Investigations by use SDMT seismic modulus to restore two historical buildings damaged by the April 6, 2009 L'Aquila earthquake

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ABSTRACT

The April 6, 2009 in L'Aquila (Italy) earthquake (M_w=6.3) caused heavy damages on the cultural and historical buildings. Historical masonry buildings are generally two storey buildings made of stone, brick or mixture of stone and bricks. The mortar is mud or lime. The foundation geometry, their base and static structural conditions are poorly known.

The subsoil conditions across the hill where the town of L'Aquila was built are quite complex non-penetrable soils. Numerical site response analysis must be preferred to reliably estimated the response of the entire deposit for design purpose. For two historical buildings, the paper shows a detailed investigations performed by use of the Seismic Dilatometer Test (SDMT) in backfilled boreholes and inclined boreholes carried out to investigate foundation base.

The methodology adopted is representative of that used for the preservation and restoration of other historical buildings in the city centre of L'Aquila.

Keywords: historical monument, site investigation, SDMT, site effect, ground motion analysis.

INTRODUCTION

Historical construction needs to be preserved in order to transmit their heritage to the following generations. In this regard, historical buildings were not designed or constructed to be earthquake resistant and so are vulnerable to collapse or to irreversible damages during earthquake in seismically active areas. Collapse frequently occurs because masonry, especially when under great ground motions, has poor resistance to bending and shear.

In situ soil test and surveys of structures following earthquake are governed by Italian building code (NTC/2018) which set out to repair damaged buildings and ensure they can withstand future earthquakes of the same magnitude. The regulations also recommended in situ testing techniques to use. The SDMT in non-penetrable soils permits to obtain V_s measurements down to unusually large depths (70-130 m). The experimental data in L'Aquila subsoil show that SDMT V_s profiles obtained are generally in acceptable agreement with the V_s profiles obtained by Cross-Hole, while the agreement with V_s profiles obtained by surface wave test (MASW) is less satisfactory.

The ground motions have certainly the most importance to explain the structural cracks in the structures, and any preservation measure designed or executed must start with a ground investigation and exploration of the bottom depth of brick foundations. For a rigorous seismic analysis of structures designers need of the results of a detailed seismic site response analysis.

Due to the close proximity of the city of L'Aquila to the ruptured fault of 2009 year, in the urban centre historic masonry buildings, major historic churches collapsed or underwent extensive damage.

Passed studies described Palazzo Centi site investigations finalized to define subsoil model affected by a peculiar local condition: lateral and vertical contrast in V_s may cause variable amplification, at the building scale, that are not considered in seismic microzonation studies.

In this paper the site response analyses are shown for two important historical buildings in city centre of L'Aquila where a detailed investigations were carried out using Seismic Dilatometer Module inserted and advanced into borehole backfilled with sand.

SUBSOIL CONDITIONS ACROSS THE HILL OF L'AQUILA OLD CENTRE

The location of the two studied ancient palaces: Palazzo Centi and Palazzo del Governo are highlighted of the old city centre of L'Aquila located at an absolute elevation of 717 m. a.s.l. (see Figure 1).
Investigations in city centre include some deep boreholes (300 m deep in Piazza Duomo) and a large number of SDMT. Many of SDMT were carried out as part of investigation planned to obtain input data for site seismic response analyses for design of restoration/retrofitting of important historical buildings, severely damaged by the earthquake.

Figure 1. The location of the two studied ancient palaces, Palazzo Centi and Palazzo del Governo, in the old centre of L'Aquila.

In a schematic geological section across L'Aquila city centre (see Figure 2), the upper portion of the subsoil is composed of the deposit known as the "Brecce dell'Aquila", consisting of fine to coarse calcareous fragments of variable size (mostly a few centimetres) embedded in sandy or silty matrix, characterized by highly variable degrees of cementation and mechanical proprieties. The breccias, about 80-100 m thick, lay on fine-to medium-grained mostly silty lacustrine deposits of about average thickness of 250 m placed on the limestone bedrock. In the city centre the bedrock is located below 300 m depth.

