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Site effects from the building scale to the seismic microzonation scale: examples from the experience of L'Aquila

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Abstract

This paper illustrates the site characterization for evaluating local ground motion amplifications at two sites in the urban area of L'Aquila, performed for the reconstruction of buildings damaged by the April 6, 2009 earthquake. The paper is focused on the comparison between results obtained from site investigations carried out at the building scale and from information contained in the seismic microzonation study. Local amplifications inferred from microzonation may be considerably different from those provided by ground response analyses based on punctual soil data, due to the complex geological setting and the marked variability in geotechnical properties of the foundation soils. The practice of using seismic microzonation data for deriving the seismic action on buildings, not infrequent in structural engineering design, should be avoided or considered with caution.

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1. Introduction

The April 6, 2009 L'Aquila earthquake (M_L = 5.9, M_W = 6.1), in central Italy, caused considerable damage to structures over an area of approximately 600 square kilometres, including the city of L'Aquila (MCS Intensity I = VIII-IX) and several villages of the middle Aterno River valley. A maximum MCS Intensity I = IX-X was

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experienced at Onna and Castelnuovo. Even for similar types of buildings the distribution of damage within the affected area was irregular, creating speculation for both rupture directivity and site amplification effects.

Soon after the earthquake evaluations of site effects were obtained from the available strong motion recordings in the epicentral area, including the municipality of L'Aquila [1]. In the middle Aterno River valley, where such recordings were not available, a preliminary assessment of site effects was carried out based on the survey of the variable damage distribution (in nearby villages, or within the same village), which was related to geological and morphological conditions, accounting for the different types of buildings. Information can also be found in [2].

In the following months quantitative evaluations of site effects based on numerical ground response analyses were made available, as a result of a comprehensive Level 3 seismic microzonation study of the area of L'Aquila [3], promoted and coordinated by the Italian Department of Civil Protection and the Abruzzo Regional Authority. Seismic microzonation aims at characterizing the territory by identifying/delimiting areas of homogeneous seismic behaviour and is an essential tool for urban planning and risk reduction after an earthquake. The 2009 L'Aquila earthquake represented, in this sense, an important test of application of the newly introduced 2008 guidelines for seismic microzonation [4], directed by the Department of Civil Protection. The MS-AQ study [3] was extended to the portion of territory affected by the April 6, 2009 earthquake with a MCS Intensity I > VII, including L'Aquila and several municipalities grouped into 12 "macroareas". The study was accomplished thanks to the contribution of about 150 scientists and experts of various universities, organizations and local institutions. Later on the MS-AQ study [3] has been generally assumed as a basic reference document for reconstruction issues. However the high quality of this reference may induce professional engineers and geologists involved in design of restoration/ reconstruction of single buildings to improperly rely on the results of the microzonation study, rather than on site investigations and ground response analyses specifically carried out at the scale of the building.

This paper illustrates two examples related to buildings of different types located in different zones in the urban area of L'Aquila (Fig. 1a): (1) an important historic public building (Palazzo Centi) located in the city centre, which includes most of the historical heritage and was heavily damaged by the April 6, 2009 earthquake; (2) two ordinary private buildings (Via Campomizzi) located in the recently developed suburban residential area NW of the city centre, mostly populated by 3-6 storey reinforced concrete frame buildings and also considerably damaged.

2. Large-scale subsoil conditions in the urban area of L'Aquila

The geological setting in the urban area of L'Aquila (Fig. 1), extensively described in [3], is quite complex. In the city centre the upper portion of the subsoil is constituted by the deposit known as "Brecce dell'Aquila" (L'Aquila Breccia), composed of fine to coarse calcareous fragments of variable size (mostly of some centimetres) embedded in sandy or silty matrix, characterized by highly variable cementation and mechanical properties. The breccias, about 80-100 m thick, lay on fine- to medium-grained, mostly silty lacustrine deposits of average thickness ≈ 250-270 m, placed on the limestone bedrock (Fig. 1b). This sequence is characterized by an inversion of the shear wave velocity V_S with depth, at the transition from the breccias (where generally $V_S \approx$ 600-1000 m/s) to the lacustrine silts ($V_S \approx$ 400 to 600-700 m/s). Gravimetric investigations [3], confirmed by deep boreholes [5], have indicated that in the city centre the bedrock is located below 300 m depth. Seismic noise measurements carried out for the MS-AQ study [3] clearly identified, in the H/V spectral ratio, the presence of a peak of f_0 (frequency of the first significant amplification peak) at 0.5-0.6 Hz, corresponding to the top surface of the deep calcareous bedrock. The thickness of the upper breccia and lacustrine deposits decreases moving from the city centre towards the residential NW districts, in direction SSW to NNW (Fig. 1b). The morphology of this area is characterized as a "belt" of alternating hills and valleys sloping towards the alluvial Aterno River plain (Fig. 1a). Intermittent erosion processes due to tributary streams of the Aterno River have partially removed the top sedimentary deposits, leading to the formation of a sequence of elongated terraces, shaped in the L'Aquila Breccia as symmetrical ridges sloping towards SSW and separated by fossilized valleys with flat bottom filled with fine-grained eluvial-colluvial sediments.

