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Site characterization and seismic response analysis in the area of Collemaggio, L'Aquila (Italy)

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ABSTRACT: The paper describes the geotechnical investigations and analyses carried out for the restoration of the ancient Basilica di Collemaggio, L'Aquila (Italy), severely damaged by the 2009 earthquake. The subsoil model was defined based on a comprehensive investigation including boreholes, measurements of shear wave velocity V_S by seismic dilatometer (SDMT) in backfilled boreholes (non-penetrable soils) to 93 m depth and laboratory cyclic tests (double specimen direct simple shear, DSDSS). An "enhanced" seismic source was designed to improve the interpretation of V_S at large depths. Site response analyses were carried out with 2D FLAC finite difference code. Literature data and DSDSS test results were used for non linear cyclic characterization of soils. The input motions were seven real accelerograms compatible with reference response spectra on outcropping rock from the Italian code. The results, expressed in terms of free-field acceleration response spectra, showed amplification up to 2.5 s with maximum values > 2 in the period range 0.1-0.4 s.

1 INTRODUCTION

The Basilica Santa Maria di Collemaggio, located in L'Aquila (central Italy), is an important catholic church founded in the XIII century. It contains the most ancient Holy Door in the world and hosts every year a unique Jubilee (Perdonanza Celestiniana), a penitential observation devised by Pope Celestine V, who is buried here. Parts of the structure of the Basilica were severely damaged by the magnitude M_w = 6.3 April 6, 2009 L'Aquila earthquake. While the beautiful Romanesque façade is intact, the cupola, the transept vaults and the arches have collapsed.

The geotechnical investigations and seismic response analyses described in this paper were carried out as part of the project for the restoration of the Basilica, funded by Eni S.p.A. and currently under construction (scheduled end: 2017). Additional ground response analyses that cross the Basilica can be found in Amoroso et al. (2013, 2015).

2 BASIC GEOLOGICAL SETTING

The complex geological setting of the L'Aquila basin is extensively described e.g. in MS–AQ Working Group (2010). In the city centre, where the Basilica di Collemaggio is located, the upper portion of the subsoil is constituted by the deposit known as "Brecce dell'Aquila", 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. Gravimetric investigations (MS–AQ Working Group 2010), confirmed by deep boreholes (Amoroso et al. 2010), have indicated that in the city centre the bedrock is located below 300 m depth.

3 SITE INVESTIGATION

A comprehensive site investigation was carried out in the area of the Basilica di Collemaggio, including deep boreholes, measurements of the shear wave velocity V_S by seismic dilatometer SDMT (Marchetti et al. 2008) and active/passive seismic surface measurements (tomography, ambient noise, 2D array, AA.VV. 2013, Milana et al. 2011), as well as short vertical/inclined boreholes across the existing church foundations.

Three boreholes (S1, S2, S3, Fig. 1) were drilled respectively to a depth of 80 m, 120 m and 275 m from the ground surface, with Standard Penetration Tests and retrieval of samples. The deepest borehole (S3), drilled partly with core recovery and partly as core-destructive, was aimed at detecting the top surface of the bedrock, which however was not reached within the investigated depth.

After completion the boreholes S1, S2, S3, plus an additional auxiliary borehole S3 bis b, were backfilled with clean fine-medium gravel (grain size 5-15 mm, no fines) in order to obtain V_S measurements by SDMT according to the procedure devised by Totani et al. (2009) for non-penetrable soils, largely employed in the L'Aquila area in post-earthquake investigations (Monaco et al. 2013). In this procedure the SDMT is inserted and advanced into a pre-drilled backfilled borehole by use of a penetrometer rig and V_S measurements are taken every 0.50 m of depth as usual, but without DMT measurements (meaningless in the backfill). In this case the SDMT acts only as a vehicle for inserting the seismic module. Such technique is based on the assumption that the S-wave travel path from the surface to the upper and lower receiver in the SDMT seismic module includes a short path in the backfill approximately of the same length, i.e. the time delay between the two seismograms and the interpreted V_S do not change (Totani et al. 2009). Comparative tests carried out at sites where both the usual penetration procedure and the backfilling procedure were adoptable indicated that the V_S obtained in the backfilled borehole are nearly coincident with the V_S obtained by penetrating the soil.

