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Focusing on Soil Foundation Heterogeneity through High-resolution Tomography

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SUMMARY

An historical building affected by differential settlements, which were triggered by an earthquake, is investigated by means of high-resolution tomography, both electrical and seismic. The objective is to image the geometric structure of the shallow soil below the building and to characterize its stiffness at low strain.

A preliminary reconstruction of the geological units has been recovered through the combined use of electrical and seismic data, where the depth of the travertine bedrock varies significantly within the study site. The range of variation of the main geophysical parameters (resistivity, P- and S-wave velocities) inferred from these models has been set as reference point for tuning the results obtained from the geophysical survey performed near the building. The inverted tomographic models obtained from data acquired alongside the building exhibit heterogeneity of the shallow subsoil, which is partly founded on a weathered layer and partly on a more rigid lithotype, probably a fractured travertine or a gravel layer. Therefore the fill anthropic soils can play a relevant role for the structural stability in case of shallow foundations built on a heterogeneous subsoil.

Introduction

Although direct inspection and destructive testing is always required in engineering design, little attention is generally given to the great diagnostic potential which can be today obtained by high-resolution non-destructive methods to identify key issues for assessing the stability of existing building (ground conditions, foundation type, soil-structure system). Increasing the knowledge on the "current status" of our architectural heritage is a priority to assess quantitatively the socio-economic benefit of risk reduction decisions, especially for historic districts. Few papers are available in literature about the study of the soil-structure system through non-invasive geophysical surveys related to existing buildings (e.g. Cardarelli *et al.* 2007; Soupios *et al.* 2007). Nevertheless there are examples of application of geophysics for in combination with geotechnical studies for the evaluation of foundation soils (e.g. Soupios *et al.* 2008),

Our goal is an improvement of the non-invasive investigations oriented to the diagnosis of the stability of existing buildings by means of high-resolution tomographic reconstruction of electrical and seismic models where physical parameters are properly addressed.

The new experimental procedure has been applied to an historical building, near the town of Rieti (Central Italy), affected by subsidence due to a differential movement of the structure.

Site description, data acquisition and processing

The study site is located near the town of Rieti (Central Italy), around 80 km northern of Rome. The analyzed structure, built in 1910, is a two-floor masonry building to be used as a National research centre for agricultural studies. The assessment of the current state of conservation of the building is needed to help in evaluating the causal relationship between the numerous cracks and fractures detected on the perimetral walls and possible differential settlements phenomena occurred in the soil foundations. From the original design we were able to reconstruct that the building foundations are maybe equally-spaced masonry walls, even though we actually ignore the effective depths of these structural elements. The geological background is characterized by important fractured carbonate units, which comprise the Mts. Sabini-Reatini ridges, belonging to the meso-cenozoic units of the Umbro–Sabina domain. Given this a priori information on the study area, we plan to execute seismic and electrical investigation along three lines (L1, L2 and L3 in Fig. 1a,b).

