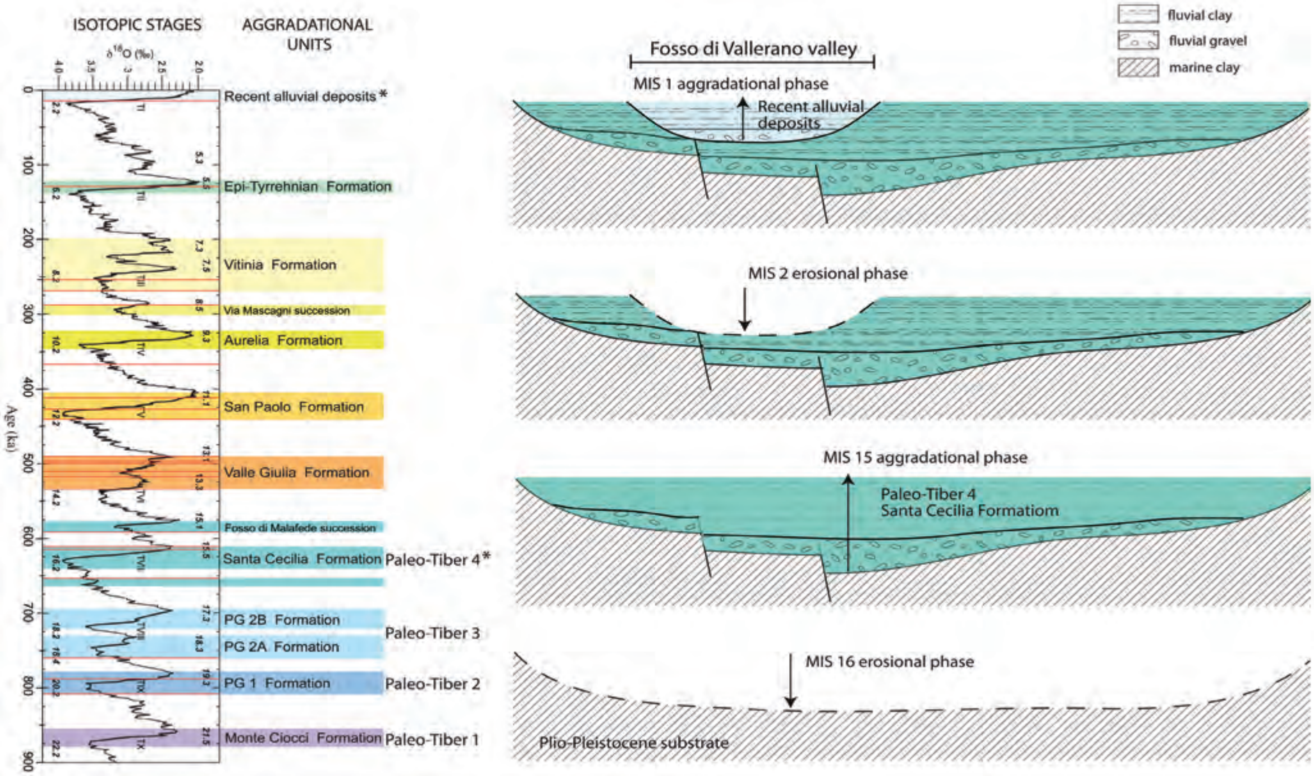

Fig. 3 - *Left column: $\delta^{18}O$‰ vs. time for the depositional units by the Paleo-Tiber River and its tributaries. The Marine Isotopic Stages (MIS) are also reported (Arabic numbers within the graph); the stars highlight the deposits of the Fosso di Vallerano area. Right column: sketch illustrating the Fosso di Vallerano valley evolution since 900 ka to present (colours correspond to the graph of the left column).*

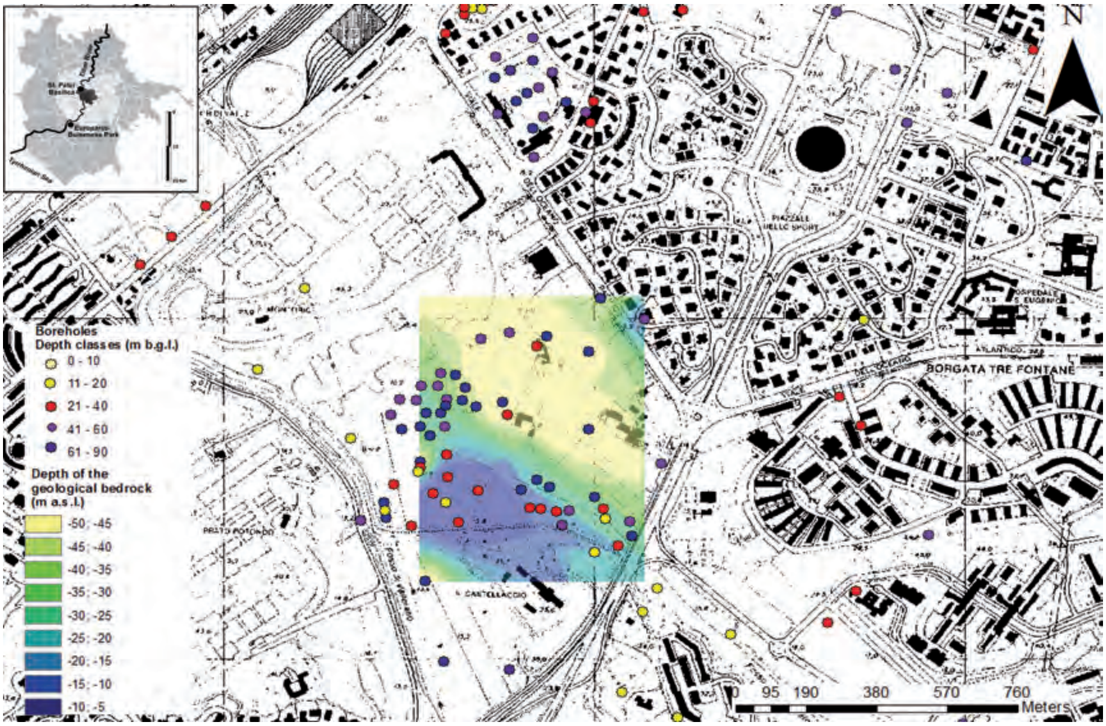

Fig. 4 - CTR (Regional technical Map) scale 10.000 - Location of the boreholes considered for the reconstruction of the high-resolution geological setting. Contour (in colours) of the bedrock depth obtained through interpolation of the available borehole data.

