Site effects along the southern flank of the L'Aquila terrace

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Introduction. The town of L'Aquila (central Italy) suffered strong damages during the April 6, 2009 M_w 6.1 earthquake. The seismic event has been caused by the activation of an about 10-13-km-long SW-dipping normal fault, i.e. the Paganica fault, located about 10 km east of L'Aquila (Falcucci *et al.,* 2009; Boncio *et al.,* 2010; Emergeo Working Group 2010). The mesoseismic area ($I_s \geq$ VIII MCS) extended over 20 km in a NW-SE direction along the Aterno river valley, comprising six localities with $I_s >$ IX MCS (Galli *et al.,* 2009). In particular, in L'Aquila town (I_s = VIII MCS) the majority of the casualties (135 victims in total with 44% caused by the earthquake over the whole affected area, including L'Aquila and several nearby villages) is concentrated downtown, namely in the area of Via XX Settembre (Fig. 1), populated by 5-7 storey reinforced concrete frame buildings, 1950-1965 in age. The huge concentration of damage within this area created speculations for poor design/construction techniques of these buildings and for an inadequate evaluation of seismic action provided by the Italian Building

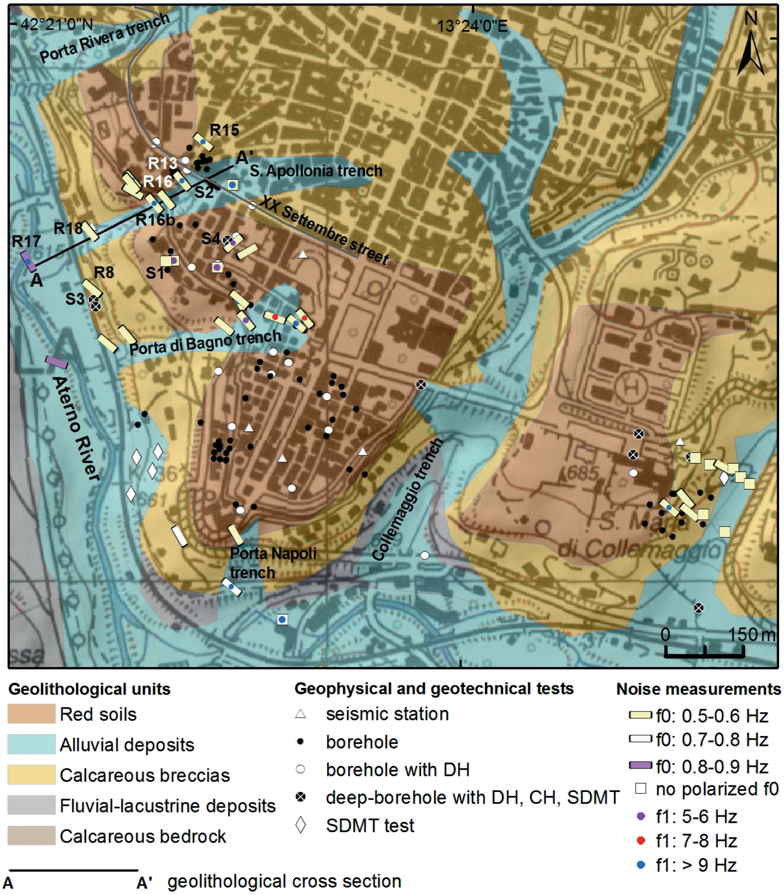

Fig. 1 – Geolithological map of L'Aquila terrace with geophysical and geotechnical investigations.

Code in use at the time of their construction. Otherwise the local subsoil condition is very complex and can cause significant amplification effects. In fact in the area site effects can be related to lithostratigraphic amplification of soft soil overlaying stiff basement; fine-grained soils interposed within, or placed above, the coarse-grained breccias (residual soils known as "red soils"); man-made fills; underground caves; topographic effect. Instead, in the historical centre of L'Aquila settled by old masonry buildings, the damage distribution seems to be greatly affected by vulnerability problems (Milana *et al.*, 2011; Tertulliani *et al.*, 2012; Totani *et al.*, 2012; Amoroso *et al.*, 2014).

