Site response estimation in the Vittorio Veneto area (NE Italy) Part 2: mapping the local seismic effects in the urban settlement

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ABSTRACT Linear site-specific response spectra for seismic design are defined in the urban area of Vittorio Veneto (NE Italy) on the basis of the results provided by geological studies, some geophysical surveys and numerical modelling. The geological survey and the analysis of the collected stratigraphies located in the Vittorio Veneto basin allowed us to characterize four soil-types. Geophysical surveys consist of seismic noise horizontal-to-vertical spectral ratio analysis (HVSR), seismic site response estimated from earthquake records, S-wave measurements from surface wave dispersion analysis and inversion, and S-wave velocity from borehole and down-hole measurements. In addition, a 2-D spectral element method (SPEM 2D) numerical modelling of the M=5.8, 1936 Cansiglio earthquake was performed along a transect crossing the centre of Vittorio Veneto in order to assess the influence of the geological structure on the seismic response of the basin. The procedure followed to define the distribution of the soil types across the area, the local response spectra and the soil amplification factors is: 1) soil class identification and definition of the maximum value of the soil factor (Smax), according to EC8; 2) computation of the amplification coefficients (Sa) from earthquake and normalized HVSR mean amplitude; 3) zonation of the area into EC8 ground types, with associated elastic response spectra. Since the earthquake dataset includes only weak events, this study provides only site response estimates for the linear behaviour. The proposed site response map identifies three narrow zones of quite high amplification, characterized by C type soils, in Serravalle Vecchia, Vittorio Veneto centre, and Ceneda.

1. Introduction

The effects of local soil conditions on ground motion (site effects) may significantly increase the destructive power of an earthquake. The heterogeneity, often characterizing the damage distribution due to a destructive earthquake, points to the strong influence of this factor (i.e. seismic wave amplification due to local site effects) in the resulting damage levels. Mapping the physical effects of local site conditions on ground motion is the main ingredient of microzonation (Kind, 2002). Site amplification maps are generally compiled from multi-disciplinary contributions such as geologic, geotechnical and geophysical data and they take into account local site conditions such as near-surface ground properties, including topography and non-linear behaviour. These maps classify the study area with zones characterized by specific ground types, possibly with associated elastic response spectra, and represent the main tool for defining specific actions devoted to mitigating earthquake risk in urban areas.

This work was developed during the third (and last) year of the research project entitled “Scenarios of seismic damages in Friuli and Veneto” funded by the National Group for the Defence against Earthquakes (GNDT) within the task-project “Site effects in the test site of Serravalle and Ceneda and microzonation of Vittorio Veneto”.

The town of Vittorio Veneto is located near two of the region’s major seismogenic structures, namely the Alpago-Cansiglio and the Montello structures (Galadini *et al*., 2005; Poli *et al*., 2008). It suffered severe damage with maximum MCS intensity of IX during the October 18, 1936 M=5.8 Cansiglio earthquake, with epicentre at a distance of about 20 km from the town. The damage distribution in the Vittorio Veneto area was quite heterogeneous and was concentrated in two localities, named Serravalle and Ceneda, located, respectively, north and south-west, suggesting the occurrence of site effects. As reported by the local newspaper *L’Azione* (1936) “… The city has been seriously hit. The earthquake, which rendered two factories useless in the Serravalle district, provoked much more severe damage in the Ceneda district ...” (“ … *La citta’ e’ stata duramente colpita. La scossa, che nel reparto di Serravalle ha reso inservibili due fabbricati, nel reparto di Ceneda ha causato rovine ben più gravi …*”).

During the first two years of the GNDT research project a number of geological and geophysical investigations were performed on the Vittorio Veneto basin, i.e. detailed geological study, seismic noise horizontal-to-vertical spectral ratio (HVSR) analysis, seismic site response estimation from earthquake records, surface wave dispersion analysis and borehole and down-hole measurements (Avigliano *et al*., 2008; Vuan *et al*., 2008). The results of these investigations pointed to the presence of some zones featuring different geological and physical characteristics as well as different resonance frequencies across the city area. In addition, a numerical modelling of the seismic wave propagation performed along a vertical plane, crossing the centre of Vittorio Veneto, pointed to the importance of taking into account the amplification of the ground motion due to the sedimentary basin where the town lies (Laurenzano and Priolo, 2008). In fact, these results represent the basic elements which have been used to define the site-specific response spectra in the area of Vittorio Veneto.

In this paper, we first describe the classification of the soil types resulting from the detailed geological study; then, we provide a short description of the geophysical studies that were performed in the area; and finally, we show a site-specific response spectra map based on the geological and geophysical characterization of local soils. This map represents a first fundamental step toward the realization of a seismic microzonation in the town of Vittorio Veneto.

2. Soil types

On the basis of the surface geology and the interpretation of the collected stratigraphies of existing water and oil wells and one *ad hoc* 80 m deep borehole, located in the urban area of Vittorio Veneto at Sant’Andrea di Bigonzo (Avigliano *et al*., 2008), four types of soils have been identified in the Vittorio Veneto basin. Their spatial arrangement and lithological characterization are shown in Figs. 1 and 2, respectively.

