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The local seismic response and the effects of the 2016 central Italy earthquake on the buildings of L'Aquila downtown

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ABSTRACT The number of seismic isolated buildings has increased in recent years in Italy. In particular, in the city of L'Aquila, mostly affected by the 2009 earthquake, many new seismic isolated buildings were built and seismic isolation systems were also incorporated into many existing buildings. The frequencies range in which these buildings operate is substantially different from that of classical buildings. In particular, the seismic isolation, allowing the periods of the first modes of vibration to be generally moved beyond 2 s, in the absence of local amplifications, drastically reduces the stresses on the structure due to seismic events. On the other hand, special conditions relating to the morphology and stratigraphy of soils can produce amplifications, even considerable, in the operating frequencies typical of such buildings. This appears to be the case for L'Aquila. The historical centre of the town, indeed, was founded on a terrace rising about 50 m above the Aterno riverbed and is formed by alluvial Quaternary breccias consisting of limestone clasts in a marly matrix over imposed to 200 m thick lacustrine sediments which lie over a 300-400 m deep calcareous bedrock. This geological context deeply affects the dynamic behaviour of the formations and the local seismic response on the surface. The microzoning studies outlined a large presence of low frequency amplification (about 0.4-0.6 Hz) in the historical centre. The paper focus on the proper assessment of the seismic action to adopt in low frequency amplification sites with reference to the current Italian seismic regulations, also in perspective to the design of seismic isolated buildings, and evaluate the effectiveness of 1D and 2D local seismic response methods to predict surface amplification effects.

Key words: local amplification, base isolation, site effects, earthquake.

1. Introduction

The seismic series that occurred in central Italy between August 2016 and January 2017, culminating with the M_w 6.5 event on 30 October 2016, strongly affected also the area of the city of L'Aquila, with an estimated V MCS intensity for the main shock of 30 October (Gdl INGV, 2016). Major events also resulted in damage to several buildings, mostly limited to non-structural components (including those repaired and strengthened after the earthquake of 6 April 2009). The characteristics of seismic motion in different areas of the city have caused the activation of seismic isolation devices in several buildings retrofitted or rebuilt using this technique. The accelerometric

Fig. 1 - Locations of the RAN and INGV network accelerometric stations in the urban area of L'Aquila.

recordings of the stations present in the area, show a great variability in the characteristics of the shaking, confirming the results of many previous studies, that highlighted the remarkable effects of stratigraphic and topographical amplification in particular areas of the municipal territory. It is interesting to analyse the accelerometric records available for the events of 24 August 2016 (M_w 6.0) and 30 October 2016 (M_w 6.5). Such records can be found on the ITACA portal, outlined by Luzi *et al.* (2008) and Pacor *et al.* (2011), and in the national accelerometric network RAN (Dolce, 2011), and relate to different accelerometric stations located near the historical centre of the city (Aquila Park - AQK and Castle - AQU) and in the western area, along a NE-SW alignment that involves the peripheral areas of Pettino and Coppito.

Examination of the signals recorded during 24 August and 30 October main shocks shows a marked difference in spectral forms relating to various areas of the city, confirming the effects of the propagation process of seismic waves in different surface layers.

Spectral forms in acceleration for the AQG, AQU, and AQK accelerometric stations relating to the events of 24 August and 30 October 2016 are shown in Fig. 2. The spectrum recorded in the same stations during the main shock of 6 April 2009 at 3.32 (a.m.) and the spectrum of the Italian Seismic code (NTC 2008) at SLV (life-safety limit state) for soil B type are also depicted for comparison. As can be seen from the figure, although the various stations have recorded peak ground accelerations (*PGA*) of a comparable magnitude and in any case lower than 55 cm/s^2, spectral accelerations reach peaks up to 280 cm/s^2 at frequencies very far from one another.

In particular, for the AQG station (which can be considered located on the carbonate outcrop) there is a strong amplification, even if for a narrow frequency range between 3.0 and 6.0 Hz. Instead, the recordings of the AQK station shows a marked acceleration peak between 0.4 and 0.6 Hz, higher, in this range, also at the spectral acceleration levels foreseen by the NTC spectrum at SLV for the site under examination (B soil).

This circumstance is due to the geological peculiarities that characterize the stratigraphy of the site on which the AQK accelerometric station and more generally the whole historic centre of L'Aquila are located. This situation strongly affects the characteristics of seismic shaking on the surface and the behaviour of the buildings present in the area.