Fig. 2 shows the Level 3 seismic microzonation map of the "Macroarea 1", including L'Aquila city centre and part of the outskirts, delivered by the MS-AQ study [3]. This map was constructed based on the results of numerical ground response analyses which, combined with information from Level 1 microzonation, permitted to identify/ delimit homogeneous "microzones" having the same amplification factor FA, calculated according to the criteria defined in [4]. It can be noted in Fig. 2 that most of L'Aquila city centre is characterized as a "stable zone prone to local amplification" (pale blue area), without indication of *FA*. In this zone ground response analyses indicated amplification only at low frequency (0.4-0.6 Hz), while no amplification was found at higher frequencies. This trend was partially confirmed by instrumental data, which recorded amplification at higher frequencies only at some sites in the southern part of the city centre. It is reminded, however, that the strong motion station in L'Aquila downtown (AQK) recorded a peak ground acceleration of about 0.3 g during the April 6, 2009 main shock. Other "stable zones prone to local amplification", characterized by *FA* ranging from 1.2 to 2, as well as "stable zones" and "instability-prone zones", are represented in Fig. 2 by areas of different colours.

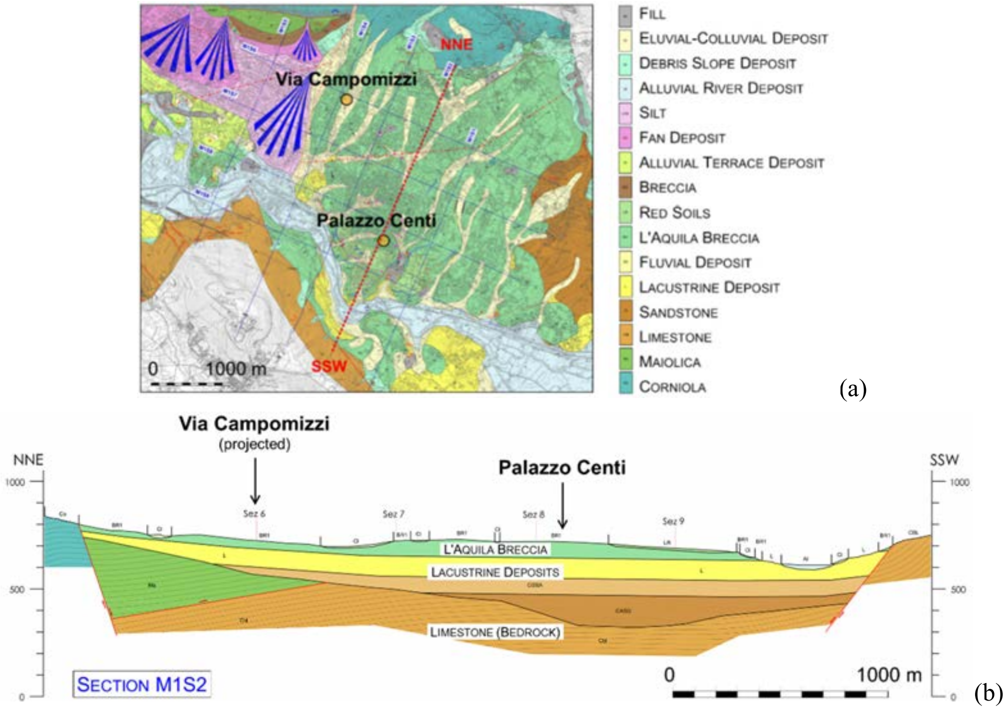

Fig. 1. (a) Geological map of the urban area of L'Aquila with location of the selected sites. (b) Schematic geological section across the city centre (both figures modified after [3]).