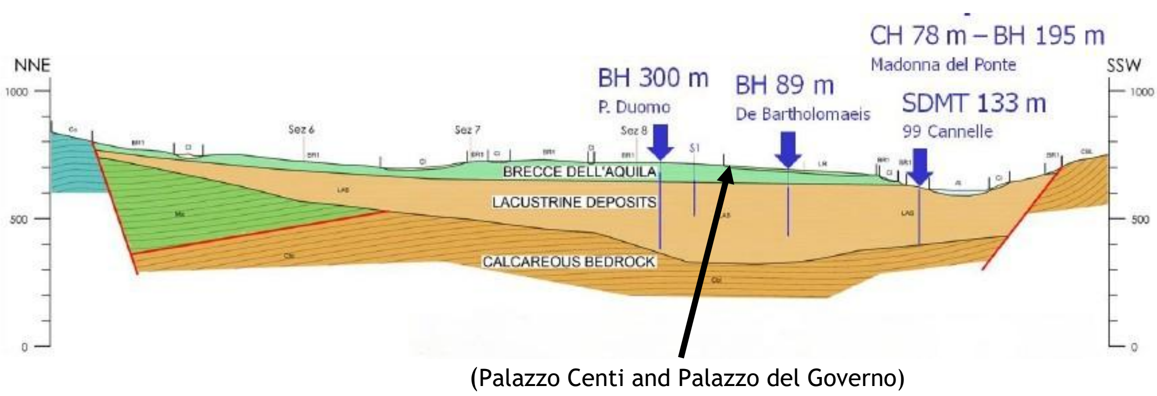

Figure 2. Schematic geological section across L'Aquila city centre.

SEISMIC MODULE (SDMT) FOR MEASURING SHEAR WAVE VELOCITY IN NON-PENETRABLE SOILS

The seismic module is a cylindrical element, with or without the Marchetti Dilatometer test (DMT) blade at the tip, equipped with two receivers spaced 0.5 m. The shear wave source, located at ground surface, is a pendulum hammer which hits horizontally a steel rectangular plate pressed vertically against the soil (normally by the weight of the truck). The plate is oriented with its long axis parallel to the axis of the receivers. The shear wave generated at the surface reaches first the upper receiver, then after a certain delay, the lower receiver. The seismograms acquired by two receivers, amplified and digitized at depth, are visualized on a PC, in real time, and the time delay between the signals is determined immediately. The determination of the time delay, Δt, from seismograms is obtained using a cross-correlation algorithm generally well conditioned. An example of seismograms, as recorded and re-phased is shown in SDMT Test lay-out (see Figure 3 left).

Figure 3. *SDMT Test lay-out* (left*). V_S measurements by SDMT in backfilled boreholes in non-penetrable soils (right).*

The procedure for the use of the seismic module (SDMT) in non-penetrable soils, gravel and coarse calcareous fragments like the Breccia (Totani et al., 2009) is the following: a) drill a borehole to require test depth; b) fill borehole with sand; c) insert the seismic module and advance it into the backfilled borehole by use a conventional penetrometer, by means its rods, or use the same machine that has performed the borehole, by means its rods (see Figure 3 right). V_s measurements are typically taken every 0.50 m of depth. Comparative test at various sites, where both the usual penetration procedure and the backfilling procedure were adoptable, indicate that Vs values obtained in the backfilled borehole are essentially coincident with the Vs obtained with the Vs obtained by penetrating the soil.

HISTORY AND STATE AFTER 2009 EARTHQUAKE OF THE HISTORICAL PALACES

Palazzo Centi in L'Aquila centre city is one of the most notable examples of aristocratic architecture. Its strategic location next to the Central Market, has made this building an essential component of the city's historical, social and urban development. The 1703 earthquake, caused many damages in the Palace and the works to repair the masonries have been going for 70 years. In 1995 the Palace became the home of Abruzzo Regional Council (see Figure 4). The Palace has three levels and rectangular plan about 42x36 m with an internal court. During the 2009 earthquake, several cracks and local collapse mechanisms have been active, in particular disconnection between the orthogonal walls, the formation of large cracks, collapse of some floors and important damages to the stairs.

The Palazzo del Governo was part of a conventual building complex erected by Augustinian friars on the year of our Lord 1282. The vertical masonry structures are built with stones and brick walls. The horizontal structures are barrel and cross shaped vaults built with bricks.

During the 2009 earthquake, kinematic mechanisms were activated, leading to the disintegration of the masonry due to the poor mechanical properties of the building materials. The deformability of the horizontal structures, together with the attainment of maximum shear stress, caused devastating collapses of the floors and parts of the vertical walls (see Figure 5).