Soil type 1: consists of a prevailing gravelly-sandy body (locally with lenses of sand and

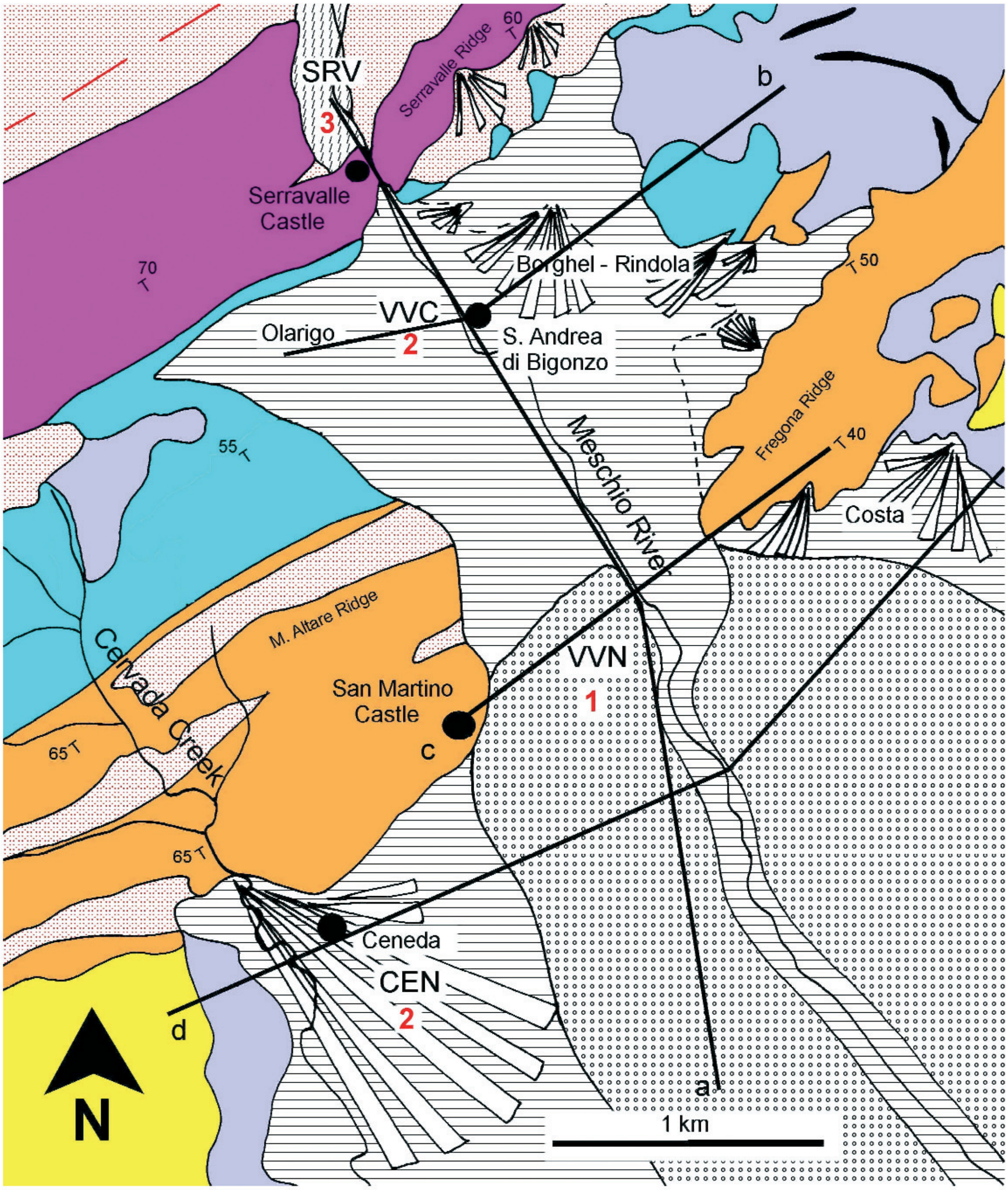

Fig. 1 - Detailed geo-lithological map of the Vittorio Veneto area. Pre-Quaternary succession (Southalpine Molasse, Upper Oligocene - Pliocene pp): violet: calcarenites; light blue: marls; orange: arenites and conglomerates; yellow: pelites and sandstones. Quaternary deposits: violet: glacial deposits; vertical line: sands with local lacustrine silts and peat levels; ruled: fine alluvial and colluvial deposits; circles: coarse alluvial deposits; red dotted: detritical talus; red sketched line: fault. Black heavy line: geological cross sections. SRV: Serravalle; VVC: Vittorio Veneto centre; VVN: Vittorio Veneto modern city and CEN: Ceneda. Relative red numbers refer to identified geological soils (see text for explanation).