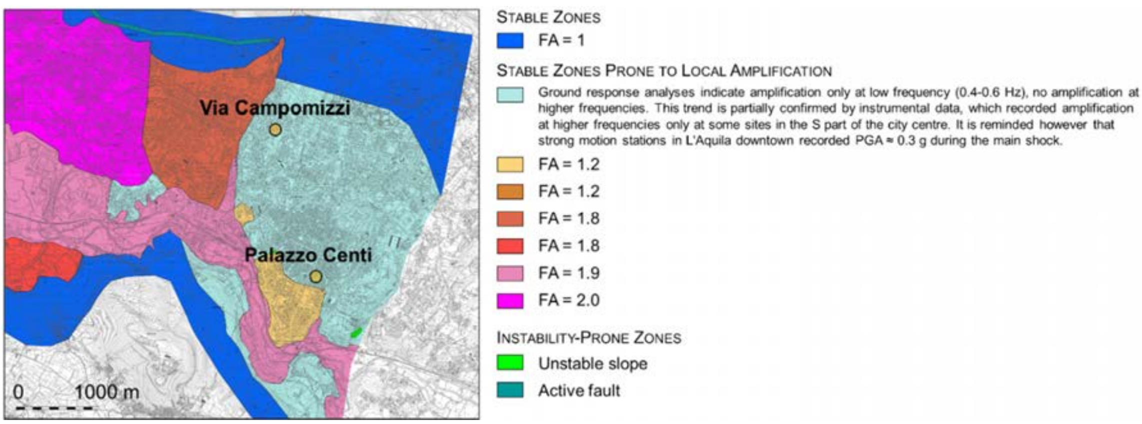

Fig. 2. Level 3 seismic microzonation map of "Macroarea 1" – L'Aquila city centre (modified after [3]).