The site investigation included V_S measurements by SDMT (Fig. 1) in four backfilled boreholes (SDMT 1, SDMT 2, SDMT 3, SDMT 3bis b) to a maximum depth of 93 m from the ground surface (SDMT 3), and a limited number of SDMT measurements by penetration in the virgin soil (SDMT 3bis a, SDMT 4).

An "enhanced" seismic source was specifically designed and tested at the University of L'Aquila to tentatively improve the quality of the signals and reduce the uncertainty in the interpretation of V_S measurements by SDMT in deep backfilled boreholes. The "enhanced" seismic source ("Tirino Hammer", Fig. 2) is composed of a pendulum hammer having a mass of 130 kg, with a drop height of 2 m, which hits horizontally a ballasted steel anvil placed along one side of the truck, with the impact line parallel to the axes of the receivers. The "enhanced" seismic source was used only in SDMT 3, while all the other tests were carried out using the "standard" seismic source.

Figure 3 shows the superimposed V_S profiles obtained by SDMT (plotted in terms of elevation above the sea level) and the schematic soil profile.

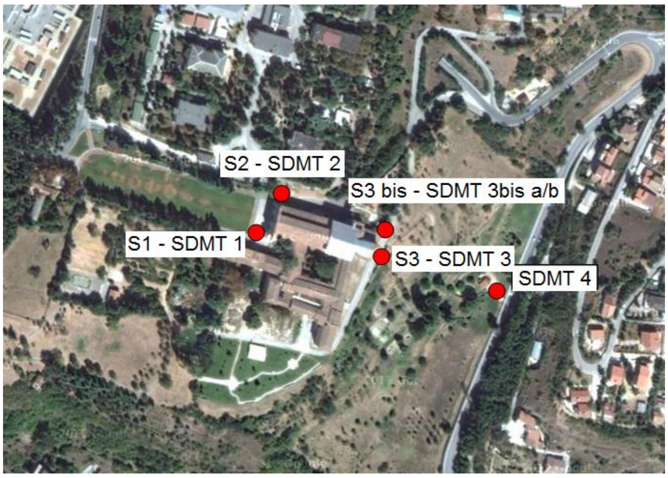

Figure 1. Location of boreholes and V_S measurements by SDMT (in backfilled boreholes and in virgin soil).

Figure 2. "Enhanced" seismic source ("Tirino Hammer").

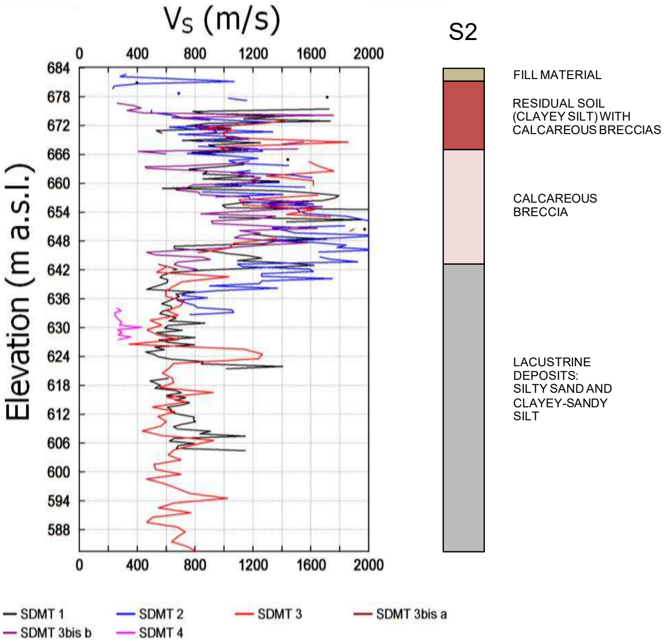

Figure 3. Superimposed profiles of V_S measured by SDMT in backfilled boreholes and schematic soil profile.