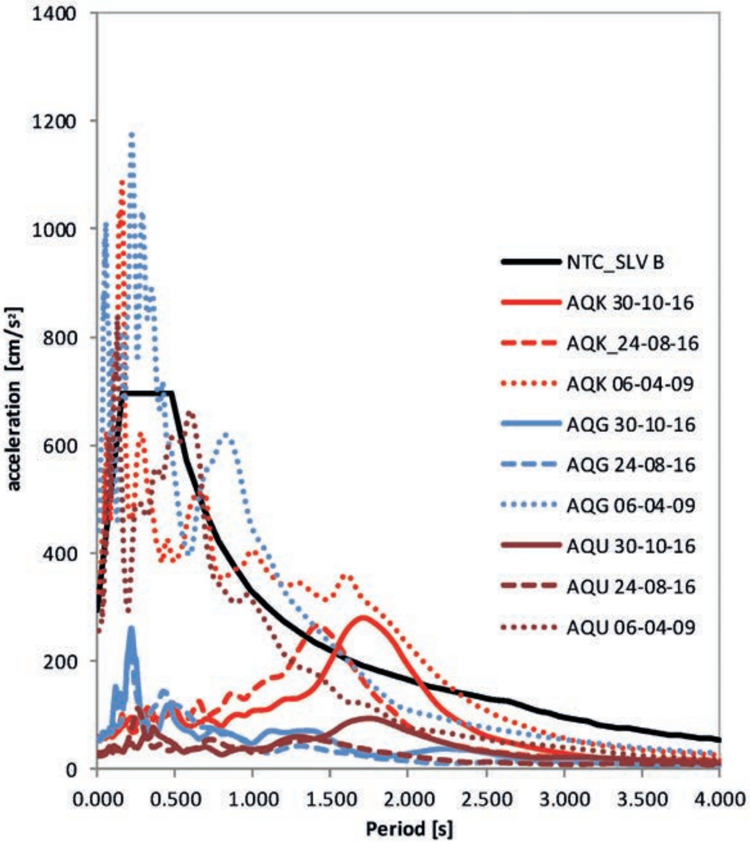

Fig. 2 - 5% damping acceleration response spectra relative to accelerograms recorded by stations AQK, AQG, and AQU in 2009 and 2016 main events and NTC 2008 SLV spectrum for L'Aquila (soil category B).

2. Subsoil model and seismic site characterization

The subsoil model of L'Aquila downtown has been reconstructed by means of more than 600 boreholes, some of which are also 200-300 m deep. They were carried out following the 2009 earthquake for building reconstruction and specific seismic site characterization projects. The geological formations of L'Aquila downtown belong to Quaternary clastic continental deposits pertaining to the Aterno River basin. These formations are surrounded by and lie on Meso-Cenozoic carbonate and terrigenous formations representing the substratum of L'Aquila downtown.

The section of L'Aquila downtown shows a Quaternary graben structure filled up by the MDS formation (alluvial pelite and sand) (Fig. 3). The northern fault of the graben represents a NW-SE oriented fault, which crosses L'Aquila downtown near the L'Aquila castle. This fault represents the SE splay of Mt. Pettino active fault outcropping NW-wards. L'Aquila Breccias, which are 20-100 m thick, are the terraced hill on which L'Aquila downtown stands. A layer of Red Soils, spanning from a few metres up to 30 m in thickness and an anthropic fill lie on

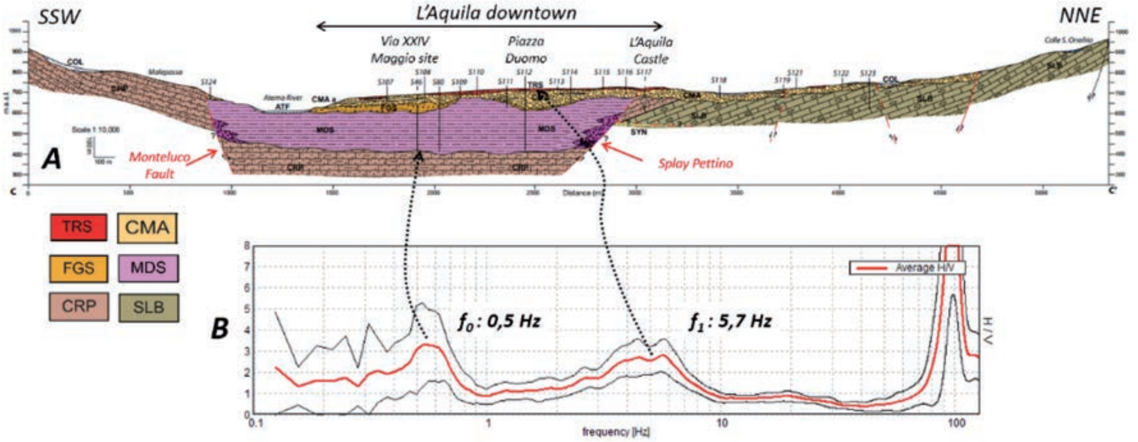

Fig. 3 - A) Geological section of L'Aquila downtown. TRS: Red Soil (Upper Pleistocene); CMA: L'Aquila Breccia (Middle Pleistocene); FGS and MDS: alluvial pelite and sand (Middle-Lower Pleistocene); CRP and SLB: carbonate and terrigenous formations (Meso-Cenozoic) (modified from Nocentini *et al.*, 2017). B) Microtremor HVSR spectrum acquired at Piazza Duomo, according to Del Monaco *et al.* (2013).

L'Aquila Breccias. The 200 m thick Middle-Lower Pleistocene MDS formations are located below the L'Aquila Breccia that, in turn, lies on the Meso-Cenozoic calcareous substrate. The southern part of L'Aquila downtown is characterized by the graben with a 200-300 m thick Quaternary stratigraphy. On the contrary, the northern part is formed by L'Aquila Breccia lying onto a shallower calcareous substratum showing a totally different stratigraphy with respect to the southern sector. The different stratigraphy influences also the seismic site characterization as demonstrated by the microtremor data.

Two resonance frequencies (f_0: 0.4-0.7 Hz and f_1: 4.0-9.0 Hz) were recorded in the southern sector by more than 300 single-microtremor measurements performed in L'Aquila downtown; in the northern part, outside the graben, the microtremor frequencies are less evident, according to Del Monaco *et al.* (2013) and Di Giulio *et al.* (2014).