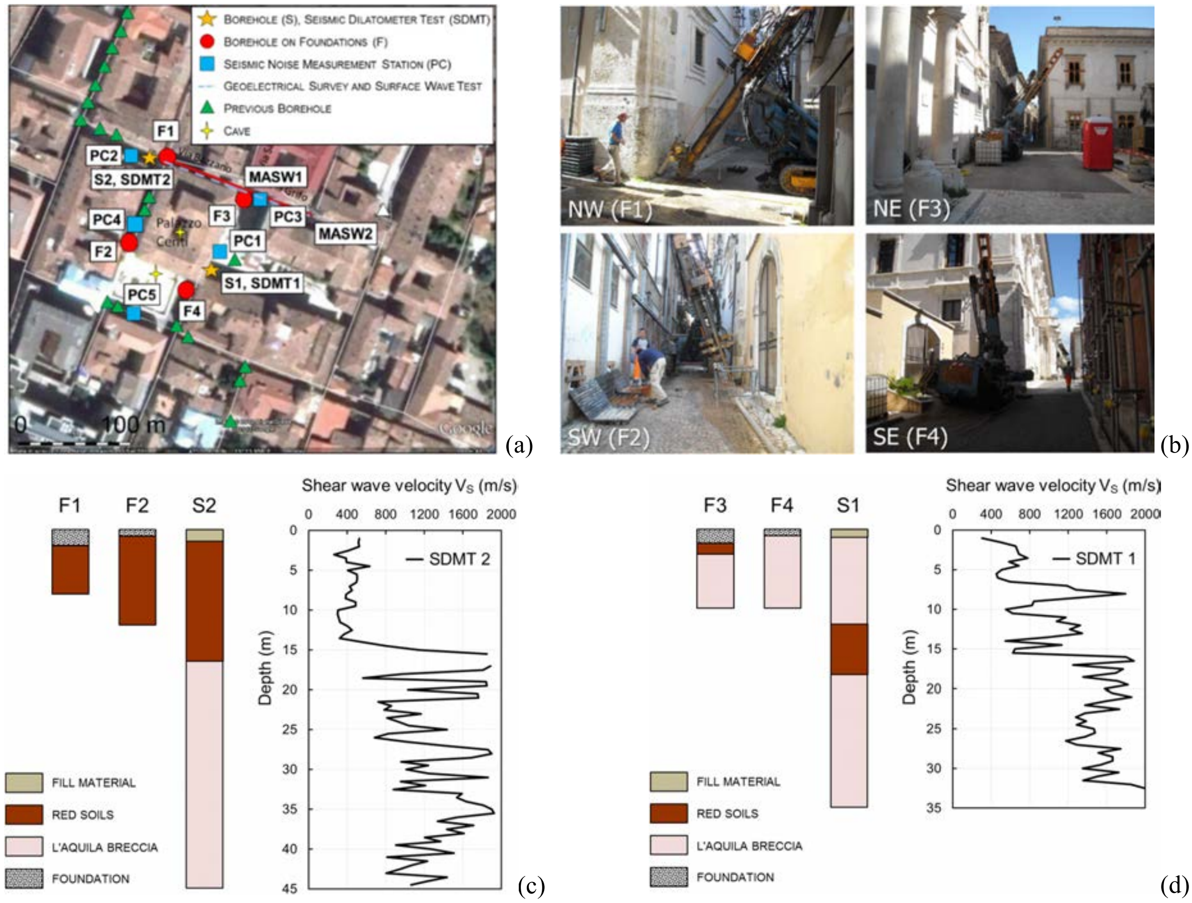

Fig. 3. Palazzo Centi. (a) Plan layout of site investigations [6]. (b) Inclined boreholes across existing foundations. (c), (d) Schematic stratigraphies and profiles of V_S measured by SDMT in backfilled boreholes along the NW-SW and NE-SE sides (modified after [6]).

3. Small-scale subsoil conditions at selected sites in the urban area of L'Aquila

3.1. Palazzo Centi (L'Aquila city centre)

Palazzo Centi is an important public building, seat of the Abruzzo Regional Authority, located in the heart of L'Aquila downtown. This historical masonry building was severely damaged by the April 6, 2009 earthquake. The site is located at the top of the morphological terrace where L'Aquila downtown was settled, characterized on a large scale by widespread outcropping of the L'Aquila Breccia (Fig. 1). However on a small scale the upper portion of the breccias may be irregularly affected by some peculiar local conditions (more frequently encountered in the southern part of the city centre), such as fine-grained residual weathered clayey-sandy silts locally known as "Terre Rosse" (Red Soils) in the top ≈ 10-15 m, as well as interbedded clayey-silty layers, underground karstic caves and man-made fill materials of variable thickness. An extensive geological, geotechnical and geophysical investigation [6] was performed in 2012 for the restoration of Palazzo Centi. The site investigation (Fig. 3a) included two boreholes to 35-45 m depth, two seismic dilatometer tests to 32.5-44.5 m depth (V_S-only measurements in backfilled boreholes according to [7], see also [8]), four inclined boreholes to 5-13 m depth across the existing foundations at the four corners of the building (Fig. 3b), five seismic noise measurement stations, two active multichannel surface wave tests (MASW) and a geoelectrical survey. Figs 3c and 3d show the schematic stratigraphies and the profiles of V_S measured by SDMT in the backfilled boreholes S2 and S1, respectively, along Via Rosso Guelfaglione (NW to SW side) and in Via San Michele (NE to SE side). The existing building foundations are based at 0.8 to 2 m depth and are placed on the stiff L'Aquila Breccia along the NW-SW side (F3, F4, Fig. 3d), while along the NW-SW side the building is founded directly on the Red Soils (F1, F2, Fig. 3c), which reach a maximum depth of 16.5 m at S2. V_S range between ≈ 600 and 1500 m/s in the breccias, in which typically a large V_S variability reflects highly variable cementation and mechanical properties [8], while in the Red Soils V_S is lower (≈ 450 m/s). As reported in [6], seismic noise measurements detected, besides a low frequency H/V peak at 0.5-0.6 Hz (typical of L'Aquila city centre), also a second peak at higher frequency (f_1) at about 6-7 Hz, broadly referable to the Red Soils. The temporary station AQ02, close to Palazzo Centi and located on the Red Soils, provided an amplification factor FA ≈ 1.61-2.00, calculated by using earthquake response spectra [9]. It is possible that the variable thickness of the upper fine-grained Red Soils and the significant lateral/vertical contrast in V_S and stiffness of the foundation soils may have originated different ground motion amplifications during the April 6, 2009 main shock.

3.2. Private buildings in Via Campomizzi (L'Aquila NW residential area)

The recently developed suburban area NW of the city centre (San Sisto – Pettino districts), where a large part of the L'Aquila residents have their homes, was also affected by considerable damage due to the April 6, 2009 earthquake. Most buildings in this area, built in the 1980-90's, are made of 3-6 storey reinforced concrete frame structures. The case here presented refers to a pair of private residential buildings located in Via Campomizzi, San Sisto district. The two buildings, 4-storey high, have an identical r.c. frame structure and both suffered significant damage. The buildings were constructed between the axis and the western side of one of the several morphological "dry valleys" engraved by extinct streams present in this area (Fig. 1a). The valley has a linear axis, dips from NNE towards SSW and has a trapezoidal cross section with a wide, deep bottom and narrow, gentle sloping sides. Massive anthropic urbanization in the '80-90's reshaped the sides of the valley, which now appear as flat terraces retained by small walls with buildings resting on the top. The site was investigated in 2010 (Fig. 4a) by one borehole to 30 m depth, two boreholes to 10 m depth adjacent to the existing building foundations, one Down-Hole test to 30 m depth and four seismic noise measurement stations.

