Geotechnical Engineering for the Preservation of Monuments and Historic Sites III – Lancellotta, Viggiani, Flora, de Silva & Mele (Eds)
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Site characterization and preliminary ground response analysis for the monumental Complex of SS. Annunziata in Sulmona, Italy

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ABSTRACT: The historical building Complex of the SS. Annunziata in Sulmona (L'Aquila, Italy), consists of a church and an adjoining building. It overlooks the square of the same name along the main street of the historic centre of the town. SS. Annunziata is considered the most important historical monument in Sulmona, not only for its huge artistic and architectural value, but also for the special significance it had in the social and political life of the city. The construction of the Complex started in the 14th century and continued for centuries. The long building duration led the Complex to take on its current appearance characterized by different architectural styles: late Gothic, Renaissance and Baroque. As a result of earthquakes that affected the area, the various buildings that are (or were) part of the monumental Complex suffered damage (perhaps in 1349, 1456 and certainly in 1706) and underwent major reconstruction works. Significant damage was also caused to the structures of the SS. Annunziata Complex by the earthquakes that struck the central Apennines in the 20th century (i.e. 1915 and 1933) and by the 2009 L'Aquila earthquake. After this latter, the damage observed to the rear of the buildings in the monumental Complex was more severe than those of the front. To verify whether the subsoil local conditions can explain the distribution of the observed damage, studies of ground response have been planned at the site where SS. Annunziata Complex is located. This work presents the preliminary results of the case study. After a general overview of the Sulmona basin and the SS. Annunziata Complex, the results of the survey carried out in the study area are described and analyzed, aimed at defining the geotechnical model. The results of numerical 1D analyses performed on soil profiles, representative of the subsoil conditions both at the front and back of the historical Complex, are also presented and compared.

1 INTRODUCTION

Sulmona (L'Aquila) lies in an intermontane basin in central Italy. It has very ancient origins, as demonstrated by continuous archaeological findings of Roman age from excavations in the old town centre and in the surrounding territory. Indeed, the northern downtown sector is founded on the ancient *Sulmo* (the Roman town), i.e. archaeological stratigraphy defines the continuity of the settlement at least since the Roman Age. The Roman *Domus*, whose remains were found in the area located along the main street of the present city centre where the historical Complex of SS.

 DOI 10.1201/9781003308867-61

Annunziata currently stands, dates back from the Roman Imperial Age. In turn, SS. Annunziata is considered the most important monument in the town and consists of a church and a large adjoining building resulting from a combination of different architectural styles: late Gothic, Renaissance and Baroque.

Sulmona basin (also called Peligna basin or Peligna valley) is one of the areas of highest seismicity in Italy and the Municipality of Sulmona is included in Italian the peninsular belt characterized by the highest seismic hazard. The CPTI15 seismic catalogue (Rovida et al. 2021, from which the magnitude reported in the next have been derived), which represents the main reference for Italian seismicity, reports numerous earthquakes that have affected the town of Sulmona with macroseismic intensity greater than 6 and up to 9-10 MCS degree. However, according to some researchers, the strongest earthquake in Sulmona's seismic history occurred in the 2nd century BC and it seems to have caused the collapse of the already mentioned Roman *Domus* whose remains were uncovered during excavations within the SW sector of SS. Annunziata (Ceccaroni et al. 2009; Tuteri 1995).

After its first construction, dating back to 1320, the SS. Annunziata Complex presumably experienced interventions because of damage caused by the 1349 and 1456 earthquakes (MCS macroseismic intensity, $I_{MCS} = 8 - 9$ and 8 at Sulmona respectively; estimated magnitude of 1456, $M_w = 7.19$) and was partially rebuilt after the 1706 earthquake ($I_{MCS} = 9 - 10$; estimated magnitude $M_w = 6.84$) which produced the collapse of the church, serious damage to the adjacent building and low damage to the bell tower. The SS. Annunziata Complex was also significantly damaged by other earthquakes: 1915 Marsica; 1933 Maiella; 1984 Monti della Meta; 2009 Aquilano. The consequence of the latterwas especially evident in the rear part where damage was significantly greater than in the front.

Recently, several survey campaigns have been carried out in the Sulmona basin, aimed at collecting geological, geotechnical and geophysical data in the context of microzonation studies (Di Capua et al. 2009; Pizzi et al. 2014; Scarascia Mugnozza 2007; Totani et al. 2009). Further data were collected through geophysical investigations and in situ and laboratory geotechnical surveys carried out at the historical centre of Sulmona as part of the FISR 2016 Top-down Project "L'Italia Centrale in 4D e ricostruzione dei processi geodinamici in atto", Task 4 "Mappe multihazard e vulnerabilità del territorio". These surveys have shown that the subsoil of the Annunziata Complex is very heterogeneous and that, in the first tens of meters, the stratigraphic sequence is very different even at very small distances.