Numerical 1D and 2D simulations were carried out with linear and linear-equivalent approach, performed with STRATA (Kottke and Rathje, 2008) and LSR 2D (by STACEC S.r.l.) software, with the purpose of verifying the subsoil model shown in Fig. 3. STRATA (Kottke and Rathje, 2008), is based on a half domain referring to an infinitely extended horizontal soil layer and the code LSR 2D can perform a 2D modelling using a finite element approach, time domain, under total stresses conditions and by using the Kelvin-Voigt model. LSR 2D performs the 2D analysis using the lumped masses approach; the subsoil model is discretized in a mesh with triangular or preferably quadrangular shape elements, interconnected at their common nodes, solving the elastodynamic computation through a step-by-step integration in the time domain with the Newmark and the Constant Average Acceleration methods.

The L'Aquila downtown section has been modelled with quadrangular mesh elements (step: from 10 m to 1 m). The LSR 2D code uses viscous dampers to simulate the deformable rock behaviour, located at the base of the mesh, and free-field pillar applied on the section edges, with the goal to adsorb the S-waves reflection from the section edges. The seismic input is applied simultaneously to the nodes of the bedrock base in the form of S waves with a vertical propagation. The nonlinear soil behaviour is considered by using a linear-equivalent approach. The dissipative properties of the soil are modelled through the matrix dissipation that derives from the assembly of the single elements dissipation matrices calculated according to the following complete Rayleigh equation:

$$C_i = \alpha_{Ri} M_i + \beta_{Ri} K_i \tag{1}$$

where α_{Ri} and β_{Ri} are the Rayleigh coefficients and M_i, C_i and K_i indicate the local matrices of the single element.

The adoption of the Rayleigh equations involves a frequency-dependent damping that affects the modelling results. To reduce the damping effect, LSR 2D uses Rayleigh coefficients calculated according to two natural frequencies of soil, ω_n and ω_m, as follows:

$$\alpha_{Ri} = \xi_i \frac{2\omega_m * \omega_n}{\omega_m + \omega_n} \qquad \beta_{Ri} = \xi_i \frac{2}{\omega_m + \omega_n} \tag{2}$$

where ξ_i is the viscous damping ratio of the i-th element; $\omega_m = \omega_1$, the first natural vibration frequency of soil; $\omega_n = n\, \omega_1$, where n is the odd integer that rounds up the predominant frequency ratio of the seismic input ω_{in} and frequency ω_1. For LSR 2D, the α and β coefficients of the Rayleigh damping equation are set starting from two control frequencies, ω_{min} and ω_{max}, defining the frequency interval where the damping can be assumed free from numerical bias. The first frequency, f_{min}, is the natural frequency of the model corresponding to the first natural circular frequency of the last iteration, ω, while the second frequency, ω_{max}, is a function of the predominant frequency of the seismic input, ω_{in} and of ω_{min}, as shown in an earlier paper (Hudson *et al.*, 1994). This procedure allows one to obtain results in good agreement with those calculated by frequency-independent damping models, according to Chopra (1995).

The geophysical and geotechnical parameters used for the 1D and 2D modelling are reported in Table 1.

Table 1 - Geophysical and geotechnical parameters of the units used for the 1D and 2D modelling, according to Macerola (2017).

Geophysical unit	**Lithology**	**Age**	***Vs* (m/s)**	**γ (kN/m³)**	**G/G$_0$**	**D (%)**
CPB - PPS - ATF	Alluvial deposits Sand and gravel	Quaternary	300	19.0	Sand - Seed *et al.* (1986)	Sand - Seed *et al.* (1986)
COL	Colluvial deposits Gravel	Quaternary	400	19.4	Rollins *et al.* (1998)	Rollins *et al.* (1998)
TRS	Red soil Silt	Quaternary	400	19.0	Clay Vs>400 m/s GdL MS-AQ (2010)	Clay Vs>400 m/s GdL MS-AQ (2010)
CMAa	Calcareous silt	Quaternary	400	18.5	De Magistris *et al.* (2013)	De Magistris *et al.* (2013)
CMA	Calcareous breccia	Quaternary	800	21.0	Modoni and Gazzellone (2010)	Modoni and Gazzellone (2010)
MDS -1	Silt	Quaternary	600	18.5	De Magistris *et al.* (2013)	De Magistris *et al.* (2013)
MDS -2	Silt	Quaternary	700	18.5	De Magistris *et al.* (2013)	De Magistris *et al.* (2013)
MDS -3	Silt	Quaternary	800	18.5	De Magistris *et al.* (2013)	De Magistris *et al.* (2013)
CRP-SLY-SLB	Bedrock Limestone and sandstone (southern - northern zone)	Meso-Cenozoic	1250	23.0	Linear elastic behaviour (G$_0$ 4000 MPa)	Cost = 0.5%

Five seismic inputs were used in the numerical modelling: NTC-08 is a synthetic free-field accelerogram compatible with the uniform hazard spectrum (UHS); DET is a synthetic free-field accelerogram at the bedrock compatible with the spectrum obtained from the deterministic attenuation relationship for specific magnitude and distance parameters (M_w 6.7, R_{epi} = 10 km), as outlined in Bordoni *et al.* (2014); AQK is a strong-motion accelerogram of L'Aquila earthquake (6 April 2009; M_w 6.3) recorded at L'Aquila downtown and Amatrice (AMA 24 August 2016; M_w 6.0) and Norcia (NOR 30 October 2016; M_w 6.5) mainshocks recorded far-field at outcrop bedrock in L'Aquila plain (7 km west of L'Aquila downtown).