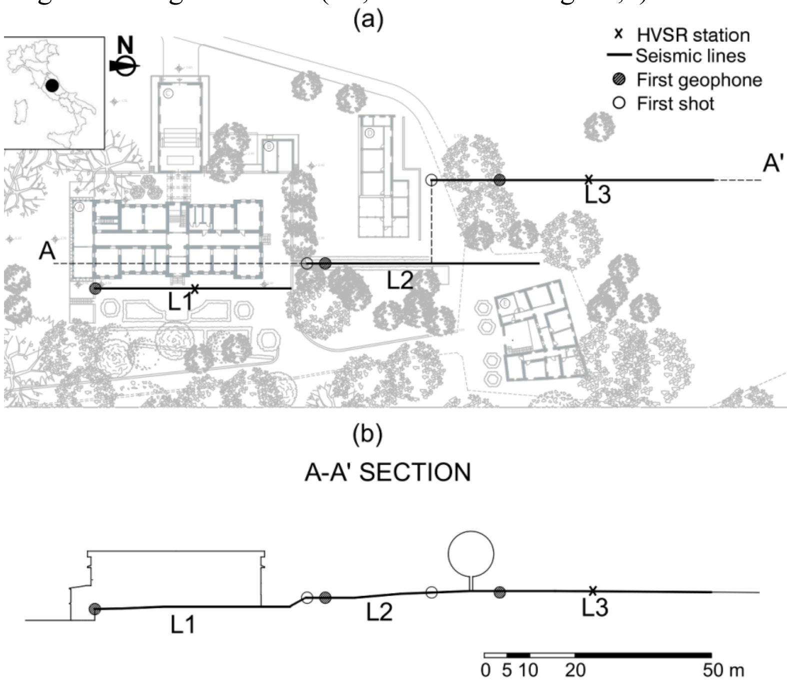

Figure 1 *Plan of the study area with indication of the ERT and seismic lines. (b) A-A' section as indicated in Fig1a.*

We make use of the L2 and L3 alignments for reconstructing a geophysical model of the shallow subsoil, while a more focused high-resolution survey was executed on the L1 line, for assessing the causes of the differential movement affecting the building.

Electrical Resistivity Tomography (ERT), P- and S-wave Seismic Refraction Tomography (SRT) data were acquired on the three lines with the aid of horizontal-to-vertical (H/V) ambient-noise dataset (Fig. 1a,b) to validate the geological reconstruction derived from the tomographic models. The 2D ERT arrays were acquired using a 48-channel IRIS Instruments SyscalPro48, using a dipole-dipole configuration with stainless steel electrodes 1 m (L1, L2) and 2 m (L3) spaced apart (Fig. 1a).

The dipole-dipole array combines consistent signal strength with good resolution and depth of investigation. 2D ERT dataset are inverted with the VEMI algorithm -Versatile Interface for Electrical Modelling and Inversion (De Donno 2013; De Donno and Cardarelli 2015), built within the EIDORS environment (Adler and Lionheart 2006). This algorithm is able to perform both 2D and 3D inversion, by solving the forward problem with a finite-element approximation of the Poisson's equation governing the physical problem while inversion is carried out using a Gauss-Newton formulation (De Donno and Cardarelli 2014). Although it is possible to add a priori information to the inversion process, in this particular case we made no preliminary assumption on the soil layering.

SRT data are recorded employing a 48 channel system of 4.5 Hz vertical (P-wave) and 8 Hz horizontal (S-wave) geophones, 1 m spaced apart operating with a 7 kg hammer source and using a Geometrics Geode seismograph with a sampling rate of 0.125 ms. For each shot gather, the first arrivals are manually picked, and the traveltime inversion is performed using the algorithm described in Cardarelli and de Nardis (2001) employing the linear traveltime interpolation (LTI) method for ray-tracing (Asakawa and Kawanaka 1993) and the iterative biconjugate gradient algorithm for traveltime inversion (Cardarelli and Cerreto 2002).