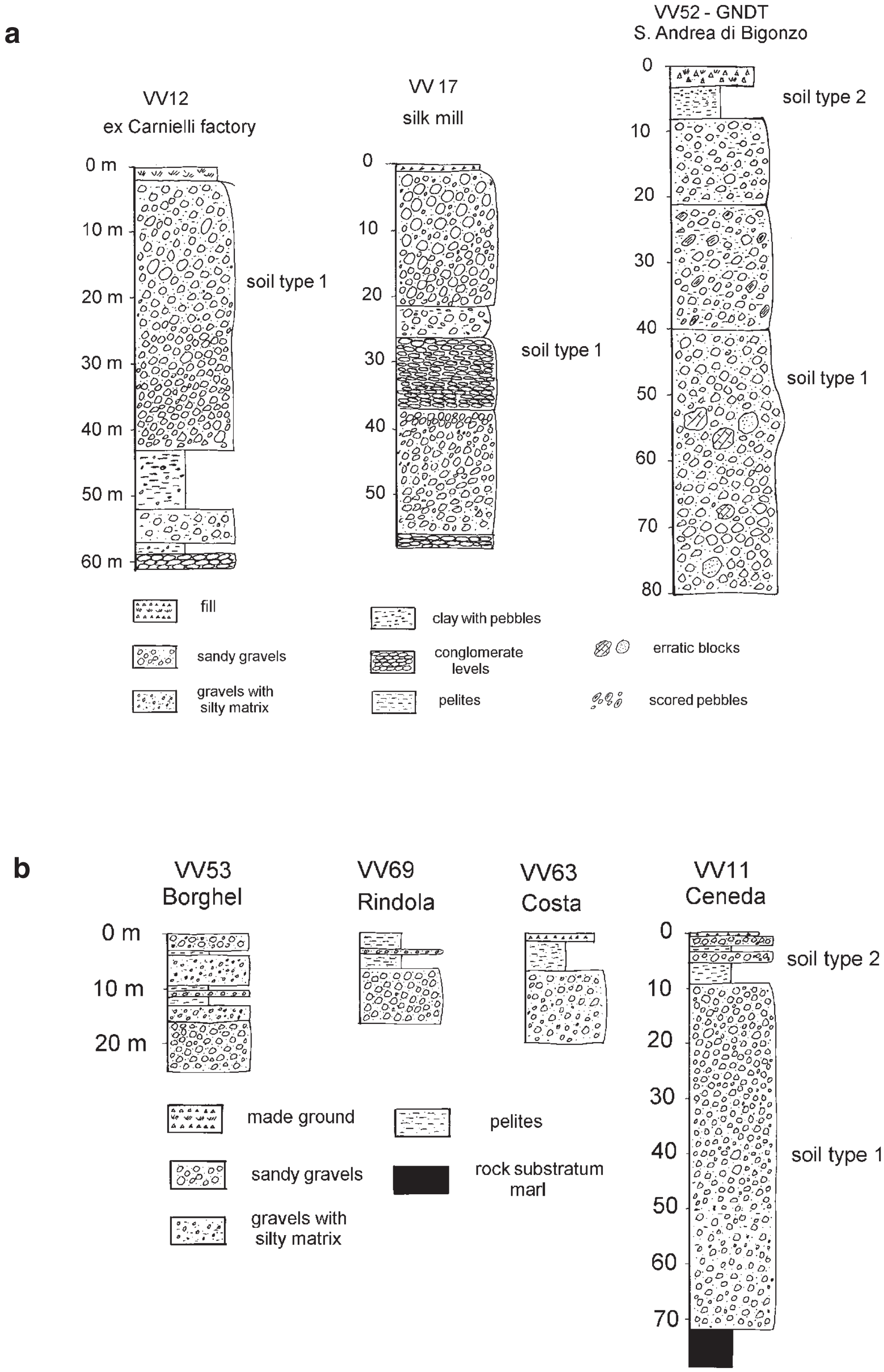

Fig. 2 - Examples of standard stratigraphies. a) for soil type 1: gravelly-sand body (locally with lenses of sands and conglomerates). 70-40 m in thickness. It characterizes the central portion of the Vittorio Veneto basin (VVN in Fig. 1). b) for soil type 2: close alternation of silts and clay interbedded with thin gravelly levels. 10-15 m in thickness. It is widespread in the northern sector of the Vittorio Veneto basin and in the Ceneda area (VVC and CEN in Fig. 1 respectively). c) for soil type 3: prevailing sands with lenses of lacustrine silts or peat deposits. Maximum thickness 20-30 m. It characterizes the northern sector of the Serravalle gorge (SRV in Fig. 1).

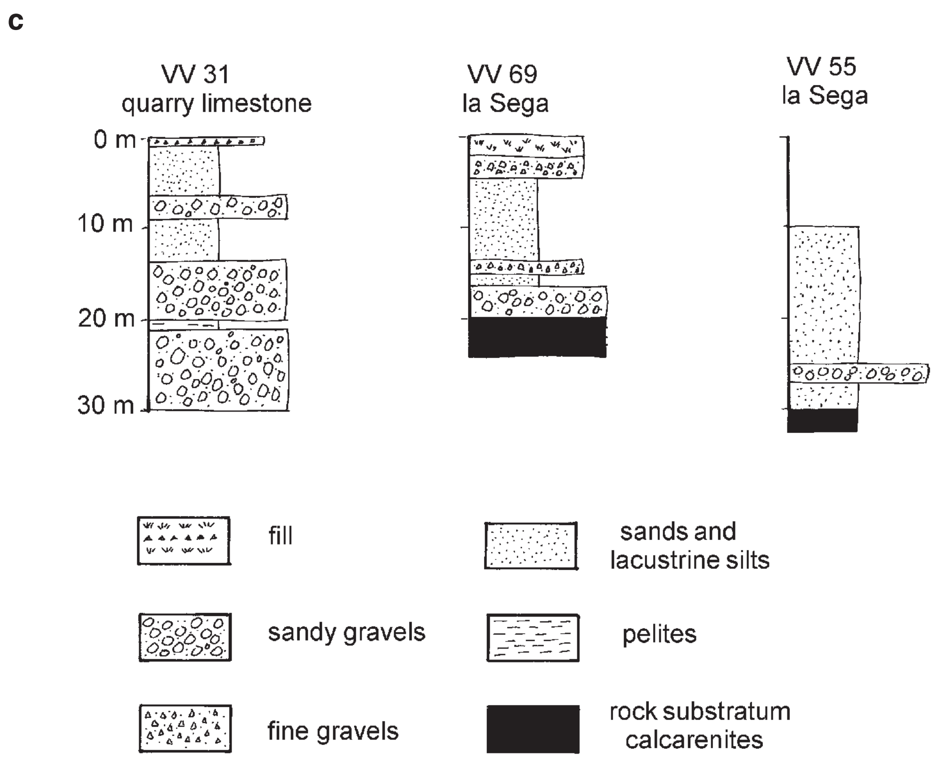

Fig. 2 - continued.

conglomerates) formed by alluvial and glacial deposits. It crops out widely in the Vittorio Veneto plain (VVN), but at the base of the surrounding hills it is covered by thin fine-grained alluvial and colluvial deposits. This sedimentary body is at least 70 m thick south of the rock step of Serravalle, but becomes thinner going southwards. The gravelly body contains the phreatic aquifer.

Soil type 2: consists of a thin alternation of pelites and sands interbedded with thin, gravelly levels. This sedimentary body lies on the gravelly-sand body and characterizes the alluvial cones at the slope of the hills (VVC and CEN). Thick colluvial deposits often match them. The average thickness is about 10-15 m.