4 SUBSOIL MODEL FOR SITE RESPONSE ANALYSIS

The subsoil model was based on the site investigation carried out in the area of the Basilica di Collemaggio, and it was used for the site response analysis, as illustrated in Figure 4. Table 1 summarizes the geotechnical parameters of the materials introduced into the analysis, in terms of unit weight γ, shear wave velocity V_S, Poisson's ratio υ, normalized shear modulus G/G_0 and damping D curves. In particular V_S values refer to the SDMTs performed in the four backfilled boreholes, while υ values were estimated considering cross-hole tests carried out in similar soils. For the lacustrine deposits "L" and "LS", the G/G_0 and D curves were derived from simple shear tests carried out at University of Rome "La Sapienza" with DSDSS apparatus (D'Elia et al. 2003). Literature curves (Vucetic & Dobry 1991, with plasticity index $PI = 15$) were assumed for the fill material "R" and the residual soils "LAC1" and "LAC2". A visco-elastic linear behavior was assumed for the calcareous breccias "Ba" and "B".

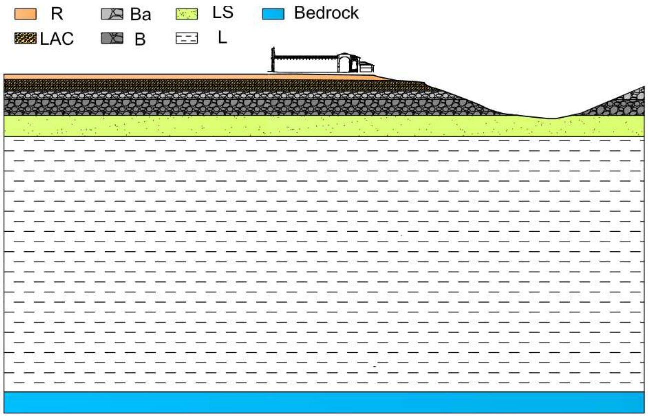

Figure 4. Subsoil model adopted for site response analyses.

Table 1. Subsoil model adopted for site response analyses (* = linear variation with depth).

Depth (m)	Material	γ (kN/m^3)	V_S (m/s)	υ (-)	G/G_0 and D curves
0-5	R	18.0	160	0.30	Vucetic & Dobry 1991 PI=15
5-10	LAC1	19.5	700	0.30	
10-16	LAC2	19.5	1000	0.30	Linear
16-24	Ba	20.0	1000	0.33	
24-40	B	21.0	1000-1800*	0.38	
40-60	LS	20.5	600	0.40	DSDSS tests
60-300	L	20.5	650-850*	0.40	
> 300	Bedrock	23.0	1250	0.33	-

5 SELECTION OF INPUT MOTION

The acceleration response spectrum with a return period of 475 years suggested by the Italian National Building Code (NTC-08) for flat outcropping rock condition (class A subsoil and topography category T1) was assumed as reference for input motion definition. Seven recordings, compatible on average with the reference spectrum, were selected as input for numerical analyses. The following procedure for selecting and scaling natural accelerograms was adopted (Pagliaroli & Lanzo 2008).