The numerical 1D and 2D simulations performed, showed two seismic impedance contrasts: an evident f_0 resonance frequency due to the overlapping of MDS formation on the calcareous substratum at a depth of 200-300 m; a less clear f_1 frequency, instead, caused by the irregular and discontinuous support of the Red Soil on the L'Aquila Breccia, as previously described in De Luca *et al.* (2005) and Tallini *et al.* (2016).

In two points of analysis named Via 24 Maggio and Duomo sites, the resonance frequency f_0 2D is quite different from f_0 1D; this result is evident both in linear and equivalent linear models; the amplitude values of the 2D simulation are higher than 1D. Instead, there is a good agreement between the main resonance frequency of the 2D simulations with the data processed in SSR of the weak motion (E-W and N-S components) and with the HVSR microtremor data. Comparison between simulation and experimental data (Chopra, 1995) confirms that the impedance contrast between MDS formation on the calcareous substratum is set at the correct depth (above 300 m) and the huge difference in amplification between 2D (amplitude value = 5-6) and 1D (amplitude value = 2) simulations have highlighted a 2D "deep valley" amplification effect, according to Macerola (2017).

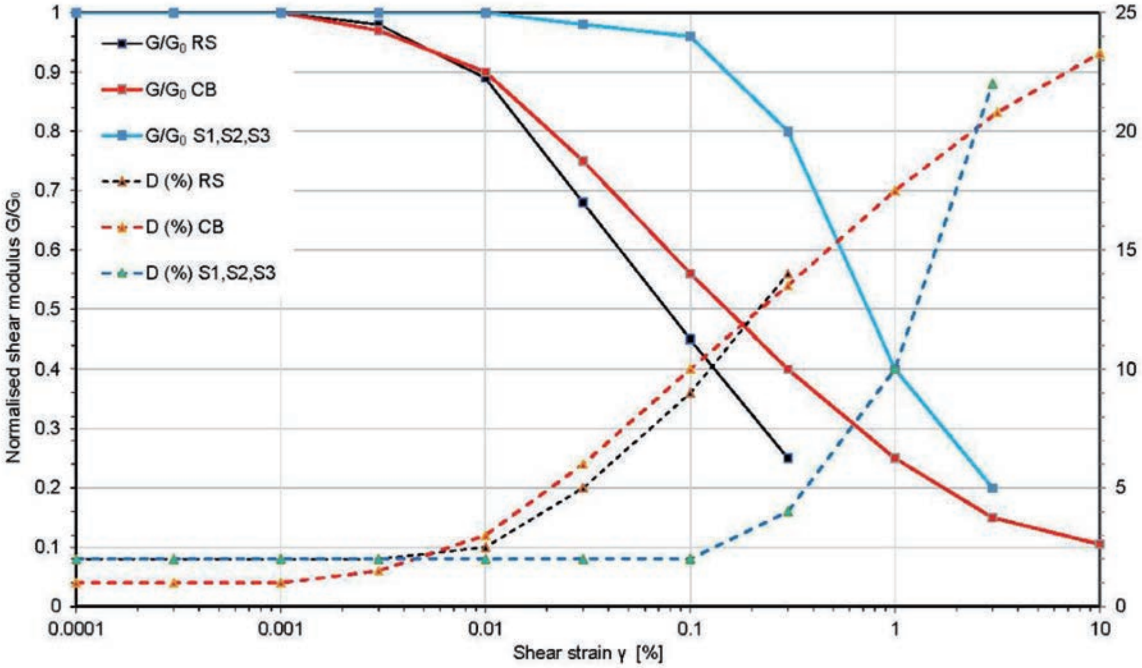

Fig. 4 - *G/G0-γ* and *D-γ* diagrams used for the 1D and 2D modelling. RS: Red Soil; CB: calcareous breccia; S1, S2, S3: silt, according to Macerola (2017).