Soil type 3: is made by prevailing sands with lenses of lacustrine silts or peat deposits. They were recognised in the stratigraphic logs located in the northern portion of the Serravalle gorge (SRV) where locally these sediments reach 20-30 m in thickness.

Soil type 4: is represented by the "geological" bedrock made by the Southalpine Molasse. It has to do with a close alternation of hard lithologies such as the glauconitic calcarenites of the Mt. Baldo formation, and the conglomerates of the Montello Conglomerate and soft lithologies such as the Tarzo Marl and the Conegliano complex (marls and sandstones with lenses of conglomerates; Avigliano *et al.*, 2008).

3. Geophysical measurements and investigations

Here, we briefly summarize the geophysical measurements performed in the area of Vittorio Veneto within this study and discuss their interpretation by using different methods. An exhaustive description of the geophysical measurements and techniques is provided in Vuan *et al*. (2008).

1) Seismic noise horizontal-to-vertical spectral ratio (HVSR) measurements. About one hundred sites were measured starting from the Serravalle Vecchia locality, north of the valley gorge, to the locality of Ceneda, in the south. The map of fundamental resonant frequencies estimated from HVSR measurements (Fig. 3) confirms the overall image of the basin provided by the geological study and suggests a zonation that is consistent with the layout of the different soil types (Vuan *et al*., 2008). In particular:

a) the area of Serravalle Vecchia (SRV) features a fundamental frequency f_0 = 3-5 Hz and soil type **3**;
b) the area of the Vittorio Veneto centre (VVC), with f_0 = 3-10 Hz and soil type 2. In this area, we can clearly see an overall increase of the fundamental frequency from north to south, with a broad area with f_0 = 5-6 Hz and a relatively small, elongated area of lower frequency (f_0 = 3-4 Hz) located mainly east of Serravalle, along the left side of the Meschio River;
c) the modern city area (VVN) is characterized by soil type 1 and features resonant frequencies in the band 10-20 Hz of scarce engineering interest;
d) the area of Ceneda (CEN) features soil type 2. The fundamental frequency decreases from about 8-9 Hz to about 1 Hz going from east to west and from the centre to the edge of the basin. The area where we observe the lowest resonant frequencies (i.e. 1.3-1.4 Hz) corresponds to the area which suffered the strongest damages during the 1936 Cansiglio earthquake as reported by the previously cited newspaper *l'Azione*.

2) Reference site spectral ratios (RSSR) from earthquake records. About 40 weak events were recorded at ten seismic stations deployed in the northern part of Vittorio Veneto (VVN) and in the Vittorio Veneto centre (VVC) and at three stations at Ceneda (CEN) (Vuan *et al*., 2008). The site response, estimated from RSSR, shows quite strong spectral amplification at sites located east of VVC (with a narrow band of amplification centred around $f_0 \approx 5$ Hz and amplification peak exceeding 5) and CEN (with a wide amplification band of 1-7 Hz, and peaks exceeding 5), and weaker amplification at VVN, along the right side of the Meschio River (with $f_0 \approx$ 7-8 Hz and amplification peak of about 3). The amplification band estimated locally by earthquake records matches the frequencies estimated by HVSR very well as shown in Fig. 6 of Vuan *et al*. (2008).

3) Shear wave velocity profiling based on the inversion of Rayleigh waves. The surface wave analysis was performed on shallow seismic refraction profiles at test sites A (Fender Park) and B (Sant'Andrea di Bigonzo) in the Vittorio Veneto centre (VVC) (Vuan *et al*., 2008). Here, we have estimated the S-wave velocities and the average thickness of the weathered layer down to a 25-30 m depth. For the two test sites A and B, the constrained inversion provides models which display a velocity contrast between 17 and 20 m and at about 12-13 m, respectively (see Vuan *et al*., 2008).

4) Borehole and down-hole measurements. This continuous core borehole, 80 m deep, drilled in the urban area of Vittorio Veneto (Sant'Andrea di Bigonzo) did not reach the top of the bedrock, but provided a detailed image of the underground geology and vertical velocity profile

(see Avigliano *et al*., 2008).

5) Numerical modelling. The numerical modelling was performed by the 2-D Spectral Element Method (SPEM 2D) along a 2-D vertical plane NE-SW oriented that crosses the centre of Vittorio Veneto just south of Serravalle (Laurenzano and Priolo, 2008). The M=5.8, October 18, 1936, Cansiglio event was chosen as a reference earthquake. The SPEM 2-D allows the estimation of the effects of the deep crustal structure, superficial geology and topography on ground shaking. In this simulation, the structural model specifies the local shallow geological structure and topography of the Vittorio Veneto area in detail. The results show, on one hand, that this area corresponds to a zone of relative minimum ground motion for the 1936, Cansiglio earthquake; on the other hand, they predict a local amplification across the basin, caused by the trapping of seismic waves within the sedimentary soils (see Laurenzano and Priolo, 2008).

4. Mapping the spectral response in the area of Vittorio Veneto

The definition of the site response map was performed with the following procedure:

1. identifying the ground types that are present within the study area and assigning the maximum soil factor value (S_{max}) for the area, according to Eurocode8 (EC8, 2002);
2. estimating the amplification coefficient (S_a) from earthquake and ambient noise HVSR, independently;
3. "normalizing" the estimated amplification coefficients S_a to the maximum value of soil factor S_{max};
4. dividing the area into zones, with specific ground type and elastic response spectrum.