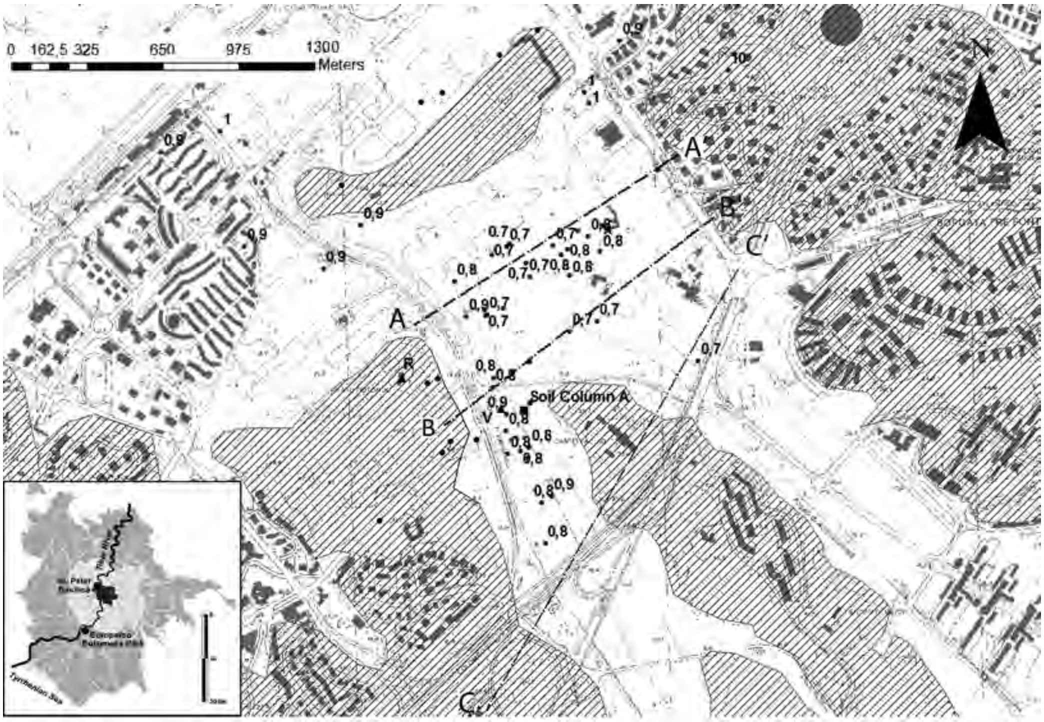

Fig. 5 - CTR (Regional technical Map) scale 10.000 – Black points indicate the location of the ambient noise recording station (the fundamental resonance frequency is also reported); black triangles indicate the velocimetric array; the black square corresponds to the position of the calibration Soil Column A. The traces of the three geological cross-sections AA', BB' and CC' are also reported; the outcropping seismic bedrock corresponds to the screened areas

Fig. 6 - a) Photo view of the outcropping seismic bedrock composed of volcanic deposits; b) seismometric array: V station (left), R station (right)

response of the valley with a fundamental resonance frequency of 0.8±0.1 Hz, instead, the surrounding reliefs show no significant resonance peaks of the HVSR functions.

From June until July 2009 a free-field seismometric array operated in STA/LTA (Short Time Average to Long Time Average) acquisition mode in the Fosso di Vallerano valley, in order to record weak-motion events during the tail of L'Aquila seismic sequence and therefore compare such results to the ones obtained from noise analysis. The array (Fig. 5) was composed of two stations (Fig. 6), whose location was selected taking into account both the noise survey results and the requirement of identifying low noise, free-field spots in an urbanized area. Each station was instrumented by three single components, 1 Hz velocimeters (SS1 Kinematrics) triaxially arranged, connected to a 24 bit data logger (K2 Kinematrics) and a GPS device for absolute timing. One station (V) was located on the alluvial deposits, in the NE sector of the valley, while a reference (R)

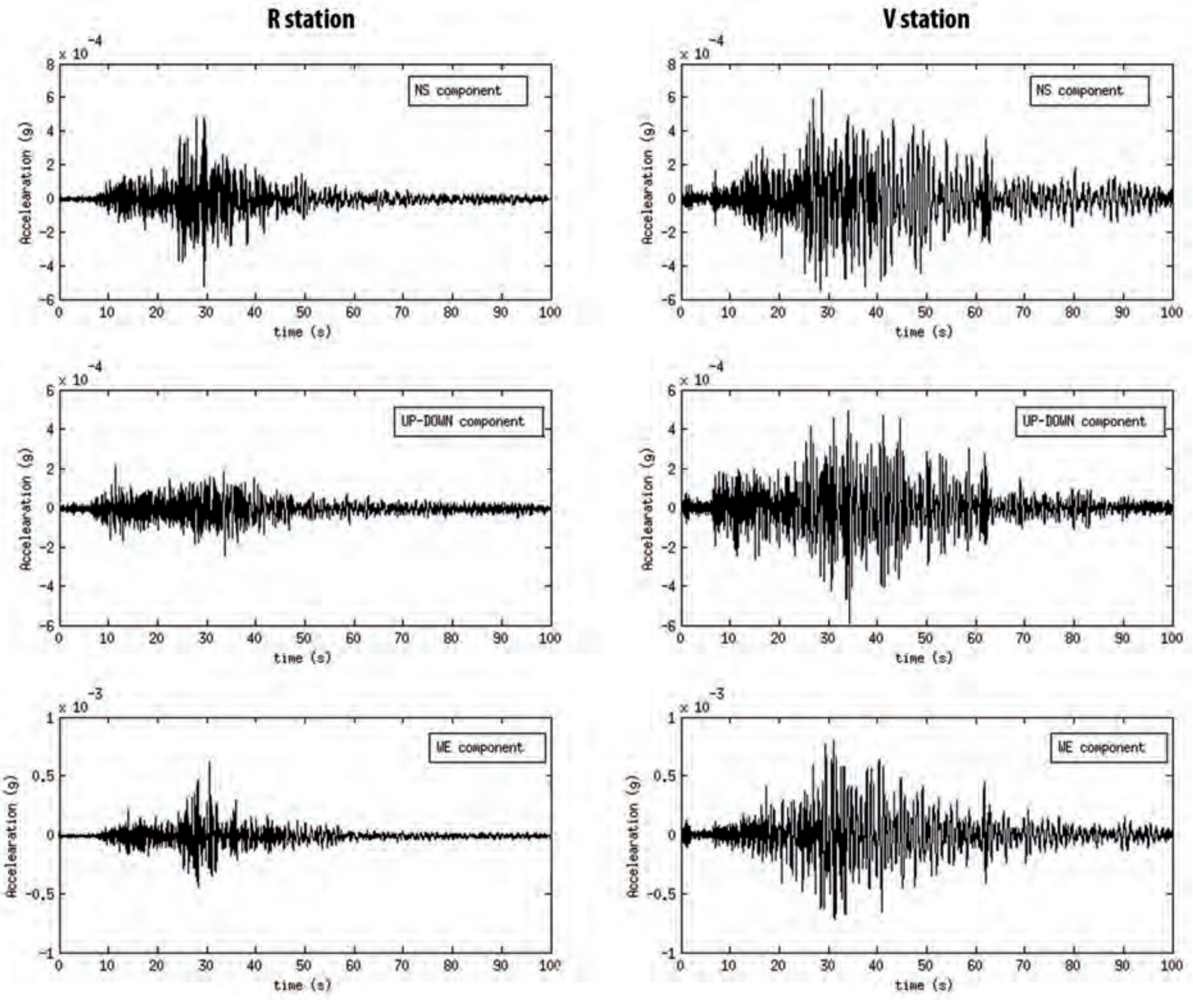

Fig. 7 - Comparison between the three-component accelerograms recorded in R (left) and V (right) stations for the earthquake EQ-12 of Tab. 1

station (*sensu* Borcherdt, 1994) was placed on the local seismic bedrock, corresponding to the volcanic hills that border the valley (i.e. where no evidence of amplification was pointed out by noise analysis). It's worth noticing that this seismic bedrock does not coincide with the one existing below the alluvial deposits. The seismometric array recorded overall about 30 earthquakes (an example is shown in Fig. 7) in the magnitude range 2.6-4.6, from Database of Individual Seismogenic Sources (DISS 3.1., Working Group 2010 - ITCS028, ITCS013, ITDS073, ITDS072).

In the present study 10 records only (Tab. 1) were considered as they do not show disturbances due to human activities. A 5% cosine-taper window starting 1 s before the P-phase onset was applied to the earthquake records to obtain signals with duration of 90 s; the signals were pass-band filtered in the frequency range 0,2- 20 Hz and converted to the frequency domain. The smoothed spectra were used to achieve both the average Receiver Functions (RF) (Lermo *et alii*, 1993) and the average Standard Spectral Ratio (SSR) at site, computed from the spectral ratios of the horizontal components recorded for each event in the alluvial valley to the equivalent components recorded at the reference site (Borcherdt, 1994). The obtained results proved the high quality of the reference site, since no significant amplification effect was pointed out by RFs; on the contrary, both the RF and the SSR function derived for V station show a well-defined peak at 0.8 Hz, in agreement with noise analysis results.