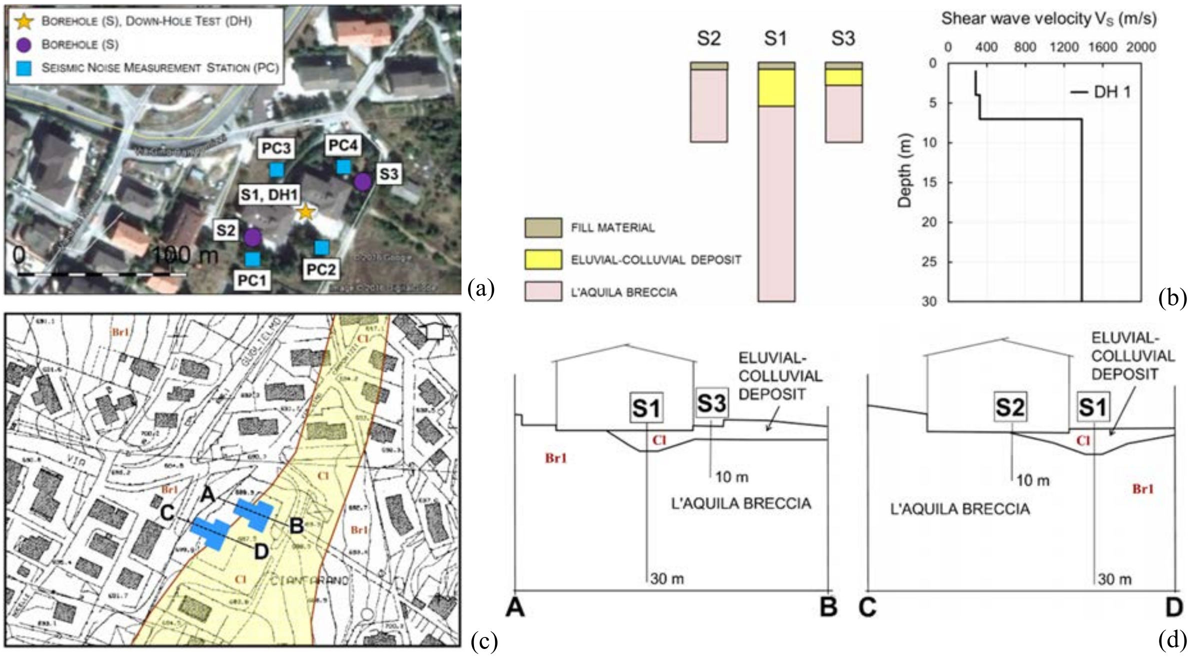

Fig. 4. Via Campomizzi. (a) Plan layout of site investigations. (b) Schematic stratigraphy and profile of V_S measured by Down-Hole. (c), (d) Schematic geological map and cross sections showing the variability of the eluvial-colluvial deposit.

The schematic stratigraphies and the profile of V_S measured by Down-Hole in S1 are illustrated in Fig. 4b. The site investigation highlighted a marked soil variability in the near-surface volume. An eluvial-colluvial deposit, mostly composed of clayey silt with some gravel, was detected in the central and eastern part of the area (S1, S3) to a maximum depth of ≈ 6-7 m metres, placed on dense calcareous gravel with variable cementation (L'Aquila Breccia). However this upper fine-grained layer was not found in the western part (S2), corresponding to one side of the morphological "dry valley" (Fig. 4c). The existing foundations of both buildings are then placed on soils with markedly different stiffness and mechanical properties (Fig. 4d). This may have also caused differential settlements during the April 6, 2009 main shock. The MS-AQ [3] amplification map shown in Fig. 2 indicates for this site possible amplification only at low frequency (0.4-0.6 Hz), as in the city centre, and no *FA* is indicated. However during an earthquake the local morphology of this area, coincident with one side of a "buried valley" and affected by considerable lateral/vertical contrast in V_S, may cause focalization/defocalization of the travel paths of the seismic waves "trapped" within the upper soft sediments, which may originate significant local amplification of the ground motion. Indeed major structural damage in this area was concentrated in buildings aligned along the western side of the buried valley, including the two under consideration.