EC8 classifies the soils into five basic group types (A-E), plus two particular types (S_1 and S_2) that require special investigation. EC8 recommends the use of two types of elastic spectra, depending on the magnitude (M_S) of the earthquake that contributes mostly to the probabilistic hazard of the site, (i.e. Type 1 if $M_S > 5.5$ and Type 2 if $M_S \geq 5.5$). For the town of Vittorio Veneto, the deaggregation analysis (Slejko and Rebez, 2002) shows that the largest contribution to the probabilistic hazard comes from the 1936 Cansiglio M 5.8 earthquake. However, since its epicentre was quite far from the town (i.e. at a distance of about 15-20 km) and the seismogenic zones are very large (Slejko *et al*., 2008), both types are taken into account.

We have identified three EC8 ground types within the Vittorio Veneto area, namely class A, B, and C (Table 1). There is no evidence of class D soils (cohesionless soil deposits). Although some areas (i.e. Serravalle and Ceneda) feature ground that could possibly fall into class E (i.e., a shallow sediment layer, 10-20 m thick, with surface velocities as much as 200 m/s, underlain by stiffer material with $V_S > 800$ m/s), we preferred to assign class C to these sites, since the sediment velocity features a uniform increase with depth that has the effect of dramatically reducing the acoustic impedance contrast with the geological bedrock. On the other hand, there was no evidence of liquefaction or yielding phenomena during the October 18, 1936, M=5.8 earthquake.

Taking into account the low velocity of the shallowest soils and the presence of water, a maximum value of the amplification factor S_{max} = 1.45 is assigned to class C soils. For sites identified as class B or class C, a further sub-classification has been introduced. In particular, class B soil is divided into sub-classes, B0 and B1, which represent soils with major and minor

Table 1 - Soil classes identified for Vittorio Veneto.

Soil type	Description	Parameters		
		$V_{S,30}$ (m/s)	Amplification range	Amplification band (Hz)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800		
B0	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterized by a gradual increase of mechanical properties with depth - *Vs*,30 (m/s) = 360 – 800	580	flat	> 10
B1		740 (measured)	1.05-1.3	4-8
C1	Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m - Vs,30 (m/s) = 180 – 360	270 (estimated)	1.4-1.5	5-9
C2				1-7

gravel content versus, respectively, sand and clay. Class C soil, that characterizes the highest amplification values obtained in Serravalle and Ceneda, is divided into two sub-classes, namely C1 and C2, to account for the different frequency bands of amplification of the two sites (i.e. a wider one for Ceneda).

Fig. 4 shows the mean amplitude estimated from ambient noise HVSR over a frequency band equal to [0.8, 8] Hz (Lachet *et al.*, 1996). The maximum value is normalized to S_{max} = 1.45. The distribution of the HVSR amplitudes fits the distribution of the soils displayed by the surface geology map very well.

Table 2 shows the amplification values estimated for the sites where earthquakes have been recorded. These values are computed as the mean ratio of the mean of Housner intensities, computed for all earthquakes recorded at each site, to those chosen as the reference sites (i.e. sites VV06 and VV10). The maximum is then normalized to S_{max} = 1.45. The use of the mean normalized Housner intensity as an estimate of the soil amplification factor has been used by other authors, such as, for example, Mucciarelli and Tiberi (2004). In Fig. 5, the same values are mapped against the amplifications estimated from microtremors. A good consistency is found between the earthquakes and microtremor estimations.

The site response map proposed for Vittorio Veneto is shown in Fig. 6. On one hand, the strong correlation with the surface geology can be appreciated, and on the other hand the identification of three narrow zones of high amplification in Serravalle Vecchia (SRV), Vittorio Veneto town-centre (VVC) and Ceneda (CEN) characterized by C type soils. Most of the area is characterized by class B soils and features, in general, low-to-medium amplification. In particular, the modern city (VVN) is characterized by gravelly soil (B0 class) and features low amplification, while the areas of Vittorio Veneto town-centre (VVC) and Ceneda (CEN) are characterized by gravelly soil with massive presence of clay and sand (B1 class) and feature medium level amplification.