1. Candidate ground motion time-histories were extracted from the ITACA database (ITalian ACcelerometric Archive available at itaca.mi.ingv.it) on the base of magnitude M, source-to-site distance d and site classification. Based on the main active seismogenic structures in the region, reference was made to a magnitude-distance window defined by $M = 5.9$-6.9 and $d < 25$ km, representative of the L'Aquila Upper Aterno valley and Ovindoli-Pezza-Campo Felice fault systems (Akinci et al. 2009). Recordings at stations of class B with $V_{S,30} > 650$ m/s were included in the selection because accelerograms at rock outcropping conditions (class A subsoil) are very few in the national database, especially for $M_w > 6$ and near-field conditions. Focal mechanism was not included in the search, even if preference was given to recordings of normal fault events dominating the activity in central Apennines.
2. All candidate records were scaled to target peak ground acceleration PGA (0.26 g) by using a scaling factor F.
3. Records characterized by $F > 4.5$ were rejected; the limit value of scaling factor was assumed higher than in previous studies (Pagliaroli & Lanzo 2008) to include available class A recordings from the 2009 L'Aquila earthquake. Parameters measuring spectral matching of single recordings with target spectrum (for example D_{rms}) were not considered because a large period range (0.2-2.5 s) was considered for the spectral compatibility with reference spectrum.
4. A selection of 7 recordings was finally made by comparing the average response spectrum with the reference one in the 0.2-2.5 s range; maximum underestimation of 10% with respect to target spectral amplitudes was assumed as requirement for spectral compatibility.

Basic characteristics of selected input motions are reported in Table 2, while single and average response spectra of input motion accelerograms are reported and compared with target spectrum in Figure 5.

6 NUMERICAL ANALYSES

6.1 *Numerical code*

The numerical analyses were carried out using FLAC 2D finite difference computer code (Itasca 2011). The code incorporates a dynamic option allowing 2D full dynamic analysis. The mesh employed for the analyses, with a detail of the Basilica area, is shown in

Figure 6. In order to achieve satisfactory accuracy, the height of the elements of the mesh was chosen as lower than $V_S/(10f_{max})$, where f_{max} is equal to the maximum frequency to be transmitted, assumed equal to 15 Hz. The aspect ratio of the elements is about 1. The radiation damping was simulated by employing a viscous boundary at the bottom and free-field boundary conditions at the lateral edges of the model. The input motions were applied at the base of the model in terms of shear stress time histories in order to simulate a transmitting base (Itasca 2011). The LAC2-Ba-B materials (Table 1) were assumed to be linear with damping properties modeled by the full Rayleigh damping formulation with a single control frequency, set at 2 Hz. This latter was assumed to be in the range between the fundamental frequency of vibration of the deposit (about 0.6 Hz, see later in the text) and the predominant frequencies of the input motions (generally 3-8 Hz, as shown in Fig. 5a). The target damping ratio for LAC2-Ba-B materials was set at 0.5% considering that a slight numerical overestimation occurs in the frequency range of interest.

For non-linear materials (R-LAC1-LS-L in Table 1), the Sigmoidal 4 hysteretic damping formulation, available in the FLAC library, was adopted. The model parameters were calibrated by using standard G/G_0 and D vs shear strain amplitude curves listed in Table 1. A small amount (0.5%) of Rayleigh damping was also added to provide a non-zero damping at very small strains.

6.2 *Linear analyses*

In order to validate the subsoil model assumed for the numerical study, linear analyses were initially carried out to compare the horizontal-to-vertical

Table 2. Main characteristics of the recordings selected as input motion: M_w = moment magnitude, d = epicentral distance, a_{max} = peak acceleration; Cat = subsoil class according to Italian Seismic code NTC-08, F = scaling factor.
All accelerograms are referred to normal fault events with exception of Friuli 4th shock.

ID	Earthquake	M_w	d (km)	a_{max} (g)	Cat	F
SRC0	Friuli 4th shock 15.09.1976	5.9	16	0.25	A	1.04
ARQ	Val Nerina 19.09.1979	5.8	21	0.08	A	3.44
ATN	Val Comino 07.05.1984	5.9	10	0.10	A	2.60
BSC	Irpinia 23.11.1980	6.9	28	0.10	A	2.70
AQG	L'Aquila 06.04.2009	6.3	4	0.45	B	0.58
MTR	L'Aquila 06.04.2009	6.3	22	0.06	A	4.17
PNT	Val Comino 07.05.1984	5.9	27	0.06	A	4.00