4. Conclusions

In the two examples described in this paper detailed site investigations permitted to define 3D models of the subsoil at the building scale, irregularly affected by peculiar local conditions. Significant lateral/vertical contrasts in shear wave velocity and soil stiffness in the near-surface volume may originate variable local amplifications of the ground motion, which may result significantly different from those inferred from seismic microzonation maps.

The availability of a high-quality Level 3 seismic microzonation study – obviously an invaluable tool for urban planning and hazard reduction – may sometimes induce professional engineers and geologists involved in design of single buildings to improperly over-rely upon microzonation results, rather than on site investigations and ground response analyses specifically carried out at the scale of the building. The practice of using seismic microzonation data for deriving the seismic action on buildings, sometimes observed in structural engineering design (e.g. for post-earthquake reconstruction in L'Aquila), should be avoided or considered with caution.

References

[1] GEER Working Group, Preliminary Report on the Seismological and Geotechnical Aspects of the April 6 2009 L'Aquila Earthquake in Central Italy, Report No. GEER-016, Ver. 2.0, 2009, http://www.geerassociation.org

[2] P. Monaco, G. Totani, G. Barla, A. Cavallaro, A. Costanzo, A. D'Onofrio, L. Evangelista, S. Foti, S. Grasso, G. Lanzo, C. Madiai, M. Maraschini, S. Marchetti, M. Maugeri, A. Pagliaroli, O. Pallara, A. Penna, A. Saccenti, F. Santucci de Magistris, G. Scasserra, F. Silvestri, A.L. Simonelli, G. Simoni, P. Tommasi, G. Vannucchi, L. Verrucci, Geotechnical Aspects of the L'Aquila Earthquake, in: Special Topics in Earthquake Geotechnical Engineering, Series Geotechnical, Geological and Earthquake Engineering, Vol. 16, Springer Science+Business Media BV, 2012, pp. 1-66.

[3] MS–AQ Working Group, Microzonazione sismica per la ricostruzione dell'area aquilana, Regione Abruzzo – Dipartimento della Protezione Civile, L'Aquila, 3 vol. & Cd-rom, 2010 (in Italian).

[4] MS Working Group, Indirizzi e criteri per la microzonazione sismica, Conferenza delle Regioni e delle Province Autonome – Dipartimento della Protezione Civile, Roma, 3 Vol. e DVD, 2008 (in Italian).

[5] S. Amoroso, F. Del Monaco, F. Di Eusebio, P. Monaco, B. Taddei, M. Tallini, F. Totani, G. Totani, Campagna di indagini geologiche, geotecniche e geofisiche per lo studio della risposta sismica locale della città dell'Aquila: la stratigrafia dei sondaggi giugno-agosto 2010, University of L'Aquila, Report CERFIS 1/10, 2010 (in Italian), http://www.cerfis.it

[6] S. Amoroso, G. Di Giulio, S. Hailemikael, G. Milana, P. Monaco, M. Tallini, G. Totani, M. Vassallo, F. Villani, The Seismic Site Characterization of Palazzo Centi in L'Aquila City Centre: The Case Study of a Historical Building Damaged by the April 6th 2009 Earthquake, in: G. Lollino, A. Manconi, F. Guzzetti, M. Culshaw, P. Bobrowsky F. Luino (Eds.), Engineering Geology for Society and Territory, Vol. 5: Urban Geology, Sustainable Planning and Landscape Exploitation, Springer International Publishing, 2015, pp. 1091-1095.

[7] G. Totani, P. Monaco, S. Marchetti, D. Marchetti, VS measurements by seismic dilatometer (SDMT) in non-penetrable soils, M. Hamza et al. (eds), Proc. 17th ICSMGE, Alexandria, IOS Press, Vol. 2, 2009, pp. 977-980.

[8] P. Monaco, G. Totani, S. Amoroso, F. Totani, D. Marchetti, Site characterization by seismic dilatometer (SDMT) in the city of L'Aquila, Rivista Italiana di Geotecnica XLVII(3) (2013) 8-22.

[9] G. Milana, R.M. Azzara, F. Bergamaschi, E. Bertrand, P. Bordoni, F. Cara, R. Cogliano, G. Cultrera, G. Di Giulio, A.M. Duval, A. Fodarella, S. Marcucci, S. Pucillo, J. Régnier, G. Riccio, The contribution of seismic data in microzonation studies for downtown L'Aquila, Bull. Earthquake Eng. 9 (2011) 741-759.