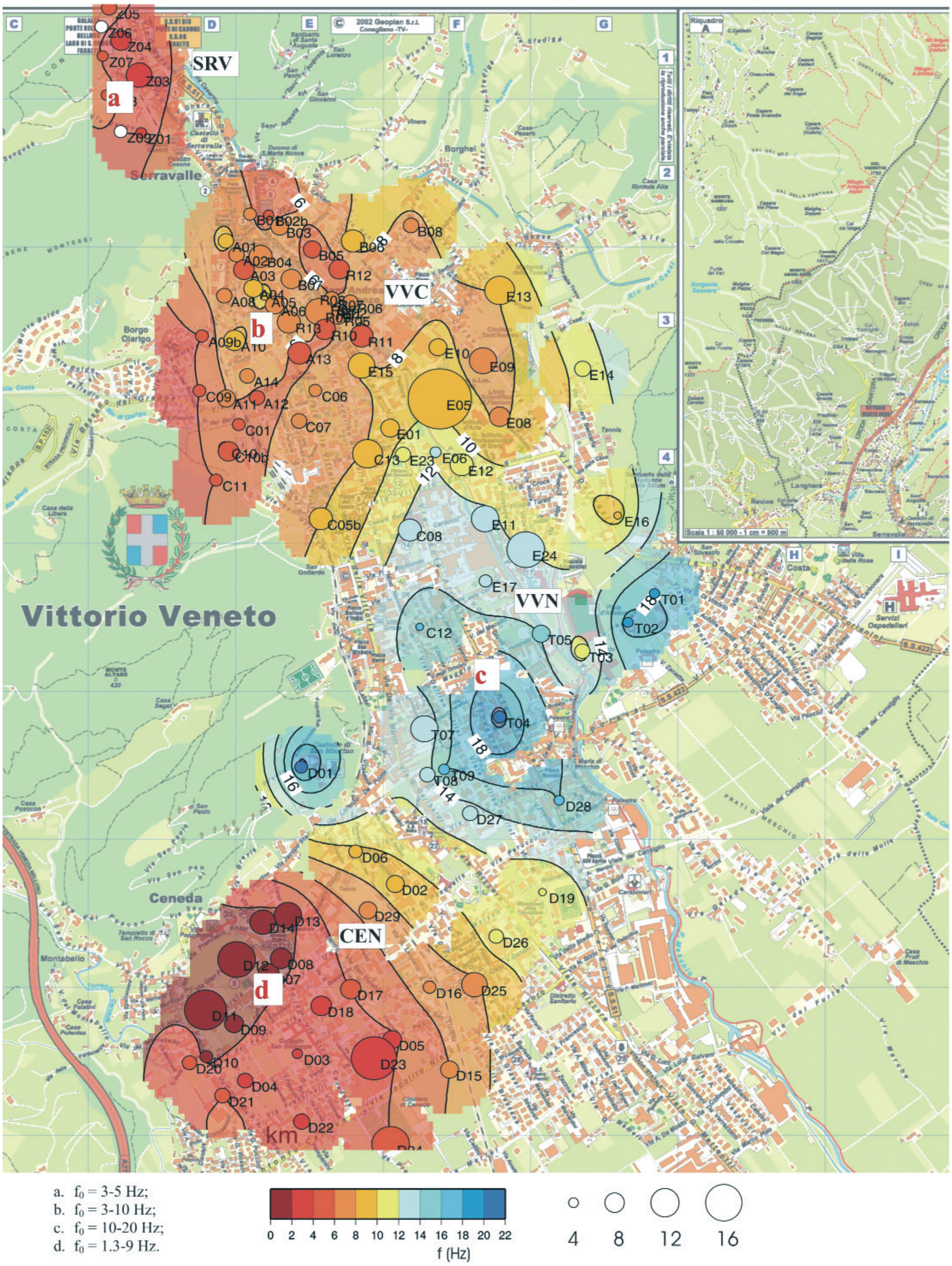

Fig. 3 - HVSR amplitude of the peak in the frequency range 0.5-22 Hz. The colour and size of the circles indicate peak frequency and amplitude of the HVSR, respectively. White circles indicate sites with very low H/V amplitude or flat response. The value of the resonance frequency is also indicated along the iso-frequency lines computed by interpolating the peak frequencies. Letters and numbers refer to the zonation based on HVSR resonant frequencies and types of soils (see text), respectively.

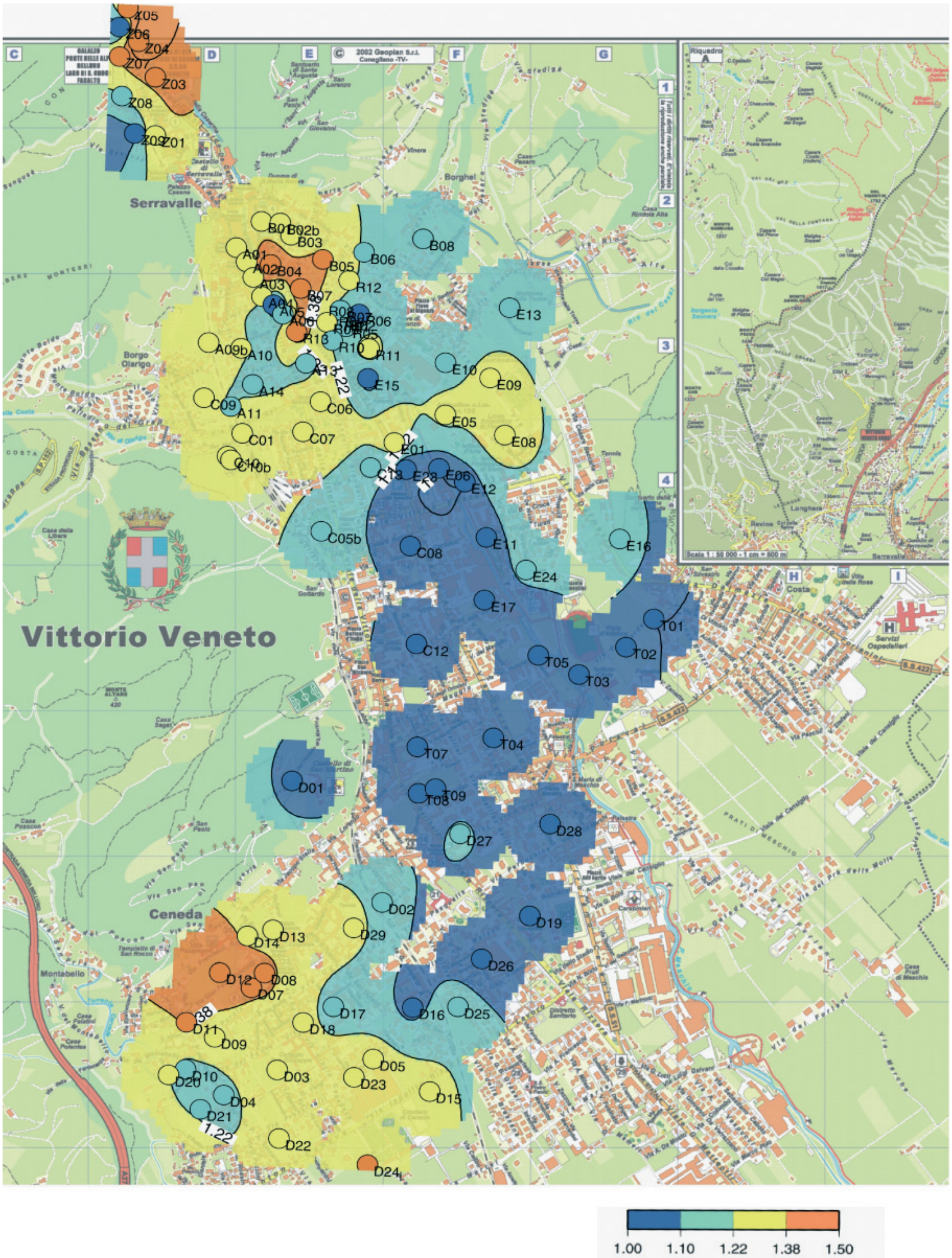

Fig. 4 - Microtremor HVSR mean amplitude over the frequency band [0.8, 8] Hz.