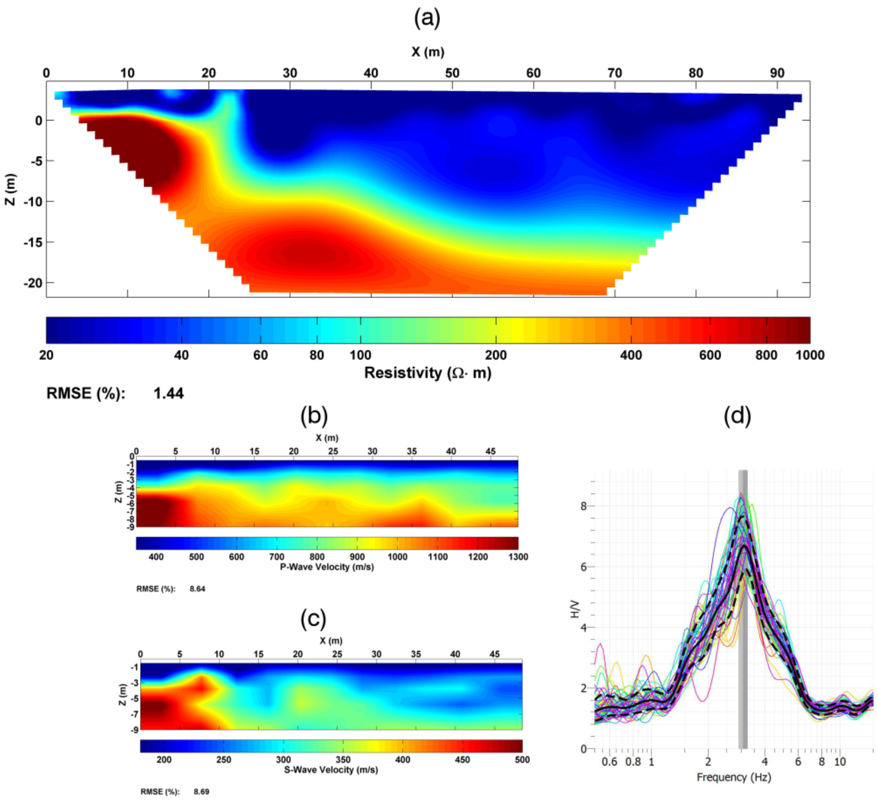

Figure 2 *L3 line. (a) Inverted 2D ERT model. (b) P-wave seismic refraction tomography. (c) S-wave seismic refraction tomography. (d) H/V spectrum recovered at the centre of the line.*

In addition to this, two ambient-noise recording station were placed in the centre of the L1 and L3 lines and dataset acquired employing a 45 minutes recording window. Recorded signal was processed with the Geopsy software, choosing a window length ranging from 25 and 50 s, overlapped by 5%. The windows for the calculation of the STA (Short Term Average) and the LTA (Long Term

Average) were equal to 1 and 25 s respectively, while the maximum threshold level of the STA/LTA ratio is 2.5. The Horizontal-to-Vertical Spectral Ratio (HVSR) was evaluated using a Konno-Ohmachi (Konno and Ohmachi 1998) smoothing filter over a bandwidth of 25 Hz and the squared average of the N/S and E/W horizontal components.

Results

The site-scale geological setting was analysed through the inversion of ERT and SRT data on the L3 line. ERT inverted models exhibit three main layers: two conductive layers (resistivity < 20 Ωm for the shallower and about 50-60 Ωm for the middle layer) overlying a resistive formation (> 400 Ωm) having growing depths moving towards the northern edge of the area (maximum depth=15-16 m). The latter layer should correspond to the calcareous bedrock.
The seismic tomography confirm the effective layering of the subsoil adding information about the elastic properties of the lithological units. The conductive shallow layer is associated with low P-wave (350 m/s) and S-wave (150 m/s) velocities, linked to a weathered material. Below, the P-wave and S-wave velocities increase progressively up to 850 and 250 m/s respectively. Since the maximum depth of these models is 9 m, the bedrock formation (V_P>1300 m/s; V_S>450 m/s) is reached only at the beginning of the model (x=0-5 m in Figs. 2b,c corresponding to x=15-20 m in Fig. 2a), where it is founded at shallower depths, also by ERT.
Through the HVSR we detect a single peak at a frequency f_0=3 Hz, corresponding to a spectral amplitude of 7. Modelling the subsoil in a first approximation as a two-layer model with an average S-wave velocity of the sediment layer overlying bedrock of 200 m/s, we retrieve a bedrock depth of about 16-17 m, similar to that displayed by the ERT model.