METHODS

Geological model

Based on the boreholes data, 5 main litho-stratigraphic groups were distinguished:

- Plio-Pleistocene Marine sediments (Marne Vaticane, Monte Mario e Monte Ciocci/dellePiche Formations) that represent the geological bedrock of the area (PP);
- Pleistocene alluvial sediments deposited by the Paleo-Tiber 4 River (Santa Cecilia Formation; MIS 15; 650-600 ka; Marra and Florindo 2014) (PT);
- Volcanic deposits erupted from the Alban Hills and the Monti Sabatini Volcanic District (561-365 ka; Karner *et alii*, 2001b) (VL);
- Pre – würmian fluvio-palustrine deposits (Valle Giulia - San Paolo – Aurelia and Vitinia Formation; 500-200 ka; Karner & Marra, 1998) (FP);
- Recent alluvial deposits filling the valley incisions since the end of the Würmian regression to the present (MIS 1;18ka-Present; Marra *et alii*, 2013) (AL);

Seven geological sections (three of them reported in Fig. 8) were realized by cross-correlating 250 boreholes and were taken into account for reconstructing a 3D geological model of the Fosso di Vallerano area. The main outcome from such a 3D model consists in the evidence of a highly heterogeneous alluvial filling that is characterized by both vertical and lateral lithotechnical contacts (Fig. 8-9). This complexity can be ascribed to the combined effect of both a major Middle Pleistocene sin-sedimentary tectonic and the intervening erosive processes.

Based on the reconstructed 3D geological model (Fig. 9), the geological bedrock of the most recent alluvial deposits of the post-würmian aggradational cycle (AL) is represented by the fluvial-lacustrine deposits of the Paleo-Tiber 4 unit (PT-Santa Cecilia Formation; MIS 15), unlike the main Tiber Valley (Bozzano *et alii*, 2008) and other tributary valleys (Caserta *et alii*, 2012) where it is represented by the consolidated clays of the Plio-Pleistocene Monte Vaticano Formation.

More in particular, intense erosive processes occurred during the last würmian glacial period due to the similar combined effect of both the regional uplift (Hearty & Dai Pra, 1986; Karner *et alii*, 2001a) and the eustatic low-stand; the erosive processes originated deep fluvial incisions that were filled, during the post-würmian eustatic rise, by the recent alluvial deposits. These recent sediments (AL) are characterized by remarkable vertical and lateral heterogeneities, originated by the coupled processes of alluvation and colluvation, as well as by possible, secondary sin-sedimentary tectonic activity (Fig. 8).

A more detailed stratigraphic analysis highlighted the presence of peaty clay and peat deposits that fill most of the valley and reach a thickness of 45 m.

Based on the aforementioned 3D model and considering the vertical stratigraphy as a time depositional sequence, more recent from the bottom to the top, the peaty and peaty-clay deposits indicate that, during the Holocene, the alluvial valley was mostly characterised by a low energy hydrographic regime, characterized by the presence of stagnant water, causing the emplacement of abundant organic matter. At the same time, the north western part of the valley was characterized by low-energy environment responsible for the deposition of clays without organic matter, so suggesting a more straightforward lacustrine conditions, that hindered the formation of peat. Active subsidence in this sector, linked to weak tectonics that reactivated the faults dislocating the Paleo-Tiber 4 deposits, may explain the deposition of the lacustrine clay as well as the capture of the river bed north of the Montorio Hill, as highlighted by Ascani *et alii* (2008).

The more recent clayey-sandy deposits are characterized by a marked volcanic component originated by erosive processes that involved the outcropping volcanic deposits. Fans composed by Paleo-Tiber 4 basal deposits, due to slope denudation processes involving the flanks of the valley are interlayered by lateral unconformities with the clays and peaty-clays. The so resulting alluvial fill is characterised by a significant lithological heterogeneity due to the presence of lens- to the disc-like depositional bodies.

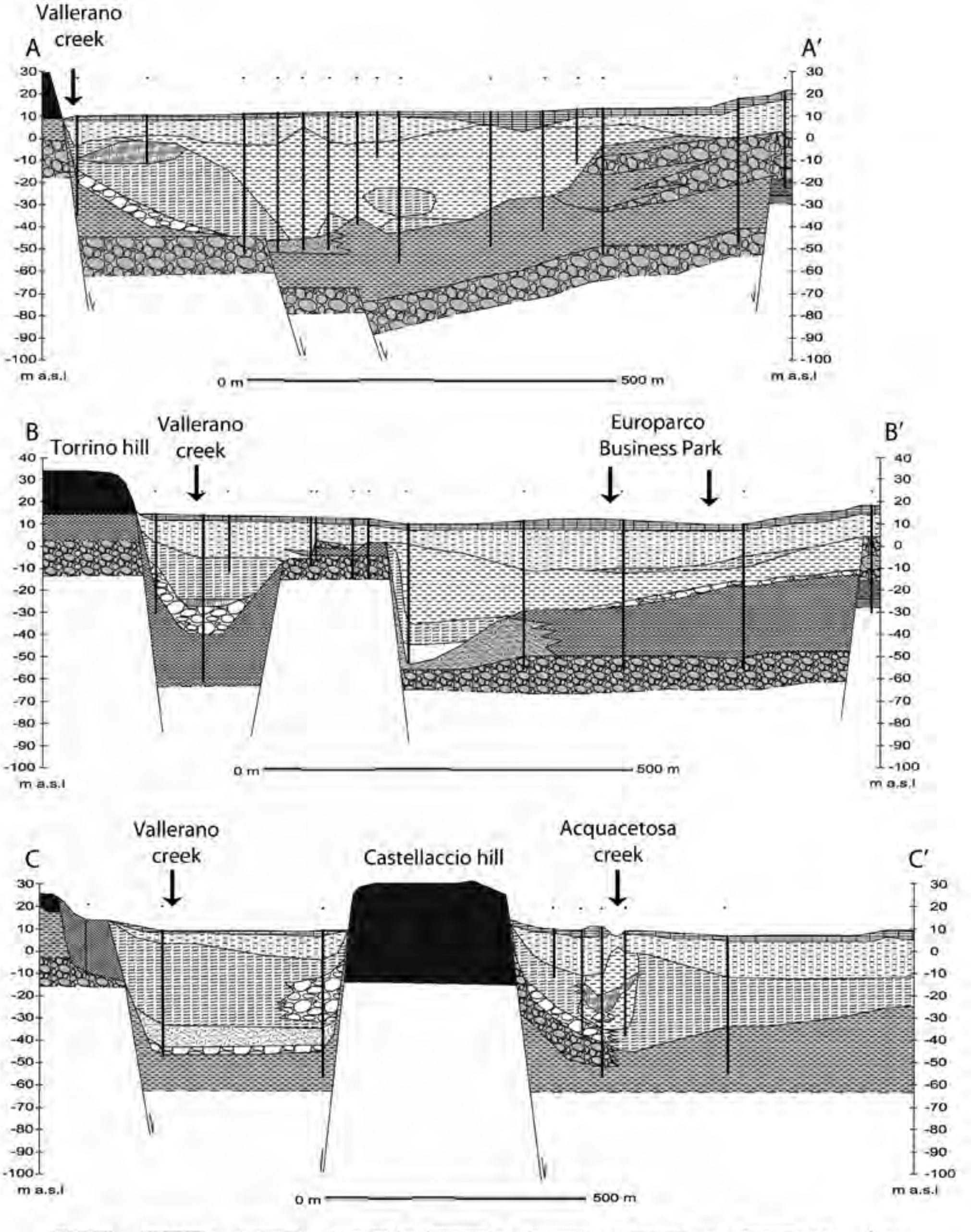

Fig. 8 - Geological cross sections along the AA', BB', CC' traces of Fig. 5 Legend: Recent alluvial deposits (18 ka-present): 1) Anthropic filling material (AL-AF); 2) Sandy-Clays characterized by a marked volcanic component (AL-VSC); 3) Peaty clays, plastic (AL-PC); 4) Clays and silts, plastic (AL-CS); 5) Peat (AL-PT); 6) Sands and silty sands, sometimes containing gravel polygenic (AL-SD); 7) Polygenic, loose and heterometric gravels, with volcanic and sedimentary components (AL-GR). Volcanic deposits from the District of Alban Hills and the M. Sabatini 561-360 ka (Marra et al.,2009): 8) Undifferentiated pyroclastic material (VC). Pre-wurmian deposits (Valle Giulia – San Paolo – Aurelia – Vitinia Formations): 9) Fluvio-palustrine deposits composed of loose gravels, sands and silts. Paleo-Tiber 4 deposits (Santa Cecilia Formation) 650-600 ka (Karner&Marra 1998 - Florindo et al., 2007): 10) Sandy clays and silts, sometimes with freshwater gastropods (PT-SC) 11). Clays and silts with peaty layers (PT-CL); 12) Sands and silty sands. (PT-SD); 13) Loose gravels with heterometric sedimentary components (PT-GR). Plio-Pleistocenic bedrock (Marne Vaticane - Monte Mario - Monte delle Piche Formation) (Marra, 1993 - Marra et al., 1995): 14) Marine clays and silty clays; 15) Marine sands and silty sands. 16) Fault. 17) Borehole