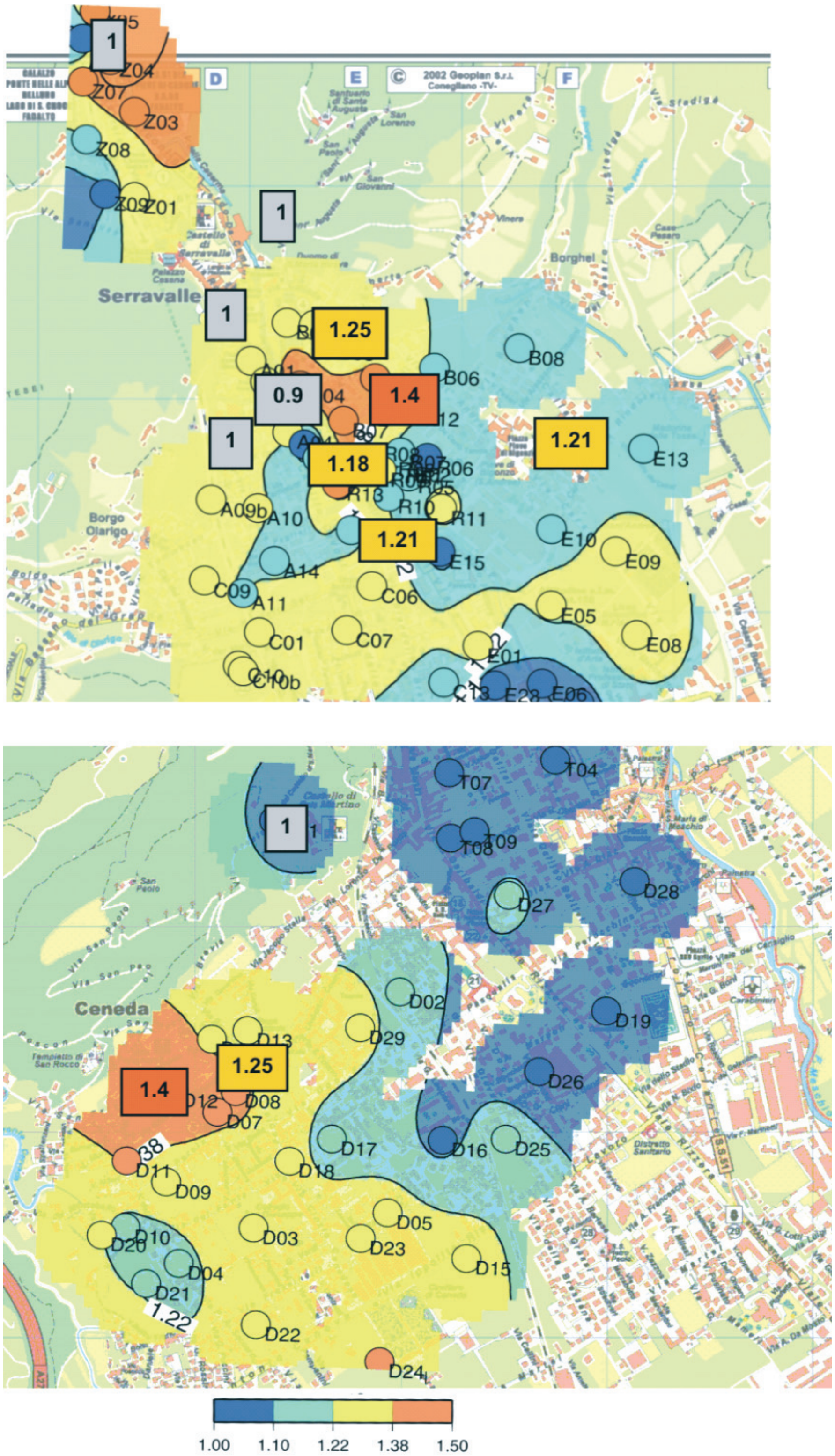

Fig. 5 - Amplification coefficients estimated from earthquake records (values in box) and microtremor measurements for Vittorio Veneto.