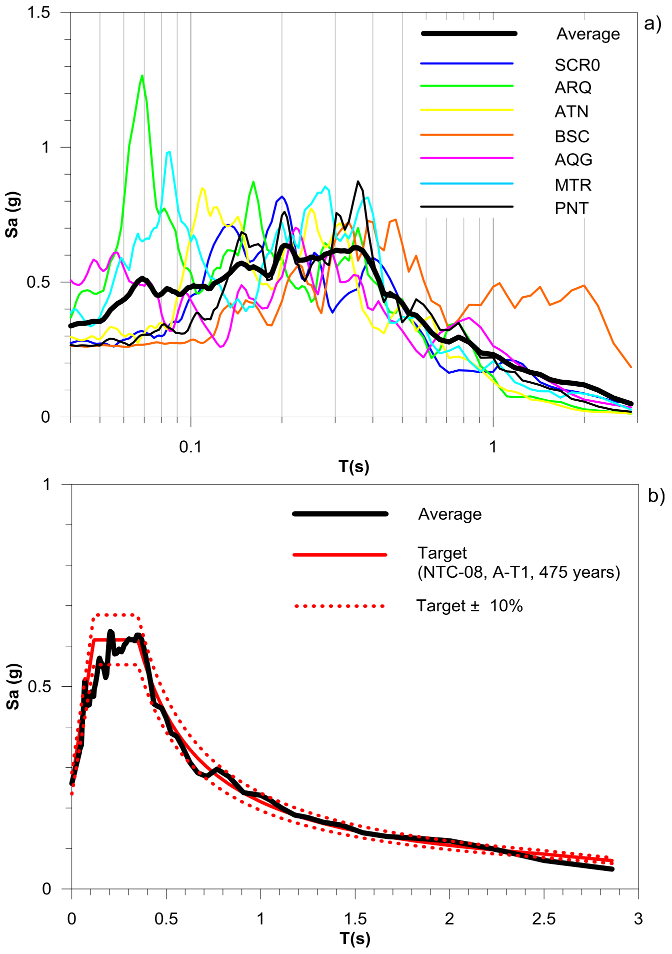

Figure 5. (a) Response spectra (5% structural damping) of accelerograms selected as input for site response analyses in semi-log scale. (b) Comparison between average input spectrum and target spectrum, linear scale (dashed lines represent target spectral amplitudes ± 10%).

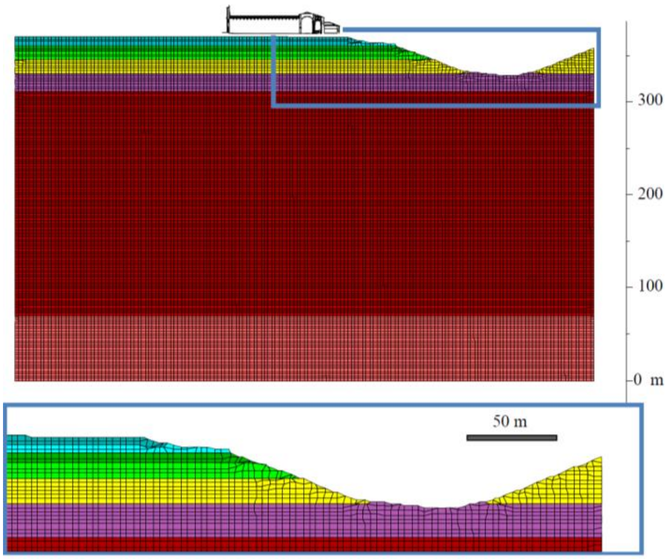

Figure 6. Mesh employed for the analyses, with a detail of the area of the Basilica.

spectral ratio (HVSR) obtained experimentally in the Basilica area from noise measurements (Milana et al. 2011) to numerical transfer functions; these latter were computed as the ratio between the smoothed Fourier spectrum in the node of interest and the corresponding spectrum of input motion. Soil behavior was assumed to be visco-elastic with mechanical properties characterized by their small strain values.