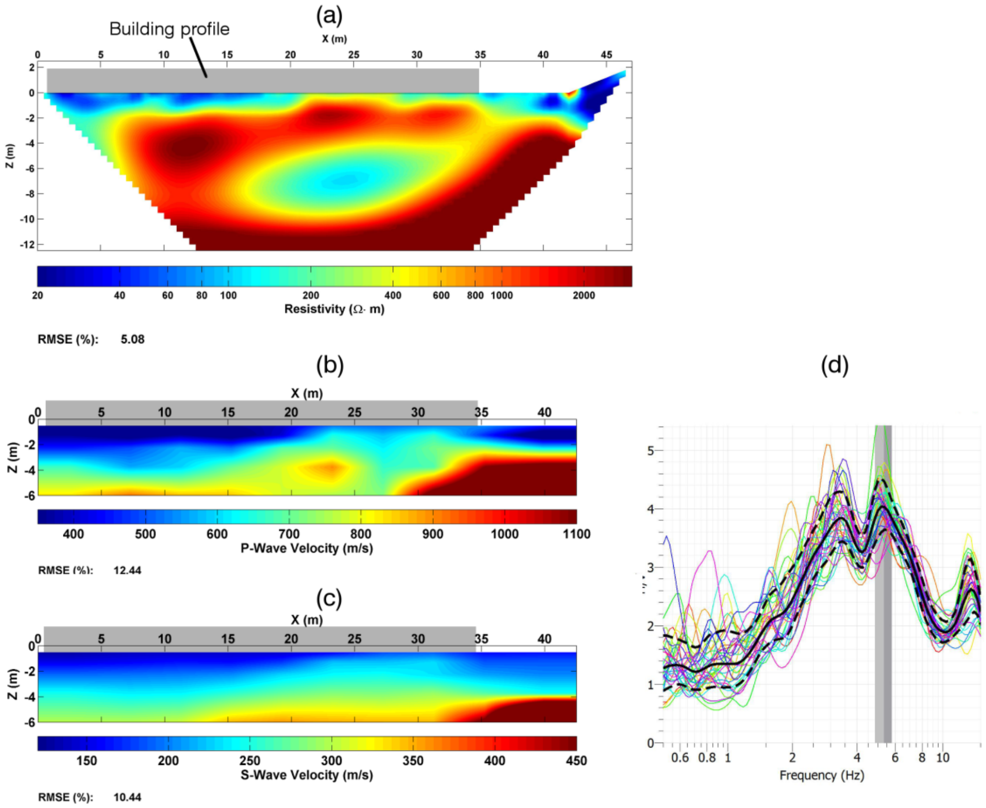

Figure 3 *Inverted model for the L1 line. (a) 2D ERT. (b) P-wave seismic refraction tomography. (c) S-wave seismic refraction tomography. The building profile is marked with a grey rectangle. (d) H/V spectrum recovered at the centre of the line.*

Figure 3 shows the results from the tomographic inversion of electrical and seismic refraction data acquired along the L1 line, where the building profile is superimposed for clarity. These models clearly demonstrate that the structure was partially built on the conductive weathered material having poor elastic properties (x=0-22 m), while the second part of the structure (x=22-34) lies on a more rigid lithotype, maybe a fractured travertine or a gravel layer, since we have V_P=800 m/s and V_S=300 m/s for this formation. The calcareous bedrock (V_P>1300 m/s; V_S>450 m/s) emerges only in the right part of the models (outside the building), while elsewhere is located at a depth of about 10 m (Fig. 3a). These results are confirmed by the H/V spectrum, where the difference with the undisturbed case (L3) is proven by the two peaks detected at 3.2 and 5.5 Hz and a velocity inversion is likely.

Conclusions

The causes of a differential movement underway on an historical building has been analysed by an high-resolution tomographic reconstruction of electrical and seismic models.
A detailed reconstruction of the geological "in situ" formations has been recovered through the combined use of ERT, SRT and HVSR data, where the depth of the calcareous bedrock varies significantly within the study site. The range of variation of the main geophysical parameters (resistivity, P- and S-wave velocities) inferred from these models has been set as reference point for tuning the results obtained from the geophysical survey performed near the building. Both seismic and electrical inverted model from the L1 line show the heterogeneity of the shallow subsoil along the building, partially founded on a weathered layer and partially on a more rigid lithotype, maybe a fractured travertine or a gravel layer.
Therefore we can conclude that the differential settlements are triggered by the heterogeneity of the foundation subsoil since the role of fill anthropic soils can be very relevant for shallow foundations.

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