After a brief description of the main geological and seismic characteristics of the Sulmona's area, this paper presents and discusses the characterization of the SS. Annunziata subsoil and the results obtained from the one-dimensional numerical ground response analyses performed on two significantly different vertical soil profiles, in order to verify the influence of the stratigraphic sequence on the damage induced by the recent 2009 earthquake.

2 BRIEF HISTORY OF THE SS. ANNUNZIATA MONUMENTAL COMPLEX

The historical building Complex of the SS. Annunziata is considered the most important historical monument in Sulmona, not only for its huge artistic and architectural value, but also for the special significance it had in the social and political life of the city, since it included the great church and the main hospital of the territory. The first plant of the Annunziata Complex dates to 1320 with the construction of the church of SS. Annunziata and its hospital in an area where a *Domus* stood in the early Roman Imperial Age and which later, only sporadically and at different times, was occupied by modest buildings of different types that were built and demolished for different purposes. In 1349 and 1456, SS. Annunziata was presumably damaged by strong earthquakes. Works during the 16th century completely modified the original Complex of medieval age. Indeed, the church of SS. Annunziata was unified with the contiguous church of Santa Croce. This involved a complete redefinition of the floor plan and spaces of Annunziata compared to those of the 14th century church. Nothing remained of the latter (Mattiocco 2008).

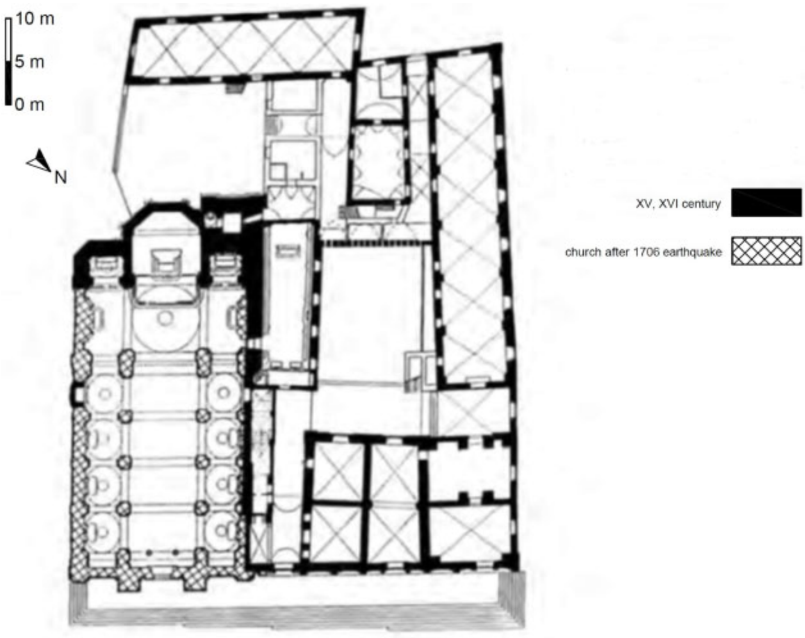

Figure 1. Current map of the SS. Annunziata Complex and construction phases (modified from Giannantonio 1997).

The chronology of the construction phases of the building adjacent to the church, which currently stands on the area where the ancient hospital founded in 1320 once stood, is more difficult to date. Construction began during the 15th century and was completed in 1483 with a significant extension of the building. This was followed by a further building phase which included the completion of the facade (1512-1522) (Mattiocco 2008).

In the 17th century no further significant works were carried out, but only modest renovations and small extensions related to contingent needs. In 1706, Sulmona was shaken by a strong earthquake which caused hundreds of victims and heavy damaged the city (I_{MCS} = 9-10). The Annunziata palace was also damaged, while the church collapsed entirely (only the sacristy did not experience damage), the bell tower and the wall adjacent to the staircase of the building were saved (Mattiocco 2008).

Reconstruction of the church began in 1710. After the major rebuilding works following the earthquake of 1706, the Complex has no longer undergone significant changes and the overall structure has remained almost unchanged until today (Figure 1).

3 MAIN FEATURES OF SULMONA BASIN

3.1 *Geological framework*

The Sulmona basin is one of the typical intermontane basins of the central Apennines. It is 5-8 km-wide in the direction NE-SW and about 21 km-long in the direction NW-SE. Its geological evolution has been conditioned by the Quaternary activity of the Mt. Morrone fault, bordering the basin to the East and emerging along the SW slope of the mentioned relief (e.g. Vittori et al. 1995, Gori et al. 2011) (Figure 2). The basin has asymmetrical shape, i.e. it is deeper in the eastern sector, at the foot of the Morrone massif (e.g. Cavinato & Miccadei 1995).