Figure 7 shows the comparisons between the numerical transfer functions at 4 representative nodes in the Basilica area (A, B, C and D) and a typical HVSR computed from microtremors (cmg11). Noise measurements highlight two resonance frequencies: the first one at about 0.6 Hz is related to the deep impedance contrast between the overall deposit and the bedrock; at about 7-8 Hz a further resonance, related to presence of the anthropic backfill over underlying LAC deposits, appears. The transfer functions computed via numerical analyses generally show a good qualitative agreement with the H/V curve; both resonance frequencies measured experimentally are properly reproduced.

The overall good match between experimental and numerical transfer functions therefore corroborates the subsoil model employed for the site response analyses, at least in the linear range.

For comparison, 1D visco-elastic analyses were carried out with STRATA computer code (Kottke & Rathje 2008). A good qualitative and quantitative matching between 1D and 2D transfer functions can be observed, thus indicating that moderate 2D effects take place in the Basilica area. In particular 2D effects appear for frequencies higher than 3 Hz, where some differences between 2D and 1D functions as well as between the 2D response at the 4 selected nodes do exist. As expected, behind the slope crest the moderate-to-high frequency motion presents a significant spatial variation. In the 6-10 Hz range, maximum amplification takes place at node C even if the aggravation with respect to 1D simulations is moderate.

6.3 *Non linear analyses*

The seismic action to be used for the analysis of the structure has been provided in terms of acceleration response spectra (5% of structural damping) at free-field. The spectra were computed as average over all 7 input signals. Results at representative nodes (A-D) are reported in Figure 8a. Significant amplification can be observed in the range 0.1-0.4 s (2.5-10 Hz), in agreement with information obtained from linear transfer functions (Fig. 7). The same spectra were regularized using the procedure proposed in the Italian guidelines for Seismic Microzonation (ICMS 2008) to be directly compared with NTC-08 code seismic action.

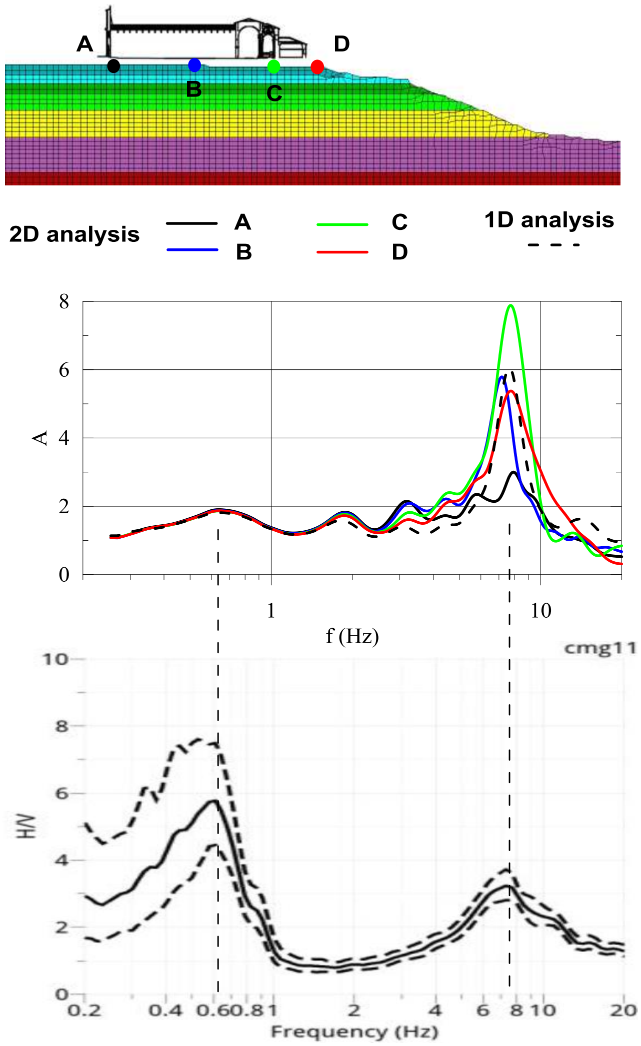

Figure 7. Comparison between transfer functions computed by 1D and 2D visco-elastic linear analyses and representative H/V ratio from noise measurements carried out in the Basilica area.