In this respect many geological, geophysical and geotechnical investigations were performed, and still ongoing, for supporting the reconstruction planning of the town mainly related to seismic microzonation studies and research activities. In this work the available data were integrated with new geological and geophysical studies along the southern edge of the downtown, the most damaged of L'Aquila, to analyze the role of morphology and geology on seismic vibration. In particular an intense campaign of noise measurements was carried out along transects from the top of L'Aquila hill towards the Aterno river valley (Fig. 1). The analyzed data show strong and polarized peaks in the horizontal-to-vertical spectral ratios (H/V) at low frequency (< 1 Hz) and locally at high frequency (> 5 Hz) highlighting a complex seismic site response of the area in terms of lithostratigraphic and topographic effects. Along Saint Apollonia trench, one of the steep scarps along the southern edge of L'Aquila hill, the subsurface geology was reconstructed joining the available geological and geophysical data. Noise measurements were used to constrain the upper portion of the subsoil along the transect.

Geological settings. The historical center of L'Aquila is founded on a fluvial terrace at about 60-80 m above the Aterno river bed. The slopes along the flanks of the L'Aquila terrace are generally steep with a mean value of about 36% and a local maximum scarp of 120%. According to the Italian Building Code (NTC, 2008) the topographic amplification factor S_T is on average equal to 1.2, even though it can reach locally $S_T = 1.4$. Fig. 1 shows the geological map of the area, as developed by the Seismic Microzonation studies (MS–AQ Working Group, 2010). The city is boarded to the West and the South by the Aterno river valley covered by actual fluvial and terraced alluvial deposits. The North and the East of the village are surrounded by mountain and hill ranges formed by Meso-Cenozoic limestone rocks and Miocene flysh units. The terraces are formed by middle Pleistocene variably-cemented calcareous breccias and calcareous gravel sediments (L'Aquila breccias Auct., Blumetti, 1995). Its thickness as testified by deep boreholes (Amoroso *et al.*, 2010) ranges from 100 m or more in the northern sector of the city centre to 0-10 m in its southern zone (i.e. Aterno river). The L'Aquila breccias lie on an about 200 m-thick lower Pleistocene-upper Pliocene (?) fluvial-lacustrine deposits which mainly consist of pelite and sand lithologies. The uppermost thin layer of the near-surface geology is composed by soft materials, mainly represented by residual soils known as "red soils", weathered breccias or anthropic filling material. The red soils are a fine-grained deposit which cover or are interposed within the L'Aquila breccias. The thickness of the red soils can reach 20-30 m in the southern part of the town and along its scarps (i.e. Porta Rivera, Saint Apollonia, Porta di Bagno, Porta Napoli and Collemaggio trenches; Fig. 1), as confirmed by many site campaigns. The man-made fills have maximum thickness of ≈ 8-10 m and they mainly consists of disposal materials such as rubbles of masonry buildings destroyed in past earthquakes. The continental deposits are overimposed to the Meso-Cenozoic carbonate substratum. Its depth decreases toward NE as testified by deep boreholes and gravimetric and seismic reflection investigations (Amoroso *et al.*, 2010; MS–AQ Working Group, 2010; Tallini *et al.*, 2011; Del Monaco *et al.*, 2013) and it outcrops in the northern part of L'Aquila hill.