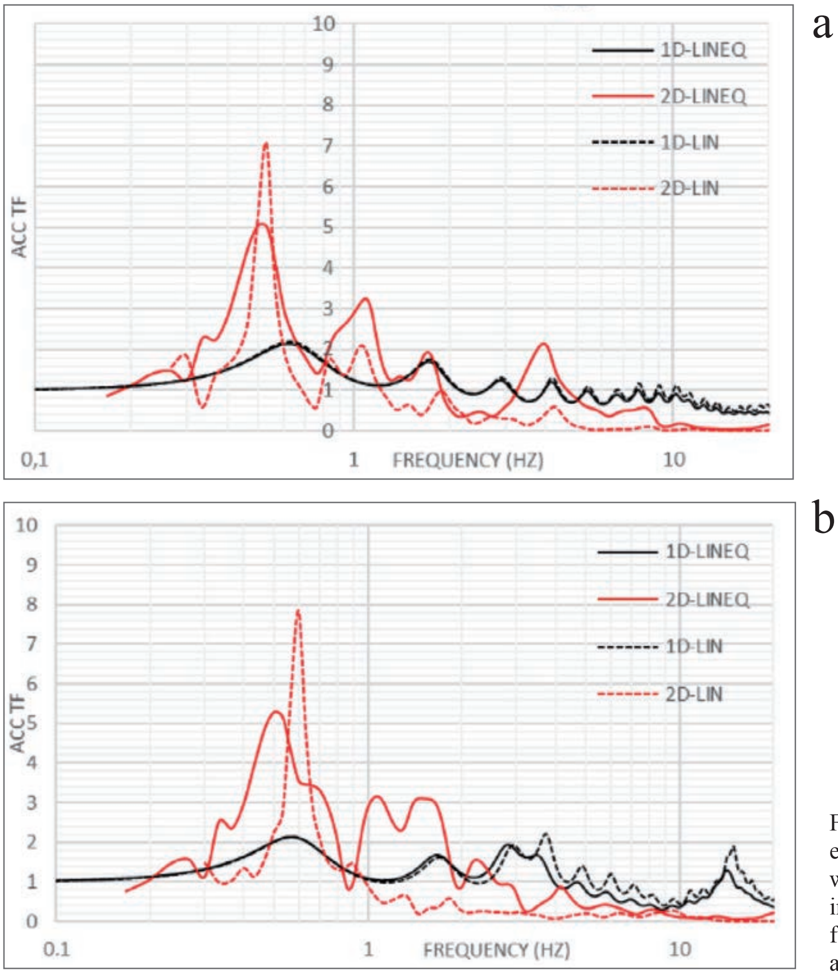

Fig. 5 - Comparison of 2D-1D equivalent linear simulation with 2D-1D linear simulation in terms of acceleration transfer function in Via 24 Maggio (a) and Duomo (b) sites.

The frequency-range (0.5-0.6 Hz) of huge amplification in 2D simulation coincides in pseudo acceleration (*PSA*) peak value and in range period between 1.5 and 2.0 s, higher than *PSA* spectra evaluated by NTC spectrum.

In particular, using NOR and AMA far-field inputs in 2D simulations, in Via 24 Maggio site, *PSA* and displacement spectra highlighted a good agreement in amplitude value in comparison with the experimental data of the AQK station strong motion recordings of Amatrice (AMA) (24 August 2016 - M_w 6.0) and Norcia (NOR) (30 October 2016 - M_w 6.5) events. Fig. 6 summarizes 1D (Figs. 6a and 6c) and 2D (Figs. 6b and 6d) simulation data with experimental data (AQK record of the Amatrice and Norcia earthquakes). This considerable agreement in 2D simulation with experimental data (Figs. 6b and 6d) with respect to 1D simulation (Figs. 6a and 6c), certifies the subsoil model supposed by our studies and confirms the 2D amplification behaviour due to the "deep valley" subsoil model. Moreover, Via 24 Maggio site is near some buildings equipped with isolated systems that during the earthquake of 30 October 2016 recorded 15-20 cm movements, as documented by video recordings from CCTVs that were in operation at the time of the shocks. The 2D simulation displacement