In Figure 8b the regularized spectra are compared with the response spectrum for subsoil class B corresponding to geotechnical profile in the upper 30 m of Basilica subsoil. Topographic amplification factor T2 (= 1.2) was also applied to consider the effect of superficial morphology. The comparison shows that the NTC-08 B-T2 spectrum leads to a significant underestimation of seismic action for period less than 0.5 s.

7 CONCLUSIONS

A comprehensive geotechnical investigation carried out in the area of the Basilica di Collemaggio, including deep boreholes, measurements of the shear wave velocity V_S by seismic dilatometer SDMT, active/passive seismic surface measurements, cyclic laboratory tests, allowed to provide an accurate subsoil model for 2D site response analyses.

Preliminary visco-elastic linear analyses were carried out to compare the numerical transfer functions with the H/V curve from noise measurements, thus corroborating the subsoil model.

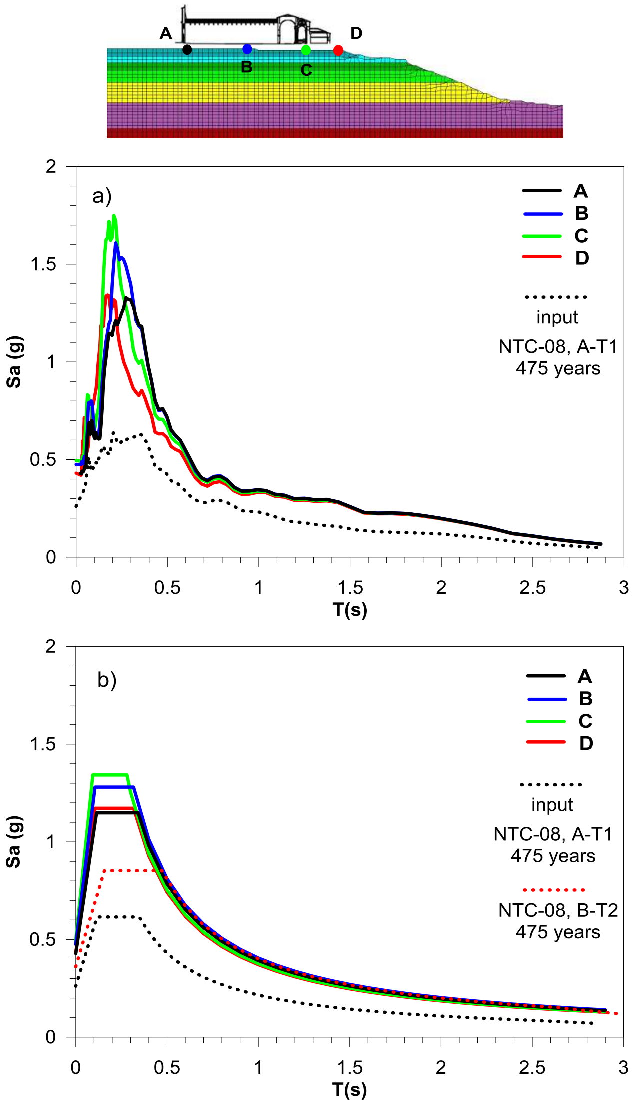

Figure 8. (a) Average response spectra computed in the Basilica area at nodes A-D. (b) The same spectra are reported in regularized form to be directly compared with NTC-08 code seismic action.

Moreover, linear 1D vs 2D results highlighted that behind the slope crest where Basilica is founded, the moderate-to-high frequency motion presents a noteworthy spatial variation. However the aggravation of motion amplification predicted by 2D model with respect to 1D simulations is moderate.

Non linear site response analyses were then executed to quantify the seismic action for the restoration project of the Basilica. Significant amplification can be observed in the range 0.1-0.4 s (2.5-10 Hz), where site response analyses give spectral acceleration considerably higher than those provided by Italian National Seismic code.

8 ACKNOWLEDGEMENTS

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