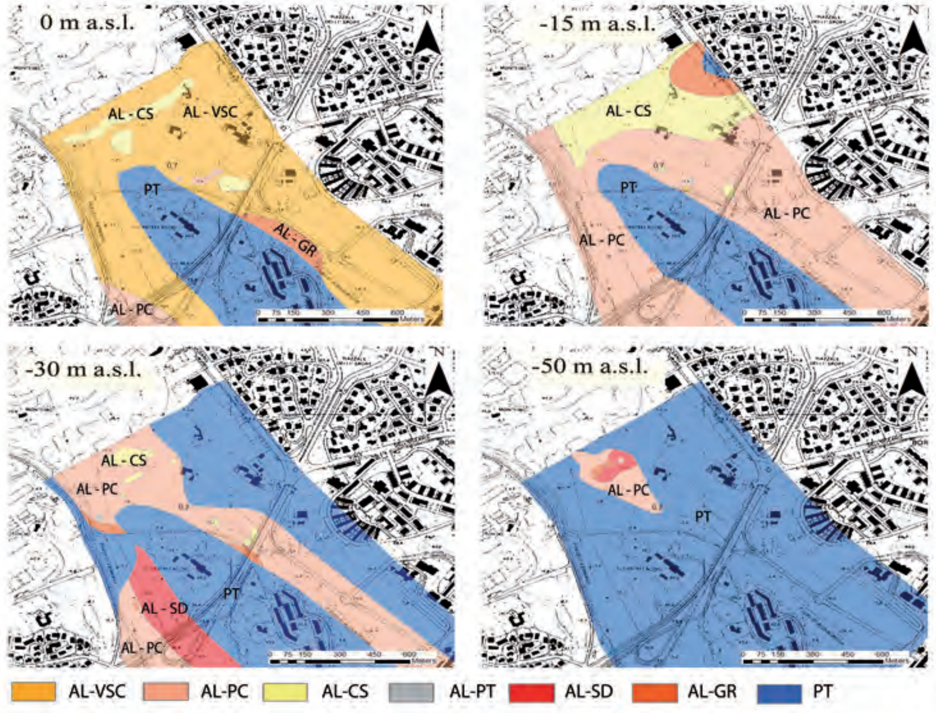

Fig. 9 - 2D planar restitution of the high resolution 3D geological model of the Fosso di Vallerano valley referred to different depths a.s.l.. See Tab. 2 for key to legend

Date	*Time*	*Epicentral coordinate*		*Magnitude*	*Seismic district*	*DISS source*	*Epicentral distance*	*V station*	*R station*	*Event code*
	UTC	*Latitude*	*Longitude*	*Ml*			*km*			
22-Jun-09	20:58:40	42 446	13 256	4.6	Gran Sasso	ITCS013	100	x	x	EQ-6
23-Jun-09	00:41:56	42 441	13 369	4.0	Gran Sasso	ITCS073	110	x	x	EQ-7
30-Jun-09	00:38:10	42 569	13 198	3.5	Monti Reatini	ITCS013	99	x	x	EQ-12
03-Jul-09	01:14:07	42 320	13 378	3.6	Aquilano	ITCS013	95	x	x	EQ-13
03-Jul-09	23:12:55	42 276	13 403	3.3	Aquilano	ITCS072	91	x	x	EQ-15
12-Jul-09	08:38:51	42 338	13 378	4.2	Aquilano	ITCS013	96	x	x	EQ-18
12-Jul-09	22:14:24	42 338	13 398	3.8	Aquilano	ITCS013	97	x		EQ-19
13-Jul-09	01:36:34	42 553	13 215	2.7	Monti Reatini	ITCS028	104		x	EQ-20
14-Jul-09	01:11:25	42 316	13 417	2.8	Aquilano	ITCS013	96		x	EQ-21
15-Jul-09	00:58:07	42 461	13 284	2.9	Aquilano	ITCS013	98		x	EQ-22

Tab. 1 - Recorded seismic events (INGV Source)

Sensitivity numerical analysis

To attribute dynamic properties to the subsoils of the Fosso di Vallerano valley, in order to obtain an engineering-geological model for local seismic response analysis, punctual data were considered to derive a seismostratigraphy that was extrapolated to the area by taking into account the stratigraphic setting that resulted by the reconstructed geological model.

At this aim, the seismometric records were used to calibrate the local seismo-stratigraphy based on the reconstructed high-resolution geological model. Such a calibration was carried out by direct comparison between the instrumental records and the outputs from 1D numerical modelling performed through EERA (Equivalent - linear Earthquake Response Analysis, Bardet *et alii*, 2000) code. The study focused on the analysis of a soil column obtained in correspondence to the velocimetric station V (Fig. 10b), located in the Fosso di Vallerano valley.

Three earthquakes, representative of the three seismogenic areas (including several seismogenic sources according to DISS 3.1. see #EQ-6; EQ-12; EQ-13 in Tab. 1), were selected to be used as seismic inputs for the numerical modelling. The velocity time histories were decimated to a 50 Hz sample frequency, corrected for the instrument response, filtered in the range 0.4-15 Hz and derived to get accelerations.

The obtained acceleration time histories were used to calibrate the numerical model; each recorded event at the R station was deconvoluted at the column base and applied as input (incrop) obtaining, at the surface (outcrop), the signal modified by the soil column. The spectral ratio between the outcrop signal at the column surface and the input signal, deconvoluted at the outcrop once again, represents the seismic local amplification function, A(f), of the ground column (BORCHERDT, 1994). This function is comparable with the SSR function obtained for the same earthquake by considering the records at the R and at the V station.

Mechanical and dynamic properties were attributed to each lithotechnical unit according to literature data (BOZZANO *et alii*, 2008; CASERTA *et alii*, 2012) (Tab. 2).

The calibration procedure was rigorously performed for the stratigraphic column A (Fig. 10b) as it is representative for the geological setting of the V station.

Each numerical modelling was carried out by separately applying the horizontal components (NS and WE) of each recorded earthquake. An average function with its standard deviation was then computed to be compared with the average SSR that represents our experimental A(f).