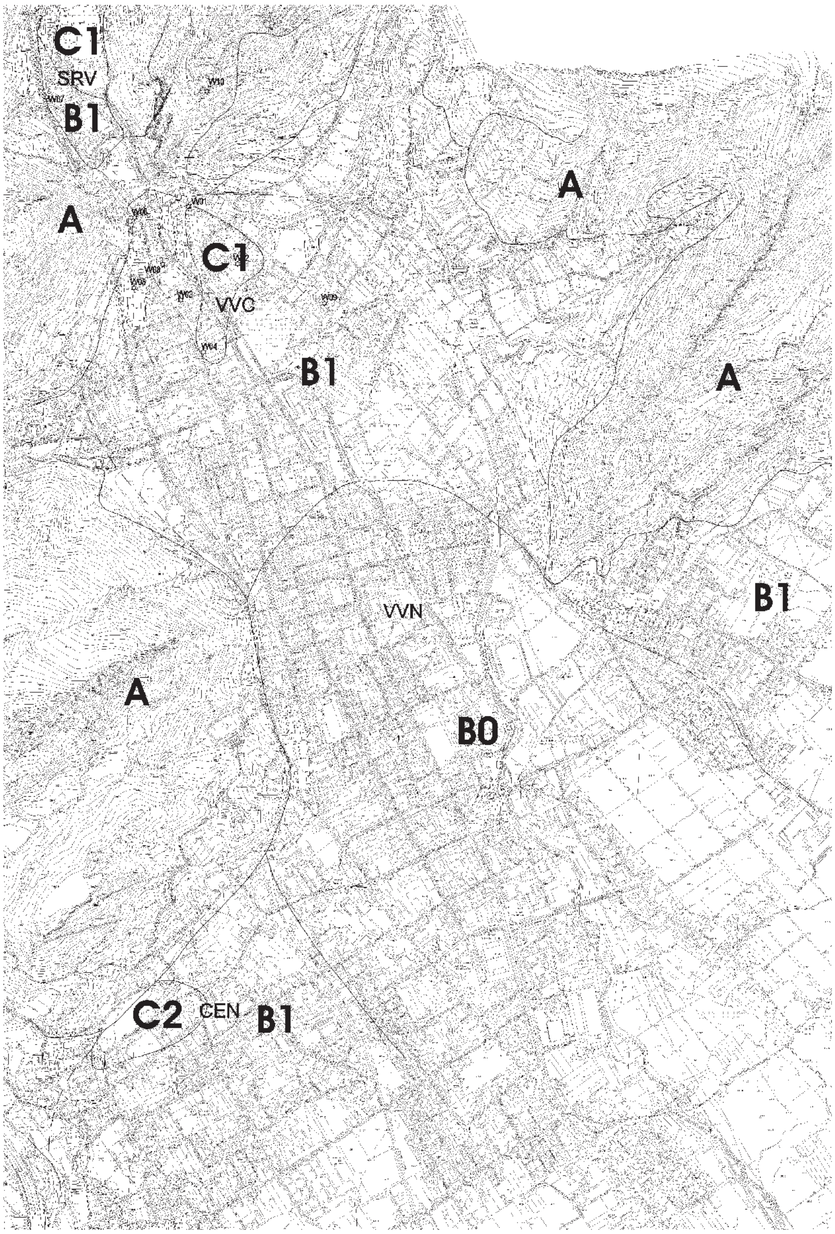

Fig. 6 - Site response map proposed for Vittorio Veneto. Ground classes as in Table 3. Red and pink labels indicate the location of microtremor measurements and wells, respectively. Blue labels indicate the 10 temporary stations for the registration of the local seismic response in Serravalle.

Table 2 - Mean Housner intensity of the earthquakes recorded at Vittorio Veneto. For location of seismic stations see Fig 6.

SERRAVALLE (Reference Sites: VV06, VV10)								**CENEDA** (Ref. Site: CAST)	
V01	**V02**	**V03**	**V04**	**V05**	**V07**	**V08**	**V09**	**ROSSI**	**SEMI**
1.25	1.4	1.18	1.21	1.0	1.05	0.9	1.21	1.4	1.25

Table 3 - Ground classification for Vittorio Veneto, according to EC8 (2002).

Type1 (large size earthquakes, M>5.5)					Type2 (medium size earthquakes, M≤5.5)			
Soil	**S**	**T_B-T_C (s)**	**f_B-f_C (Hz)**		**Soil**	**S**	**T_B-T_C (s)**	**f_B-f_C (Hz)**
A	1	0.15-0.4	6.66-2.5		**A**	1	0.05-0.25	20-4.0
B0	1.05	0.15-0.5	6.66-2		**B0**	1.05	0.05-0.25	20-4.0
B1	1.10	0.15-0.5	6.66-2		**B1**	1.25	0.1-0.25	10-4.0
C1	1.15	0.2-0.6	5-1.66		**C1**	1.45	0.1-0.25	10-4.0
C2	1.15	0.2-0.6	5-1.66		**C2**	1.45	0.1-1.0	10-1.0

Table 3 shows the ground classification proposed for Vittorio Veneto. The values of the parameters estimated for ground motion type 2, i.e. for medium size earthquakes and mainly linear behaviour of the soil, are defined on the basis of the results of the geological and geophysical studies shown above. Note that parameters proposed for type 2 spectra closely resemble those proposed by EC8, except for soil class C2, for which the frequency band of the design spectrum plateau has been widened to [1, 10] Hz. For type 1 spectra, we have no indication from the geophysical studies. Therefore, the parameterisation of EC8 has been adopted for all class of soils.

5. Conclusions

There are several reasons why the town of Vittorio Veneto has been chosen as a test area for a site-specific response spectra study. It is located in an area prone to earthquakes; it suffered severe damage during the October 18, 1936, *M* 5.8 Cansiglio event; it is important from a historical and artistic point of view, as well as for its geographical location and economic value for the Friuli Venezia Giulia and Veneto regions.

For this area, several geological and geophysical data were collected, i.e. shallow geological structures from well stratigraphies and an *ad-hoc* borehole, the distribution of resonance frequencies along the entire basin from seismic noise HVSR, the spectral amplification at some sites from earthquake records, velocity profiles from surface wave dispersion analysis and down-hole measurements. Moreover, numerical simulations provide additional information on the site response along a transect crossing the town centre.

The site response map displays a good correlation with the local surface geology and identifies three main types of ground classes (i.e. A, B, and C, respectively), with a finer subdivision into two subclasses for classes B and C. For these classes, amplification factors and elastic response spectra are provided. The area of Vittorio Veneto features three zones of quite high amplification in Old Serravalle (SRV), Vittorio Veneto town-centre (VVC) and Ceneda (CEN), respectively. These zones are all characterized by C-type soils, while the remaining area features B-type soils.

Since Vittorio Veneto is located in an Alpine valley, this study can also be useful in the near future to characterize some generic "Alpine" response spectra that represent the seismic response of fluvio-glacial valleys filled by sediments and are fundamental for seismic hazard assessment.

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