Data and methods. The whole studied area (Fig. 1) counts a lot of geological, geotechnical and geophysical investigations, which were used in this work to characterize the sub-surface geology of the area such as the geometry of the bedrock at depth, the geotechnical property of the soft layers and the related shear-wave velocity (Vs). In a large part those investigations were promoted by the Department of Civil Protection (MS–AQ Working Group, 2010) for seismic microzonation studies; the deep boreholes in the historical centre were promoted by the University of L'Aquila – Centre for Research and Education in Earthquake Engineering (CERFIS) (Amoroso *et al.*, 2010; Cardarelli e Cercato, 2010), the deep investigations were promoted by ENI (Italian oil and gas company) for the seismic reinforcement and rebuilding project of Santa Maria di Collemaggio Basilica (AA.VV., 2013), and further investigations carried out for the reconstruction of private damaged buildings (Totani *et al.*, 2012; Monaco *et al.*, 2013; Amoroso *et al.*, 2014). In particular, the available data (Fig. 1) consist in: at least one hundred boreholes to 20-35 m depth, eight deep boreholes to 50-270 m depth, twenty down-hole tests to 30-50 m depth, one cross-hole test to 80 m depth, five seismic dilatometer tests to 5-17 m depth, four seismic dilatometer tests in a backfilled borehole to 50-80 m depth, few resonant column/cyclic torsional shear tests, and several surface wave tests, electrical tomography surveys seismic noise measurements. In addition, seven temporary stations (AQ04, AQ09, PAOL, AQ01, NAPO, AQ03, AQ11) were installed in the southern edge of L'Aquila after the April 6, 2009 within the microzonation activities, that recorded earthquakes from May 28, 2009 to July 2, 2009 (MS–AQ Working Group, 2010; Milana *et al.*, 2011; white triangle in Fig. 1).

These available data confirm the subsoil conditions are quite complex. L'Aquila terrace is characterized by a shear wave velocity V_S inversion at the transition from the calcareous breccias with highly variable cementation ($V_S \approx$ 600-1200 m/s) to the underlying fluvial-lacustrine deposits ($V_S \approx$ 500-800 m/s), placed on the calcareous bedrock ($V_S \approx$ 2000 m/s). Low V_S values were detected in the upper portion of the breccias (i.e. residual soils $V_S \approx$ 250-350 m/s) and close to Aterno river (i.e. alluvial deposits $V_S \approx$ 200 m/s).

In this work extensive noise measurements were collected along the steep scarps that borders the southern edge of L'Aquila hill, the most damaged area of the town (Fig. 1). The aim was to investigate the relationship between horizontal-to-vertical amplitude spectra ratio (H/V method) with the geological and geomorphological variations present along the flanks of the L'Aquila terrace. In particular the analyzed sections cross the Saint Apollonia (i.e. 20 % to 45 % of medium slope), Porta di Bagno (i.e. 10 % to 30 % of medium slope) and Porta Napoli (i.e. 20 % to 45 % of medium slope) trenches, and Collemaggio scarp (i.e. 10 % to 30 % of medium slope). Otherwise the seismic stations were mainly located on the calcareous breccias geological and/or red soils units. Few measurements were performed on the alluvial deposits of the Aterno River. Each noise acquisition was recorded by a seismic three-components velocimeter (Le3d-5s manufactured by Lennarts Electronic; http://www.refteck.com/), powered by an external battery. The time synchronism was provided by an external GPS antenna connected to the digitizer. The velocimeters were oriented to the North and in many cases buried for about 20 cm. The average time-length of each noise recording was about 45 minutes. The ambient vibration data were processed mostly by Geopsy (http://www.geopsy.org/) and SAC2000 code (Goldstein *et al.*, 2003). Single-station noise technique computes the horizontal-to-vertical spectral ratio, *H/V* method (Nakamura, 1989). The peak of the *H/V* ratio identifies the resonance frequency (f_0) of the subsoil, which is related to the thickness (*H*) and to the shear wave velocity (V_S) of the soft deposits. In general, in one dimensional (1D) assumption and in first approximation f_0 is derived from the formula $V_S/4H$.