Figure 4. *Palazzo Centi during soil investigations (left). Cracks after 2009 earthquake (right).*

Figure 5. *Palazzo del Governo before (left) and after earthquake (right).*

GEOTECHNICAL PROFILES AND FOUNDATION LEVELS

The site investigations have been carried out to determine soil profiles, geotechnical propriety and the depth of the foundation laying. The results of the SDMT test, combined with the stratigraphic profiles from the boreholes, helped to define the variability of the upper portion of the subsoil and enabled to measure the shear wave velocity (V_s) every 0,50 m of depth. The V_s profiles obtained were used for local seismic response analyses. Fine-grained residual soils, locally known as "Terre rosse" (red soils), are frequently encountered in the upper portion of the breccias, particularly in the area of the two palaces. The values measured in the "Terre rosse" are typically 400 m/s.

The profiles of Vs from SDMT show a marked variability in the breccias: are mostly 600-1000 m/s or higher, generally increasing with depth (see Figure 6). It is supposed that the observed dispersion of the measured V_s could reflect some variability in grain size distribution, cementation and/or mechanical properties, cementation and/or mechanical properties typical of this material (see Figure 7).

Figure 6. *Vs Profiles from SDMT at Palazzo Centi.*

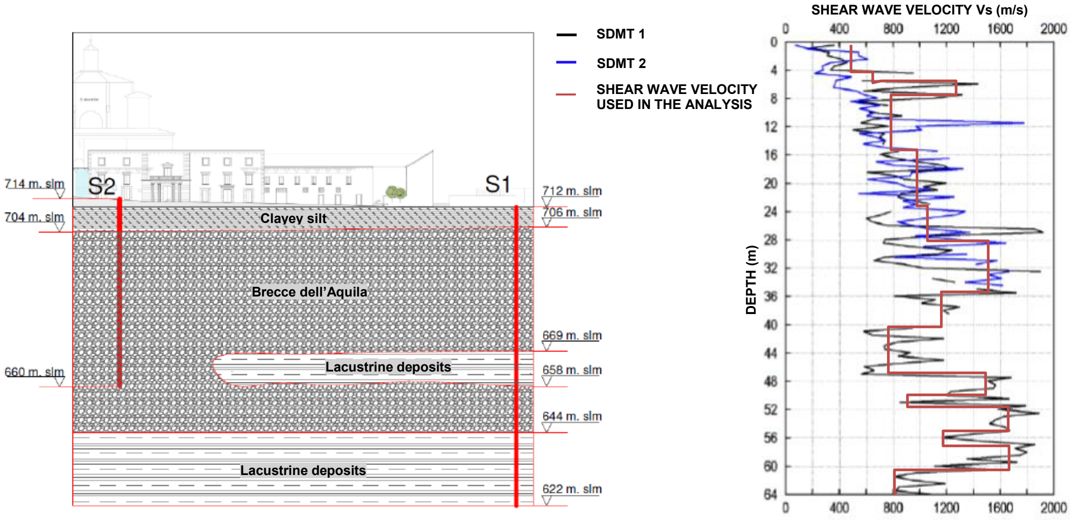

Figure 7. *Stratigraphic section under Palazzo del Governo (left). Vs Profiles (S1, S2) from SDMT (right).*

The foundations are based beneath the ground level with its bottom on the natural soil layer at different levels (see Figure 8). They fulfil just sufficient bearing capacity and serviceability. From the point of view of middle to long term serviceability, during seismic movements appears to require actions as stabilisation using soft micro piles drilled through the masonry with across beams and strip footings.

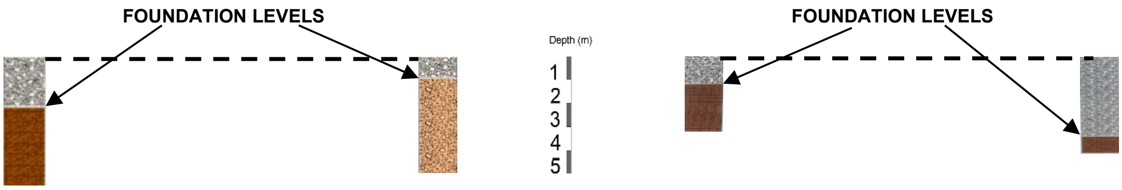

Figure 8. *Foundation levels Palazzo Centi (left). Palazzo del Governo (right).*

SITE SEISMIC RESPONSE ANALYSES

Ground response analyses can properly satisfy the needs for realistic and precise seismic excitation in analysis of structures or in soil-structure interaction. Considering horizontal or gently sloping grounds and soil profiles having parallel set of layers beneath the foundations of the palaces, the 1D ground response analysis were performed by using the computer codes STRATA.