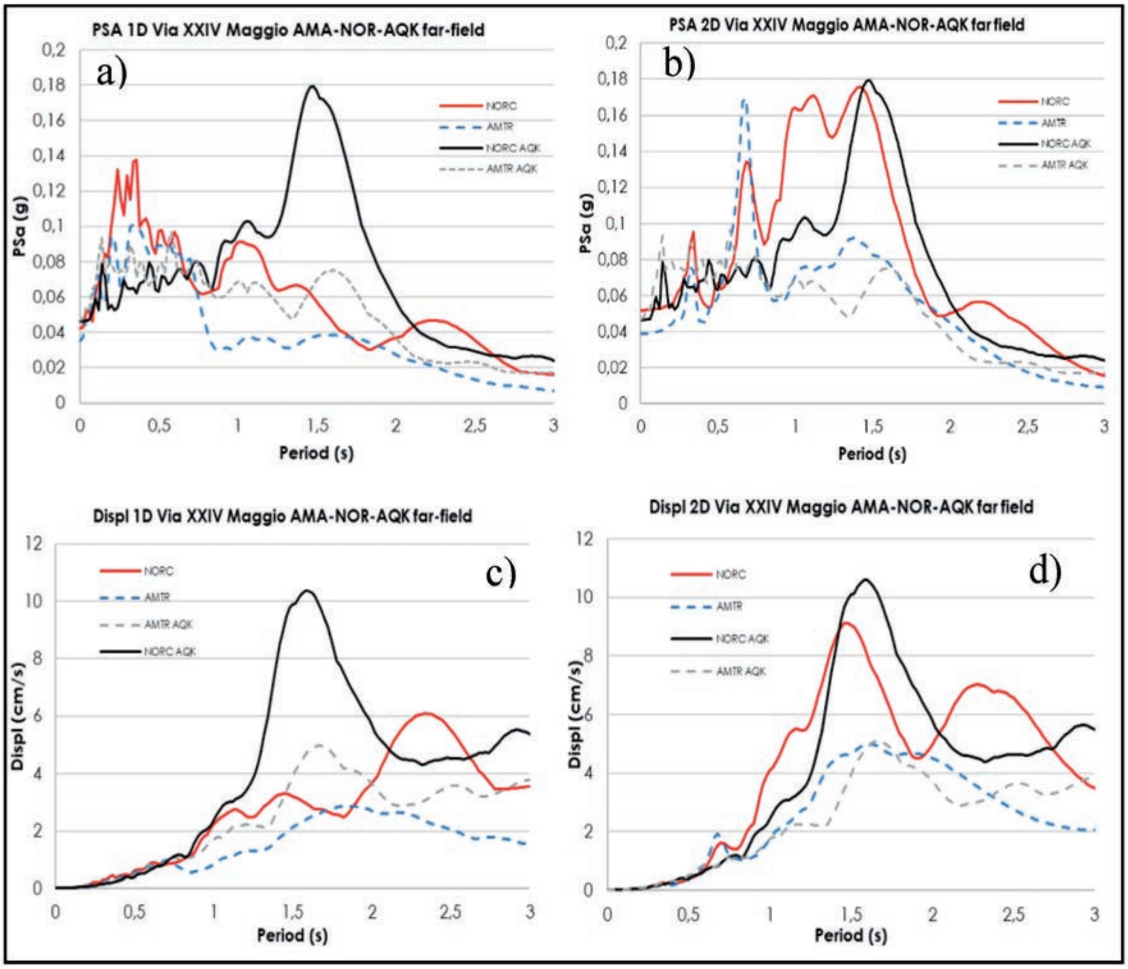

Fig. 6 - Comparison 1D (a and c) and 2D (b and d) equivalent linear simulation NOR and AMA input with AQK experimental data recorded in terms of *PSA* spectra (a and b) and Displacement spectra (c and d) in Via 24 Maggio. For each diagram, the red line identifies NOR 1D or 2D simulations, the black line represents the recorded AQK NOR, the dashed blue line identifies the AMA 1D or 2D simulations and the dashed gray line represents the recorded AQK AMA.

data are shown in Fig. 6d (red line 2D simulation NOR input and black line AQK earthquake recorded), with the maximum value of displacement recorded in this area by the AQK station, as showed in Macerola (2017).

3. Effects of site amplification on the dynamic response of base-isolated buildings during the seismic series of central Italy

The considerations set out in the previous paragraphs call for a reflection on the performance of buildings located in the area of the historic centre of L'Aquila, with particular reference to those buildings with a period of fundamental vibration falling within the range of site amplifications, experienced during the earthquakes in central Italy. As already highlighted above, the main events of 24 August and 30 October 2016 were the first significant occasions to detect the real functioning