The here adopted calibration procedure was performed through a sensitivity analysis, by assuming the stratigraphy

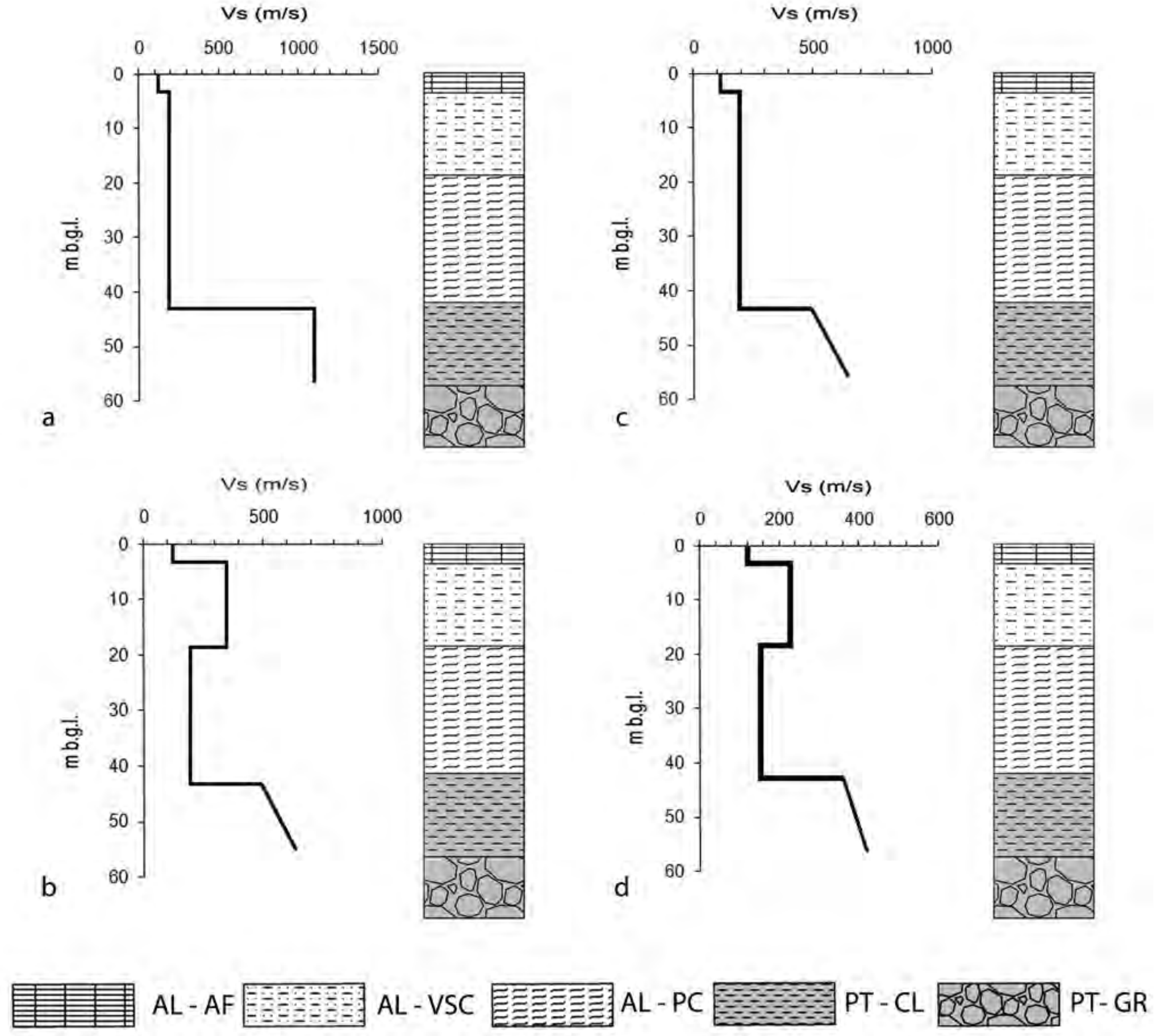

Fig. 10 - Vs profiles considered in the trial and error calibration process. a) T1 b) T2 c) T2b d) T3. See Tab. 2 for key to legend

	Lithology	Initial values			Best fit values
		γ (kN/m^3)	Vs (m/s)	G_0 (MPa)	Vs (m/s)
Alluvial Body - AL	AF (Anthropic fill material)	17	118	82	118
	VSC (volcano- clastic sandy clays)	16.5	180	53	**225**
	PC (Peaty clays)	17.2	190	64	**150**
	CL (Silty clays)	18.3	235	66	235
	PT (Peat)	12.7	140	25	140
	SD (Sands)	19.2	417	334	417
	GR (Gravel)	21.0	713	1068	713
Paleo-Tiber Deposits - PT	CL (Silty clays)	18.3	1100	101	**357**
	SD (Sands)	19.2	1100	334	417
	GR (Gravel)	21.0	1100	1068	1100

Tab. 2 - Initial values of the dynamic properties attributed to the litotechnical units and best fit values obtained by the sensitivity analysis performed assuming the T3 Vs profile

derived from the high resolution 3D geological reconstruction and by varying the shear wave velocity (Vs) values along the calibration soil column A. A "trial and error" convergence was performed to best fit the experimental A(f) with the numerical one. At this aim, the Vs values obtained by extrapolating literature data (Bozzano *et alii*, 2008; Caserta *et alii*, 2012) as well as the results of the local cross-hole test were assumed as starting conditions (Fig. 10a T1) while the thickness of layers and their juxtaposition were fixed according to the available geological constrains. A first calibration test (T1) was performed assuming that the Paleo-Tiber 4 deposits (Santa Cecilia Formation-PT) could represent the seismic bedrock of the area (Fig. 10a T1). The obtained A(f) does not fit the experimental one (Fig. 11a) so demonstrating that, in agreement with the results by Caserta *et alii* (2012) for the Grottaperfetta alluvial valley in Rome, such a hypothesis is not suitable for the area.

A second calibration test (T2) was performed, by considering a Vs value of 350 m/s within the volcaniclastic sandy – clay deposits (AL-VSC) and a linear increase of the Vs (5 m/s for meter) within the clay-silty layer of the Paleo-Tiber 4 deposit (PT-CL) from an initial value of 488 m/s; a velocity contrast of about 500 m/s with respect to the gravel deposits of the Santa Cecilia Formation (PT-GR), taken to be the local seismic bedrock, was moreover set (Fig. 10b T2). The shape of the resulting A(f) (Fig. 11b) is in good agreement with the experimental one. The significance of the velocity inversion within the soil columns, i.e. between the sandy-clays volcaniclastic (AL-VSC) layer and the peaty-clay layer (AL-PC), was evaluated by assuming in a third test (T2a) that the aforementioned velocity inversion does not exist, i.e. assuming the same Vs value (118 m/s) for both the considered lithotechnical units (Fig. 10c T2a). As it results from the modelling, the A(f) shape significantly changes and does not fit anymore the experimental one (Fig. 11c); indeed, the characteristic "trough shape" of the average SSR function (2-6 Hz) as well as the peaks in the 7-10 Hz frequency range are no more visible.

The shape of modelled A(f) in the calibration test T2 was not yet in a suitable agreement with the experimental one in terms of both frequency value and amplitude of the first resonance mode (about 1 Hz) as well as of the higher resonance modes.

Therefore, an additional calibration test (T3) was carried out by varying the impedance contrasts between each layer from 1.5 up to 3.The best results (Fig. 11d) were obtained considering the V(s) values shown in Fig. 10d (T3), and assuming impedance contrasts of 1.8 - 1.4 - 2.5 - 2.9 respectively.

The performed sensitivity analysis allowed to best tune the Vs profile along the soil column (Tab 2 - Fig. 9); the final resulting seismo-stratigraphy is in good agreement with other literature data (Bozzano *et alii*, 2008; Caserta *et alii*, 2012) but points out a significantly different value for the AL-VSC deposits of the Fosso di Vallerano valley compared to similar alluvial deposits by the Tiber River and its tributaries.

Moreover, it is worth noticing that in the Fosso di Vallerano valley the seismic bedrock is located at the top of the Paleo-Tiber 4 gravel (Pleistocenic) and it does not correspond not to the local geological bedrock (i.e., the Holocene/Pleistocene discontinuity contact) neither to the outcropping seismic bedrock, which consists of volcanic deposits. This represents a relevant difference if compared to the main Tiber River valley, which hosts the largest part of the Rome historical centre, where the seismic bedrock is coincident with the top of the gravel level at the basis of the most recent alluvial deposits (Bozzano *et alii*, 2008).