For the study area the subsurface model is composed of the following properties: (i) residual soil and Clayley Silt V_s whit a 400-600 m/s and ; (ii) the L'Aquila Breccias with a V_s of 600–1500 m/s; (iii) lacustrine/fluvial deposits with a V_s of 600–800 m/s; and (iv) carbonate substratum (BC), considered to have a V_s of 1250 m/s in the simulation of the seismic bedrock. The depth of the bedrock is about 350 m. The soil parameters for the geotechnical units used for the 1D and analyses including the unit weight and references to the stiffness decay G/G_0 and damping ratio D curves (Totani, 2023). In addition, the bedrock was modelled with an elastic behaviour and an initial critical damping ratio D_0 equal to 0.5%.

The selection of natural accelerograms consists of seven unscaled horizontal natural records, selected by the ITACA archive. The average of the selected spectra respects the compatibility with the Uniform Hazard Spectrum (characterized by a return period T_R = 475 years) at rock conditions referred to subsoil class A, in the 0.1–1.5 s period range. This is proposed by the Italian Building Code (NTC 2018). The corresponding 5% damped response spectra show the comparison between the average input spectrum and the IBC reference shape (see Figure 9). The tolerances chosen for the average spectrum are +30% for the upper one and -10% for the lower one respect to the reference spectrum.

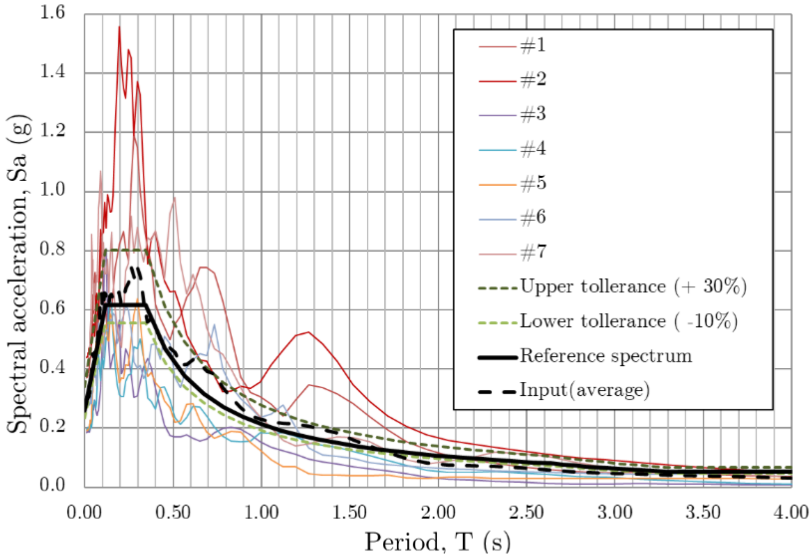

Figure 9. *Input time histories (different colours) from ITACA selection, average shape spectrum (dashed black line) and reference spectrum from IBC18 (continuous black line).*

The first results (see Figure 10) are the average transfer function (TF). In particular, a low-frequency resonance of basin was identified in good agreement with the deep rock fundamental frequency of 0.5-0.6 Hz in each site. On the contrary, the secondary natural frequency between 5 and 8 Hz is strictly related to upper soil soft layers.