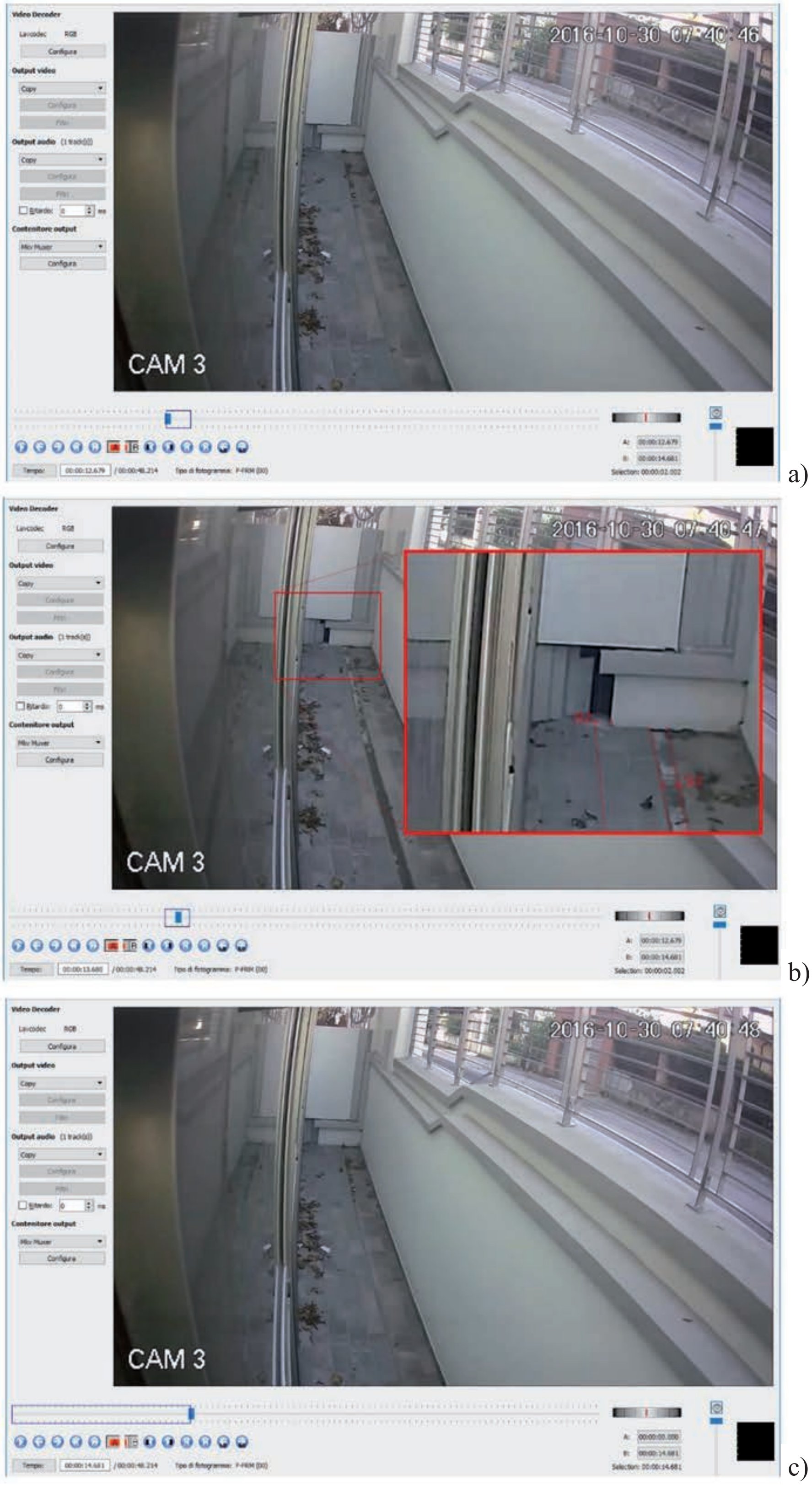

Fig. 7 - Phases of the complete oscillation at the interface between the isolated system and fixed structures during the main shock of 30 October 2016, recorded by a CCTV camera: a) frame 1, time 00.12.679 s, maximum positive displacement; b) frame 2, time 00.13.680 s, maximum negative displacement; c) frame 3, time 14.681 s, oscillation completion. The zoom window shows the maximum displacement (12.2 cm), estimated on the basis of the floor tiles size, with the smallest side being 20 cm.

of the isolated systems installed on various buildings repaired or rebuilt following the 2009 L'Aquila earthquake. In some cases, the effects on these structures have been very important. The motion of the isolated systems was also documented by video footage of video surveillance systems that were in operation at the time of the shock, as shown in Fig. 7, with movements, of the order of about 15-20 cm. The frames extracted from the video recording also allow one to estimate oscillation period and displacement magnitude with reference to the adjacent fixed base structures. Pictures show, indeed, a 12.2 cm maximum displacement in one direction, and time-counter readings in following frames permit to estimate a 2-s period to complete an oscillation. Similar displacements were also observed in seismic isolated buildings for which images and video recordings are not available. Such displacements were detected by examining deformations and damages of the joint covers installed between the isolated structure and the fixed structures (metal casings, etc.), as shown in Fig. 8.

The *PGA* levels recorded during the mentioned events (lower than 72 cm/s for all stations in the city of L'Aquila), the spectral shapes and the demand in terms of acceleration spectra provided for by the Italian seismic regulations were compared. As clearly shown in the graph of Fig. 9a, the 5% damping acceleration spectra for the main shocks of 24 August and 30 October 2016 for several RAN stations located in the urban area of L'Aquila lie well below the 30 year return period NTC spectrum, with the exception of the AQK records, which show a very important peak around 1.5÷2.0 s (280 cm/s^2). Furthermore, Fig. 9b reports spectra of various main events recorded by AQK and differing in magnitude and epicentral distance in order to represent, albeit partially, the variability of ground motion at AQK site as a function of these parameters.

The circumstances above are an indicator of the important amplifying effect produced by the subsoil of the area and of the importance to ensure a satisfactory behaviour of the seismic isolated buildings in order to keep them fully operational in case of low return period events.

Considering resonant frequencies, also on the basis of the commercial products available in Italy, it is possible to narrow the field of buildings affected (or likely to be affected in the future) by phenomena related to site amplification, to just those equipped with a seismic isolation system with fundamental period close to 2.0 s. For FPS (Friction pendulum System), for instance, the geometric characteristics of the commercial devices available on the Italian market make it easy

Fig. 8 - Damages of the interface elements installed between the isolated structure and the fixed one (metal casings, fence, etc.).