The so calibrated seismo-stratigraphy was extrapolated to the Fosso di Vallerano valley by: i) considering geometry and juxtaposition of stratigrafic levels as resulting from the high-resolution geological model; ii) verifying the correspondence between geological units and the seismic strata; iii) attributing to

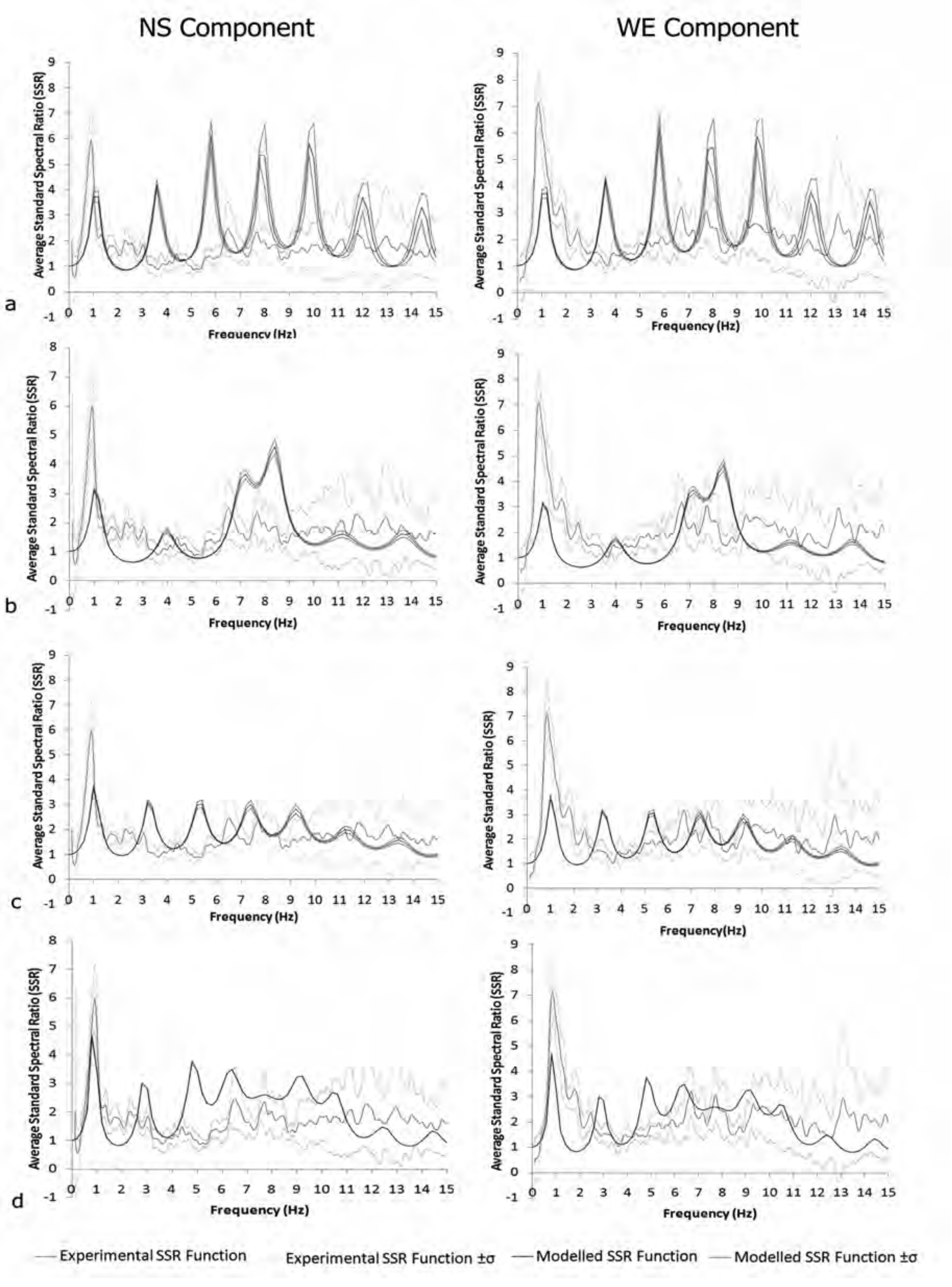

Fig. 11 - Comparison between results of the numerical modelling and experimental data for the T1 (a) T2(b) T2a (c) and T3 (d) Vs profiles.

the seismic strata the dynamic properties used for the calibration model. A coincidence was found between the Holocene alluvial units and the seismic strata as they represent visco-elastic deposits, up to 75 m thick, with Vs varying in the range 118-713 m/s. The Pleistocene deposits were distinguished in a upper seismic stratum, from 5 up to 50 m thick, including the geological units PT-CL and PT-SD, with a visco-elastic behaviour and Vs ranging from 357 m/s up to 607 m/s and in a lower seismic stratum corresponding to the PT-GR that represents the local seismic bedrock with a Vs of 1100 m/s. The resulting engineering-geological model is summarised in the synoptic diagram of Fig. 12.

Numerical modelling along cross sections

The seismo-stratigraphy calibrated at V station was extrapolated to three geological sections crossing the Fosso di Vallerano valley (Fig. 8 - AA’- BB’- CC’ cross sections). At this aim, the three sections were discretized by 50 - 56 - 64

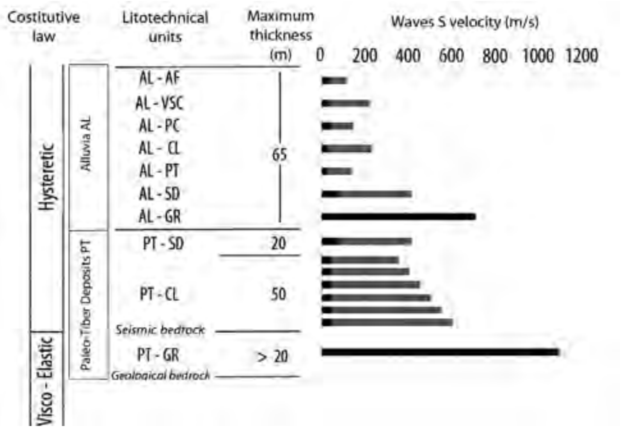

Fig. 12 - Engineering geological model, in terms of rheology and Vs velocity, assumed for the subsoil of the Fosso di Vallerano valley. The velocity value corresponding to the volumetric threshold is also indicated

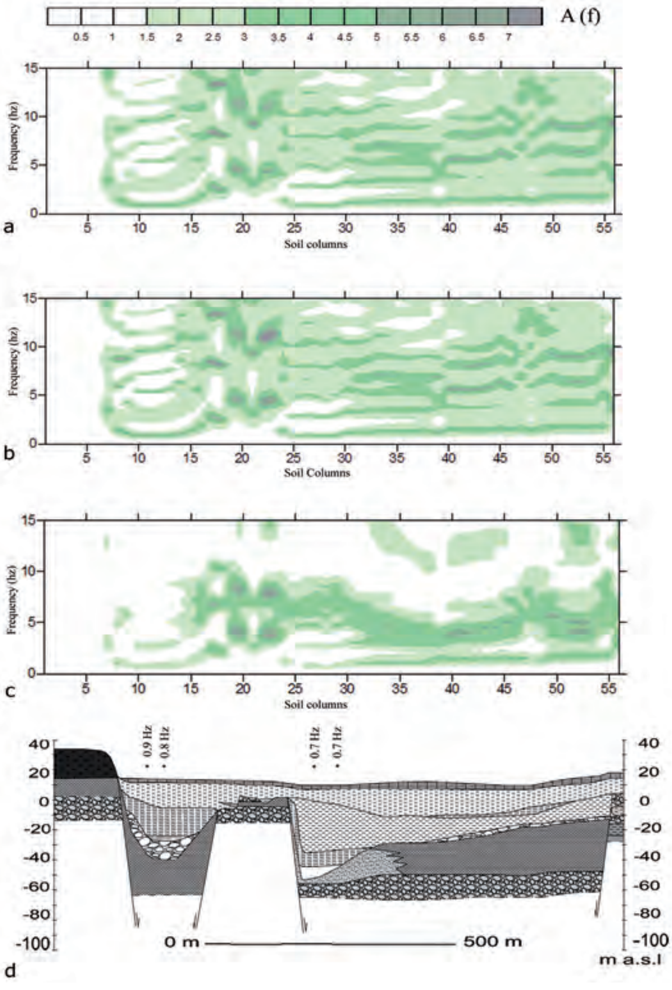

Fig. 13 - Output of the numerical modelling in terms of A(f)x obtained along the cross section BB’ of Fig. 8. a) Linear condition, LC; b) Equivalent-linear condition (weak motions), ELC1; c) Equivalent-linear condition (strong motions), ELC2. White to green colours indicate the A(f) intensity; d) Modelled geological cross section. The fundamental resonance frequencies derived by the ambient noise measurements is also reported

soil columns respectively, each one having an average lateral representativeness of 20 m, in order to obtain through EERA the spatial distribution of the amplification function (A(f)x) under free field conditions.