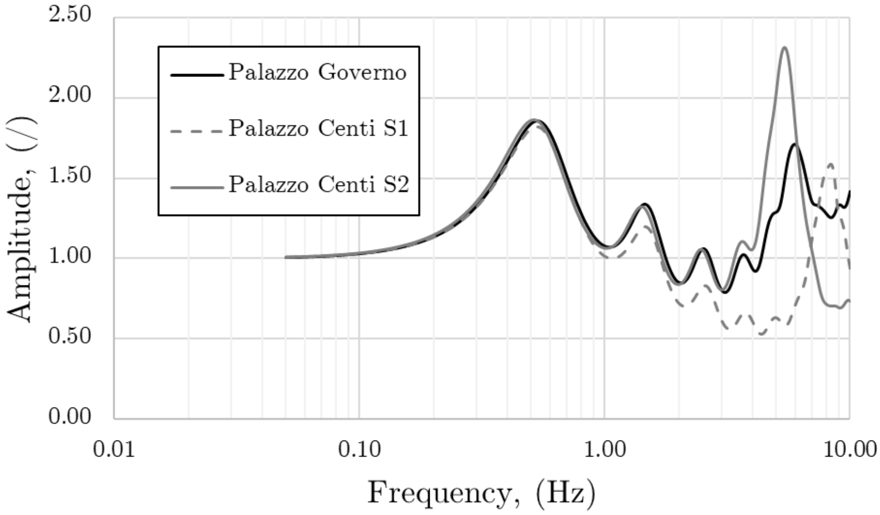

Figure 10. *Amplification range vs frequency range.*

The spectral acceleration values (see Figures 11-12 and 13), reflect the amplification range according to TF_s in Figure 10 and the V_s profiles used. The role of upper local subsoil conditions produces changing in the shapes of spectra at lower period (high frequencies). In addition, at this range of frequencies is important to consider the non-linear soil behaviour in numerical analyses.

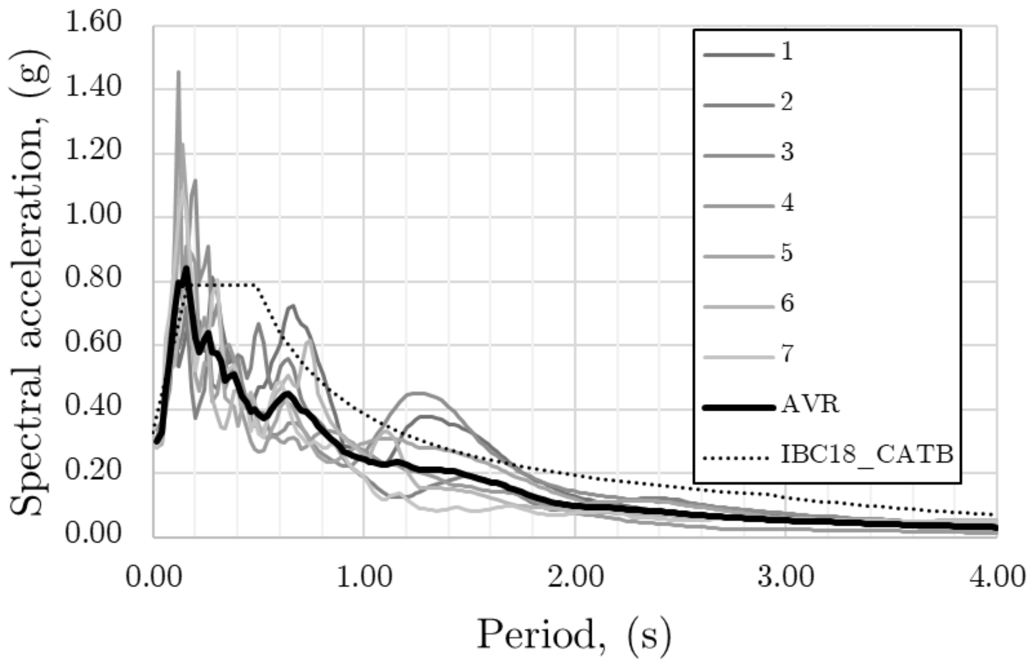

__Figure 11.__ Seven elastic acceleration response spectra (grey scale lines), Average "AVR" (black line) and the Italian Building Code spectra for the subsoil category B "IBC18_CATB" (dotted black line) for Palazzo del Governo.