Results and discussion. In L'Aquila downtown the horizontal-to-vertical spectral ratio curves show strong and polarized resonance peaks at low frequency (< 1 Hz) and locally at high frequency (> 5Hz). The low-frequency resonance peak f_0 (in Fig. 1 f_0 is represented by squares or barrettes, when the noise signal is polarized) varies from about 0.5 to 0.9 Hz for sites at the top of terraces and in proximity of the Aterno river valley, respectively. The strong low-frequency resonance, centered at about 0.5–0.6 Hz, is very diffuse in L'Aquila terrace, as

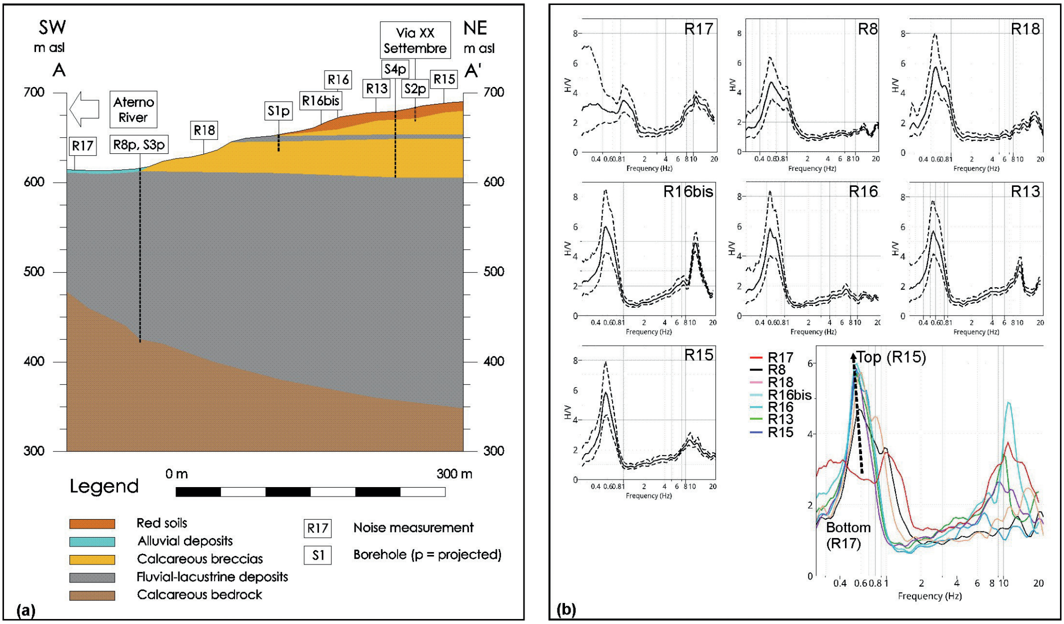

Fig. 2 – Geolithological section (a) and noise measurements along Saint Apollonia trench (b).

already evidenced by seismic data recorded in the town (De Luca *et al*., 2005; Milana *et al*., 2011; Di Giulio *et al*., 2014). It is interesting to highlight as the H/V features observed on the new and available noise data show a good correspondence with the H/V ratios computed on earthquakes (Milana *et al*., 2011).

Systematic differences on f_0 values emerge in terms of frequency, amplitude and shape of the H/V curves moving along each trench. In particular, from the bottom to the top of L'Aquila terrace the low-frequency peak shows an increase of its amplitude and a shift towards lower frequencies (Fig. 2b). Furthermore, moving towards the base of the hill the low-frequency peak ranges in a broad frequency band displaying a bump shape. This variation in the H/V shapes is mainly related to a different behavior of the vertical component. Indeed the vertical recordings show a spectral minimum shifted at higher frequency for measurements nearby the Aterno river (Di Giulio *et al*., 2013). These H/V difference around f_0 between the top and the bottom of L'Aquila terrace are dubitatively explained in terms of 1D stratigraphic variation of thickness and seismic velocity between the soft soils and the stiff limestone bedrock. Moreover, the low-frequency resonance shows a significant directionality in the response at about N130°-N150° measured clockwise, as it can be observed through the oriented barrettes in Fig. 1. This polarization is parallel to the mean strike of the Aterno river valley, and perpendicular to the direction of the main elongation of L'Aquila terrace. According to Matsushima *et al*. (2014), the lateral heterogeneity related to the geomorphologic condition of L'Aquila hill could explain the strong polarization at f_0 on noise data. In terms of amplification, the polarization appears stronger at the top of the terrace and along the scarps than in the valley.