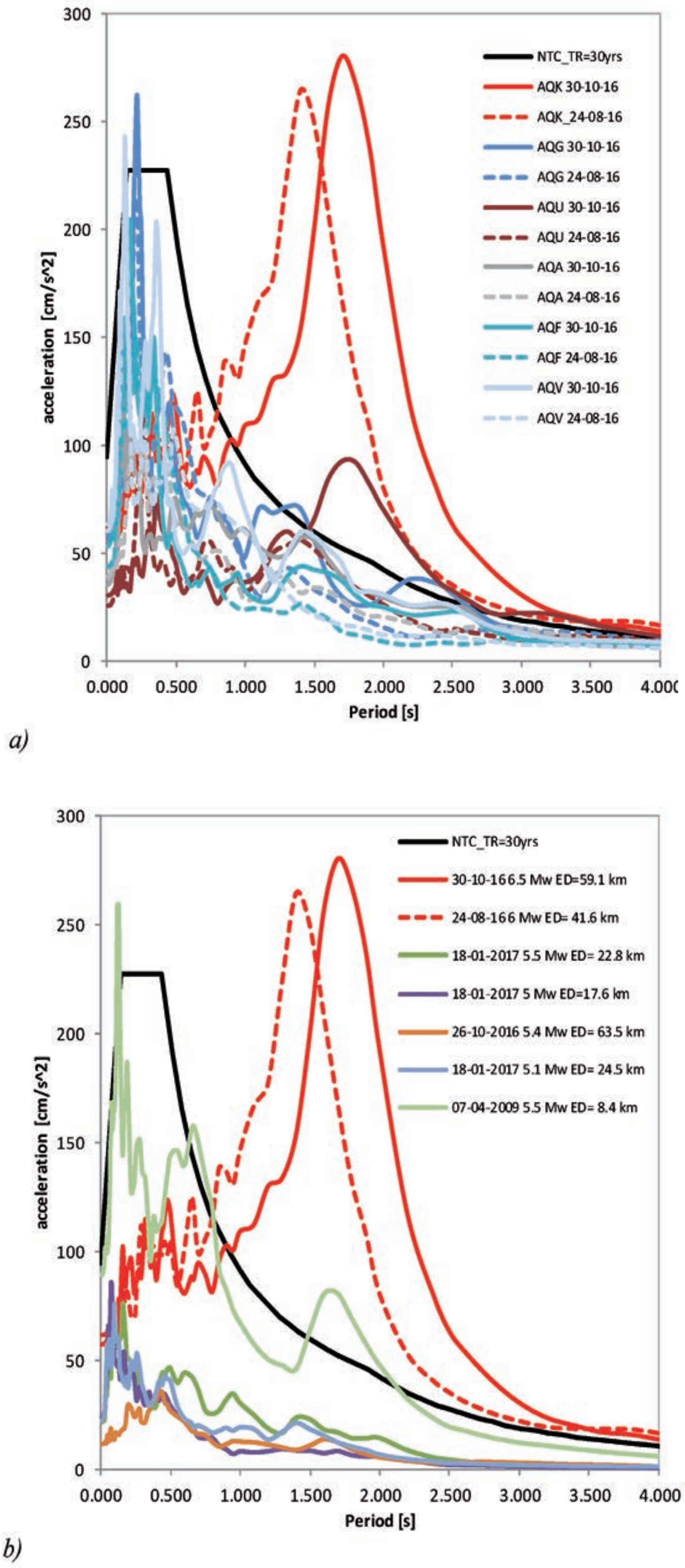

Fig. 9 - Comparison between 5% damping acceleration spectra: a) for RAN and INGV stations AQG, AQK, AQU, AQA, AQF, and AQV for 2016 main shocks and NTC2008 spectrum for the 30-year return period (soil type B); b) for various main events (7 April 2009 aftershock and 2016 - 2017 main shocks) recorded by RAN station AQK.

implement, isolated systems with fundamental periods of vibration beyond 3 s. and therefore, outside the range of frequencies amplified by deposits characterizing the stratigraphy of the site under examination.

Some numerical analyses were carried out on an isolated reference building designed according to the NTC regulation. Their goal was to assess the deviation between the maximum displacements of the seismic isolation system subject to seismic action resulting from the NTC spectrum and defined according to the simplified methodology of 2008 section 3.2.2 of D.M. 14 January 2008, and those obtained from seismic actions resulting from the use of accelerograms recorded by the AQK accelerometric station during the event of 30 October 2016, as illustrated in Mannella *et al.* (2017).

The comparison shows that the AQK resulting displacement is clearly higher than the average of the maximum displacements obtained from analyses conducted with the set of NTC compatible spectrum accelerograms. Furthermore, maximum design displacement was almost reached during the event of 30 October.

Therefore, it is possible to affirm that the assessment of the maximum displacements with respect to the SLV carried out using NTC spectrum and the simplified approach for defining the subsoil category, leads, in this case, to a clear underestimation of their magnitude and thus it could possibly result in an undersized seismic isolation system.

There is currently no evidence available to show that such site conditions can lead to a systematic underestimation of the seismic action obtained by using the simplified method provided by the NTC standard, and further studies and investigations are currently underway to verify this condition.

It should also be considered that the underestimation of the effects is not limited to an improper assessment of the maximum displacement of the devices, but also to an incorrect evaluation of the actions transferred to the superstructure. The above considerations are also important because the stratigraphic and geological conditions in the area of the historic centre of the city of L'Aquila, and, therefore, related to the presence of a deep basin produced by a tectonic depression filled by river or lacustrine sediments, are quite frequent in the intermountain basins of the central Apennines. Further to this aspect, it is important to underline that, in many cases, these basins host human settlements and medium-sized cities (L'Aquila, Avezzano, Sulmona, Rieti and others) and finally, that these areas are prone to high seismic hazard. All these factors contribute to increasing the risk of an incorrect seismic action evaluation.

4. Conclusions

This article has illustrated the effects caused by the seismic series in central Italy in 2016 produced to some seismic isolated buildings located in the historic centre of L'Aquila. Interest has been oriented to this specific area and typology of buildings because of the particular stratigraphic and topographical conditions that characterize the morphological terrace, on which the historical centre of the city is located, that produce an important amplification phenomenon in the operating frequencies of this type of buildings.

In the case of the main seismic events of 2016 and 2017, in fact, despite the considerable distance from the epicentral zones in relation to the intensity of the occurrences events, some structures equipped with a seismic isolation system, showed important displacements. The results of specific numerical simulations showed that the assessment of seismic actions carried out using the simplified method proposed in section 3.2.2 of D.M. 14/01/2008 for the evaluation of stratigraphic and topographic amplification, does not allow one, in this case, to obtain plausible, or at least precautionary, assessment of possible amplification factors. Seismic local response analysis shows that it is necessary to conduct 2D modelling in order to properly capture amplification phenomena. In consideration of the frequency of the stratigraphic and geological conditions that can produce these amplification phenomena in the Apennine area and the high seismic risk that characterizes it, it appears appropriate to verify that the simplified method proposed by the NTC standard does not lead to a systematic underestimation of the seismic action in the field of the frequencies of seismic isolated buildings.

In addition, to highlight an aspect related to the local hazard of the site under study, not specifically addressed by the regulations and planning tools, the above considerations illustrate the many factors associated with the phenomena of site amplification (geometry, characteristics of the signal at source, distance, magnitude, etc.). Furthermore, the effects of site amplification, that are not yet fully covered and are currently under further research, are crucial and difficult to quantify in order to define trends and general characteristics of the amplification phenomena, also for similar geological contexts, such as the intermountain basins of Italy.

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