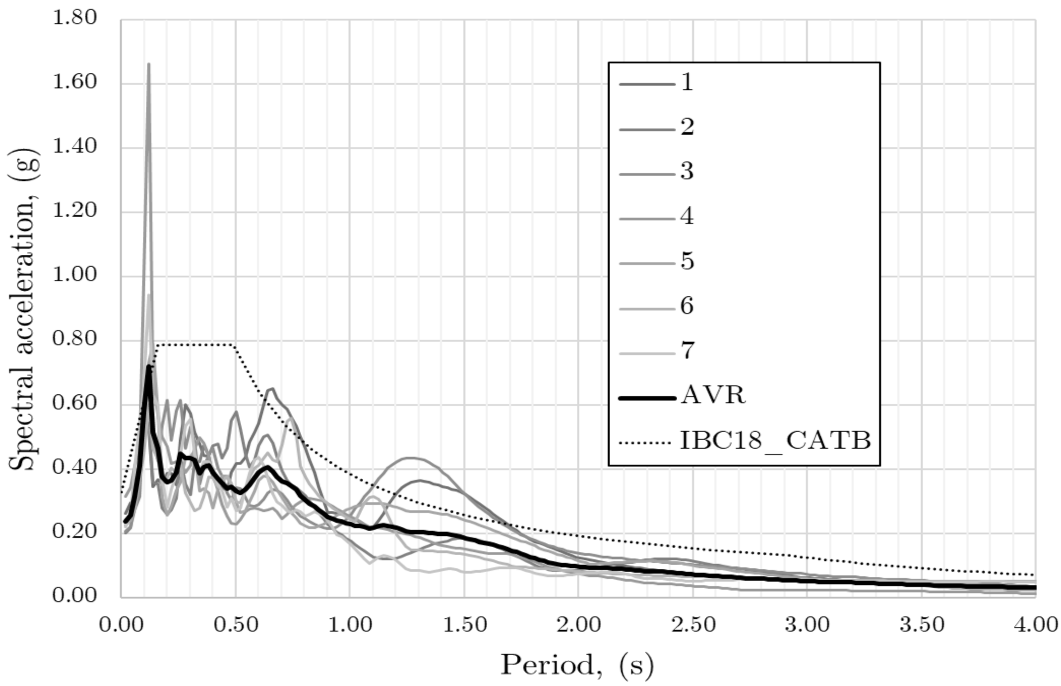

__Figure 12.__ Seven elastic acceleration response spectra (grey scale lines), Average "AVR" (black line) and the Italian Building Code spectra for the subsoil category B "IBC18_CATB" (dotted black line) for Palazzo Centi using SDMT1.

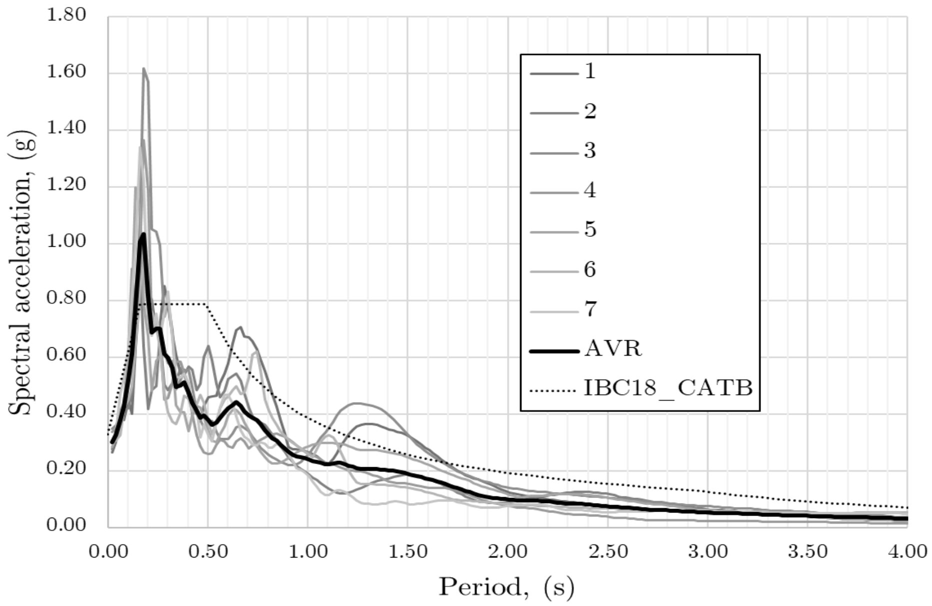

Figure 13. *Seven elastic acceleration response spectra (grey scale lines), Average "AVR" (black line) and the Italian Building Code spectra for the subsoil category B "IBC18_CATB" (dotted black line) for Palazzo Centi using SDMT2.*

CONCLUSIONS

The methodology adopted for the retrofit of Palazzo Centi and Palazzo del Governo is representative of those generally involved in the preservation and restoration of historical buildings in the city of the L'Aquila. V_s profiles obtained by SDMT have been used to define the input data for 1D ground response analysis were performed by using the computer codes STRATA.

In post-earthquake reconstruction is very common the practice of using in design a spectra acceleration shape derived from microzonation seismic studies. The simplified elastic response spectra prescribed by Italian Technical Code of Construction (NTC 2018) appear inadequate and should be used with caution in the case of shear wave velocity inversion with depth, typical in the historic centre of L'Aquila. So, numerical site response analysis must be preferred to reliably estimate the response of the entire deposit for design purpose.

It is evident that the ground response analysis offers important information at high frequencies that influence dynamic behaviour of masonry building and local mechanism of collapse.

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