The modelling was performed by assuming three different conditions:

- Linear condition (LC - viscoelastic rheology; non iterative approach)
- Equivalent-linear condition 1 (ELC1 - viscoelastic rheology; iterative approach performed by applying the recorded weak motions (#EQ-6; EQ-12; EQ-13 in Tab. 1) as seismic inputs)
- Equivalent-linear condition 2 (ELC2 - viscoelastic rheology; iterative approach performed by using the strong motions required by the current Italian Regional regulations for the regulations for the "3rd level of Seismic Microzonation" as seismic inputs).

RESULTS

The A(f)x function was obtained along the geological cross sections by interpolating through a Kriging regression the A(f) values computed for each soil column. For each section, the results are summarized in contour maps, corresponding to the different assumed conditions (Fig. 13-14-15).

The comparison between the results obtained under LC (Fig. 13a) and ELC1 (Fig. 13b) conditions demonstrates that the A(f)x functions are coincident and therefore the recorded weak motions are not affected by singularities in their frequency content, that can alter the seismic response if compared to the theoretical one (i.e. under LC).

This suggests that, in future studies aiming at the evaluation of the "Site-City Interaction", the recorded weak motions could be used for the 2D modelling in the Fosso di Vallerano valley. Based on these considerations, the results of the modelling of

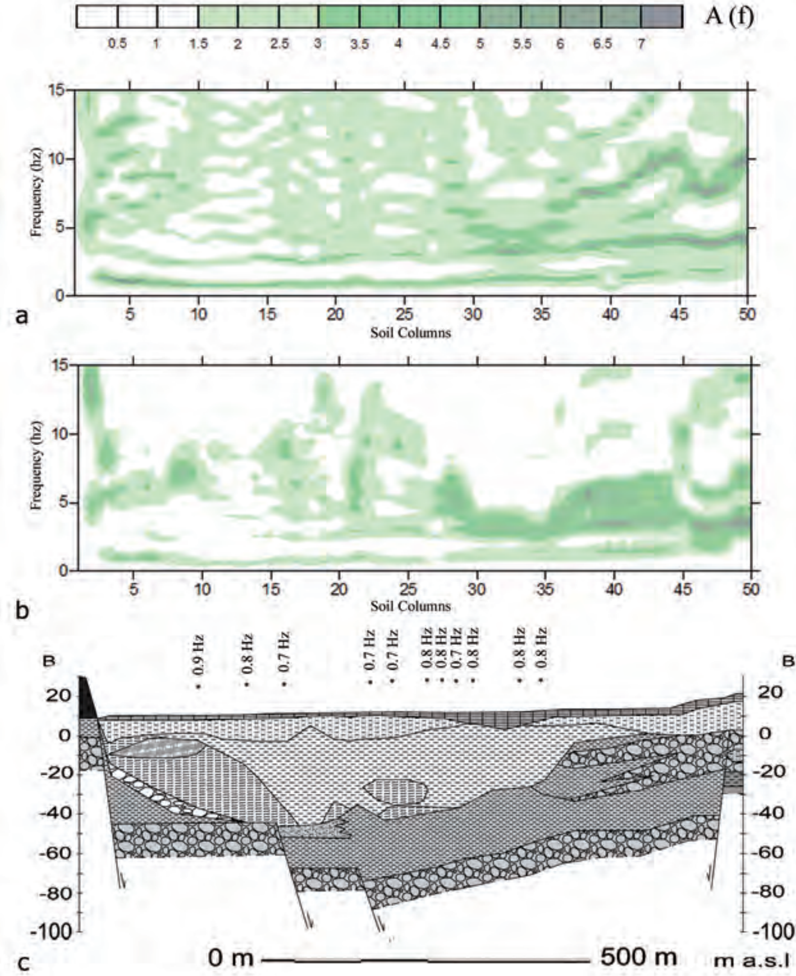

Fig. 14 - Output of the numerical modelling in terms of A(f)x obtained along the cross section AA' of Fig. 8. a) Equivalent-linear condition (weak motions) ELC1; b) Equivalent-linear condition (strong motions), ELC2. White to green colours indicate the A(f) intensity; c) Modelled geological cross section. The fundamental resonance frequencies derived by the ambient noise measurements is also reported

the three cross-sections are discussed for the ELC1 and ELC2 conditions only.

The results obtained by assuming ELC1 (Fig. 13b -15a - 15a) show a fundamental resonance mode of 1 ± 0.2 Hz within most of the valley; these values, that are in good agreement with the HVRS results, are due to the stratigraphic position of the PT-GR, i.e. the local seismic bedrock and the thickness of the resonant body (35-65m). However some particular geological-structural conditions are present in which the first resonance mode increases to higher frequency values (2.0-4.5 Hz), this is the case of the middle part of the cross section BB' (Fig. 14a) where the thickness of the alluvia significantly decreases (down to 15-20 m).

On the contrary, the secondary resonant modes are influenced by specific seismo-stratigraphic settings of each cross-section, i.e. of each modelled soil column.

As it results by analysing the AA' cross-section, the amplifications functions characterizing the eastern portion of the valley, are characterized by multiple upper modes (amplification intensity from 3 up to 7) due to the presence of paleo-slope debris (Vs= 550 m/s) within the upper part of the PT deposits. Where the alluvia are composed by silty-clay deposits (AL-CL Vs=235 m/s) the A(f)x shows upper modes characterized by amplification levels up to 5; on the other hand, where the alluvia are characterized by lower Vs values (AL-PC Vs=150 m/s; AL-PT Vs=140 m/s), the upper modes are negligible in the A(f)x function as the computed intensity results lower than 3. It is worth noting that, when the upper modes of resonance are not relevant, the amplitude of the first mode significantly increases.

The results obtained for the cross-section AA' show a different amplification level of the upper modes linked to the different geological setting of the valley:

i) in the eastern part of the valley, mainly composed by AL-

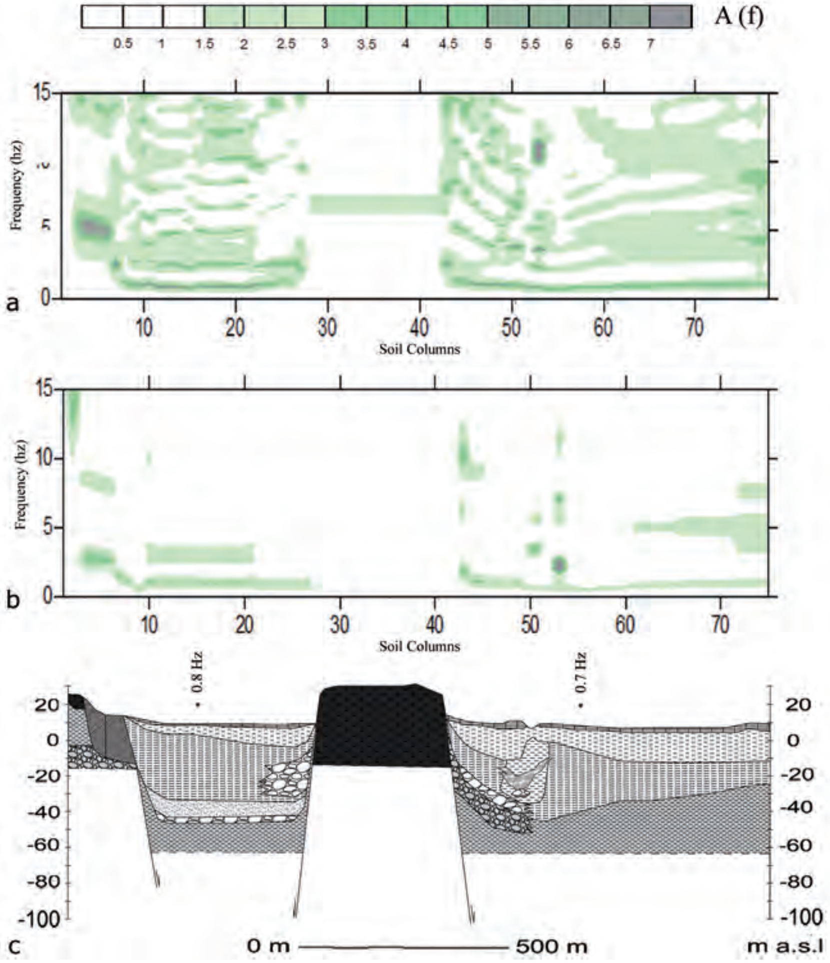

Fig. 15 - Output of the numerical modelling in terms of A(f)x obtained along the cross section CC' of Fig. 8. a) Equivalent-linear condition (weak motions) ELC1; b) Equivalent-linear condition (strong motions) ELC2. White to green colours indicate the A(f) intensity; c) Modelled geological cross section. The fundamental resonance frequencies derived by the ambient noise measurements is also reported.

CL (Vs=235 m/s), the upper modes are characterized by amplification values ranging from 4 to 7 (Fig. 13b);

ii) in the western part of the valley, characterized by deposits with lower Vs values (Al-PC Vs= 150), the upper modes show amplification values < 3. As already observed in the AA' cross section, the portion characterized by higher Vs values shows upper modes characterized by higher amplification level. Very similar results were also obtained for the cross-section CC' (Fig.14).

The comparison between the results obtained by assuming ELC1(Fig. 13b-14a-15a) and ELC2 (Fig. 13c-14b-15b) shows that, if non-linear conditions are considered, all the resonance frequencies visible in the A(f)x functions are characterized by a not negligible shift (i.e. up to a maximum of 0.5 Hz) towards lower frequency values, while the amplitude of the A(f)x functions remains almost constant or decreases in relation to the presence of softer soil (AL-PC , AL-PT).

DISCUSSION

The numerical modelling performed along three geological cross sections in the Fosso di Vallerano valley shows that: i) the first resonance mode generally varies in a close range between 0.8-1.2 Hz and is related to an average soft-soil thickness of about 60 m ascribable to the whole Holocene alluvia and partly to the Pleistocene deposits; ii) the first resonance mode corresponds to higher frequency values (2.0-4.5 Hz) where the thickness of the soft-soils significantly decrease (15-20 m) due to the local geological setting, i.e. to the horst-type structure of the Plio-Pleistocene bedrock; iii) the secondary modes become negligible on behalf of the principal resonance mode where the soil columns are characterized by lower V(s) values, i.e. high presence of peaty clays deposits; iv) the nonlinearity due to strong motions produces a down-shift of the principal modes of resonance as well as an amplitude reduction of the A(f)x in the portion of the alluvial body characterized by high concentration of peaty clays deposits. Nevertheless, the here obtained A(f)x functions only express the effects of 1D stratigraphic setting, i.e. thickness and layering of the alluvial deposits; on the contrary they do not take into account either the lateral heterogeneity of the alluvial filling or the shape of the valley. Moreover, based on the numerical model that best fits the empirical A(f)x function for the calibration soil column, it is worth noticing that in the Fosso di Vallerano valley the seismic bedrock is located at the top of the Paleo-Tiber 4 gravel (Pleistocenic) and it does not correspond to the geological bedrock (i.e. the Holocene/Pleistocene discontinuity contact) neither to the outcropping one (i.e. volcanic deposits). This result represents a relevant difference respect to the main Tiber River valley where the seismic bedrock is coincident with the Holocene gravel of the G level, according to Bozzano *et alii* (2008). Based on the high-resolution engineering geological model and, in particular on the location of the geological bedrock respect to the alluvial deposits, the Fosso di Vallerano test site is typified by a complex "valley system" (properly considered as soft soils within a bedrock container) as it changes from SE toward NW in: a) a double-valley system that coincides with a double-valley topography; b) a double-valley system that corresponds to a single-valley topography; c) a single-valley system that corresponds to a single-valley topography. Such a peculiar condition is strictly related to the Holocene depositional system of the Vallerano River which buried the more ancient alluvial deposits and part of the geological bedrock, specifically represented by the Pleistocene Paleo-Tiber 4.

By considering the shape ratio (*sensu* Bard & Bouchon 1985) of the Fosso di Vallerano valley along the three sections AA' (0.18) BB' (Eastern valley: 0.87 Western valley: 0.20) CC' (Eastern valley:0.44 Western valley: 0.19) as well as the impedance contrast resulting from the Pleistocene silty-clayey deposits and the local seismic bedrock, i.e. the top of the basal Paleo-Tiber 4 Pleistocene gravels (AA'= 2.8; BB'= eastern valley: 2.7 western valley: 2.8; CC'= eastern valley: 2.8 western valley: 2.6), a 1D-plus-lateral-wave local seismic response should be expected according to Bard & Bouchon (1985). Nonetheless, it is reasonable to assume that: i) the local seismic response as well as the stress-strain effects due to the heterogeneous alluvial deposits are significantly conditioned by lateral contacts related to the lithological hetereogeneities (Martino *et alii*, 2015), ii) the building agglomerate should be regarded as a physical system interacting with the subsoil (Kham *et alii*, 2006; Semblat *et alii*, 2009) and leading to a "urban-field" more than to a "free-field" local condition. In this regards, future analyses will be focused on the 2D numerical modelling of the seismic response and the induced stress-strain effect by assuming both free field conditions and Site-City Interaction.

CONCLUSIONS

The high-resolution geological model derived for the Fosso di Vallerano valley revealed a very complex setting for both the alluvia and the local geological substratum. More in particular, erosive and slope processes, placed in a context characterized by geodynamic activities, led to complex stratigraphic relationships among the deposits that filled the valley from the Pleistocene to the Present.

A local seismo-stratigraphy was calibrated based on earthquake records collected during the 2009 L'Aquila seismic sequence as well as noise measurements; such a calibration allowed to model a 1D seismic response by obtaining amplification functions all along three selected geological cross sections and put in evidence the peculiar geological setting of the valley that changes from a double- to a single-valley system moving from South-East to North-West. As it resulted from the here performed calibration process at the soil column A, representative of the V seismic station: i) the main resonance of the valley is observed in a very narrow frequency range, between 0.8 and 1.2 Hz; ii) where the alluvial body is characterized mainly by peaty clays deposits, i.e. V(s) value about 150 m/s, the secondary modes become negligible on behalf of the principal resonance mode; iii) the local seismic bedrock does not correspond to the geological one as it is represented by a gravel level within the Pleistocene Paleo-Tiber 4 deposits, i.e. it does not corresponds to the bottom of the most recent alluvia; iv) nonlinear effects are clearly visible by applying strong motion inputs to derive the 1D A(f)x functions as they produce a down-shift of the principal modes of resonance as well as an amplitude reduction of the A(f)x in the portion of the alluvial body characterized by high concentration of peaty clays deposits.

The resulting engineering-geological model, for local seismic response analysis, is significantly different respect to the one obtained by Bozzano *et alii* (2008) and Caserta *et alii*, (2013) for the historical centre of Rome as it consists in a three-layer seismo-stratigraphy including a first heterogeneous soft-layer of Holocene alluvia, a second homogeneous soft-layer of Pleistocene paleo-river deposits and a seismic bedrock which does not coincide to the geological one (represented by the Plio-Pleistocene marine clays) as it corresponds to fluvial gravels, part of the Pleistocene deposits.

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