In addition, H/V curves sometimes show a secondary resonance frequency f_1, variable from about 5 to 9 Hz (in Fig. 1 f_1, when observed, is represented, by circles into squares or barrettes). The high-frequency resonance peak can be related to the thin uppermost soft layer of residual soils which reaches the maximum thickness of 20-30 m in the southern part of the town and along its scarps (Del Monaco *et al*., 2013). The layer characterized by low shear wave velocity ($V_S \approx$ 250-350 m/s) defines a strong impedance contrast between its surface and the stiff calcareous breccias ($V_S \approx$ 600-1200 m/s).

Fig. 2 illustrates the results on Saint Apollonia trench, from the Aterno River valley to Via XX Settembre. A geolithological cross section, namely A-A' (Fig. 2a), was constrained using the available geological, geotechnical and geophysical data: two deep boreholes, S3 to 195 m depth with a cross-hole test to 80 m, and S4 to 80 m depth with a seismic dilatometer test to 50 m; two shallow boreholes, S1 and S2; the geogravimetric map of L'Aquila city centre (MS–AQ Working Group, 2010) and new noise measurements performed for this work (R8, R13, R15, R16, R16b, R17, R18, see Fig. 2b). The first resonance frequency f_0 was used to confirm the depth of the geological and seismic bedrock (0.5-0.9 Hz), by means the deep impedance contrast between surface soils and stiff limestone. This result confirms the subsurface soil thickness already estimated by the geogravimetric map and found by S3 sounding. Instead, the secondary resonance frequency f_1, when identified, was introduced to verify the thickness of the red soils (7-12 Hz), partially known from the surrounding boreholes. For example, R13 detected this peak at about 10 Hz, which is related with the 7.5 m of residual deposits ($V_S \approx$ 300 m/s). The identification of this layer is very important considering the amplification effect due to this upper portion in L'Aquila terrace, as also confirmed by 1D ground response analysis (Amoroso *et al*., 2014).

Fig. 2b plots the single H/V curves with their standard deviation (dashed line) along Saint Apollonia trench, and an overlay of all these noise measurements. The trend of the results shows the considerations previously introduced, hypothesizing the possible sensitivity to a topographic effect. From Via XX Settembre to the Aterno river valley f_0 shows a decrease of H/V amplitude (from 6 to 3) and a shift towards higher frequency (from 0.5 to 0.9 Hz). Moreover, moving towards the base of the hill the low-frequency peak ranges in a broad frequency band displaying a bump shape.

Conclusions. The huge concentration of earthquake damages within the southern edge of L'Aquila terrace and the complex local subsoil conditions (soft soil overlaying stiff basement; fine-grained soils interposed within, or placed above, the coarse-grained breccias known as "red soils"; man-made fills; underground caves; topographic effect) focused to deeply study this area for its restoration.

In particular, the combination of the available geological, geophysical and geotechnical data carried out for the restoration and the redevelopment with the noise measurements contributed to detect the local subsoil conditions of the southern part of L'Aquila. In particular information on the highly variable thickness of the red soils were estimated through the high-resonance frequency f_1, and considerations on the possible influence of a topographic effect were introduced through the low-resonance frequency f_0, in terms of frequency, amplitude and shape of the H/V curves.

Further studies are necessary to validate these preliminary results, considering in detail the available data along Porta di Bagno and Porta Napoli trenches, and Collemaggio scarp, and performing additional measurements along the other scarps that border L'Aquila terrace (e.g. Porta Rivera and Collemaggio trenches).

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