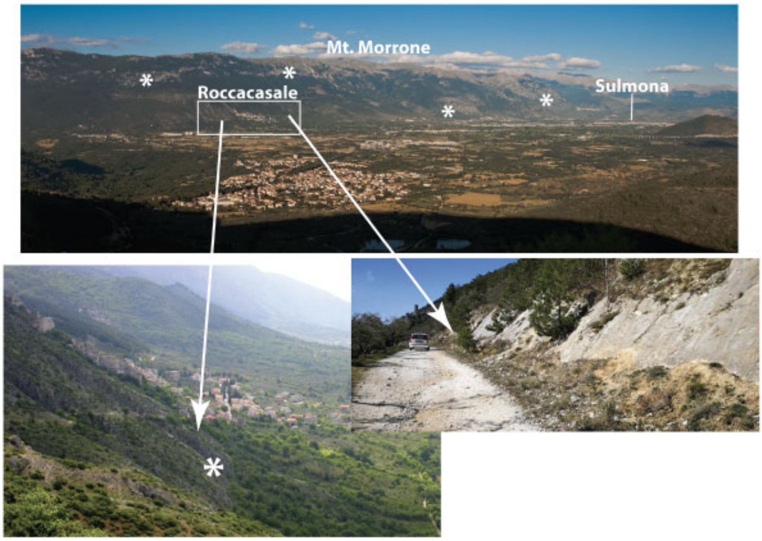

Figure 2. Panoramic view of the Sulmona Plain. Asterisks indicate some places where Mt. Morrone fault is emerging. Rectangle defines the area of Mt. Morrone bedrock fault scarp north of Roccacasale and the place where the fault plane is exposed south of the village.

The marine substratum has been tectonically lowered below the plain and outcrops in the reliefs surrounding the depression mainly carved into Mesozoic carbonate rocks. The basin is characterized by a large gently sloping surface related to the fluvio-lacustrine Quaternary history of this intermontane sector. Part of this history is testified by the thick lacustrine sediments, related to an ancient Quaternary lake (Miccadei et al. 1998) which characterised the local environment until the final drainage due to the regressive erosion of Pescara river from Adriatic sea towards the Apennines as a response to the chain uplift.

Remnants of continental deposits have also been found along the slopes of the carbonate reliefs that surround the basin (Gori et al. 2007, 2014; Vittori et al. 1995; and outcrop in many areas due to natural actions (mainly river incisions) and anthropic interventions (Miccadei et al. 1998). In summary, the lithostratigraphic units of interest for studies on the town of Sulmona are (from old to recent): 1) carbonate bedrock, probably located at a depth of about 300 meters below the centre of Sulmona; 2) lacustrine and marsh deposits, consisting of silty clayey with peat levels and lenses of gravels and sands; their thickness certainly exceed 200 m; 3) alluvial sediments, mainly made of gravel and sandy gravel with sandy-silty or clayey-silty levels especially in the deeper parts; thickness in the order of 30 m below the centre of Sulmona; 4) reworked material and archaeological deposits. A geologic section crossing the historical centre of Sulmona is shown in Figure 3 (Pizzi et al. 2014).

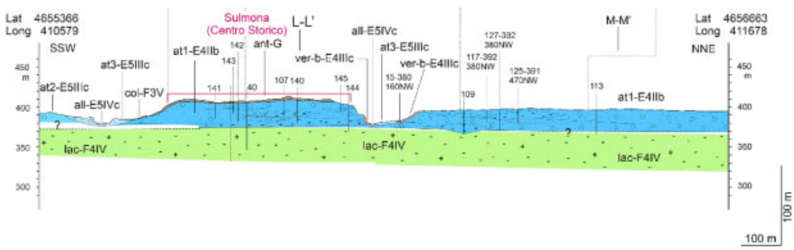

Figure 3. Geologic section crossing the historical centre of Sulmona (from Pizzi et al. 2014).

3.2 *Seismicity of the area*

The Sulmona basin is one of the areas of highest seismicity in Italy. Some of the main seismic events that struck the area were related to the well-documented active normal fault systems oriented in a direction parallel to the Apennine trend.

The CPTI15 seismic catalogue (Rovida et al. 2021) shows that Sulmona was hit by at least 6 events with $I_{MCS} \geq 7$: among them, only one originated from a near-field active fault ("Valle Peligna" in 1905 – $I_{MCS} = 7$, $M_w = 5.15$), while other four originated in adjacent seismogenic areas ("Appennino Centro Meridionale": 1456 – $I_{MCS} = 8$, $M_w = 7.19$; "Maiella": 1706 - $I_{MCS} = 9\text{-}10$, $M_w = 6.84$ and 1933 - $I_{MCS} = 8$, $M_w = 5.90$; 1933 "Marsica":1915 - $I_{MCS} = 8$, $M_w = 7.08$) and one (1349 - $I_{MCS} = 8\text{-}9$) is related to a still undefined source (Galadini & Carrozzo 2014).

In the Italian seismogenetic zonation (ZS9) proposed by Meletti and Valensise (2004) the area falls in the seismogenic zone 923 for which a maximum magnitude $M_w = 7.06$ is expected for a 475-year return period. The seismogenic potential has been confirmed by more recent studies on past seismicity and fault activity of the Sulmona basin (Ceccaroni et al. 2009; Galli et al. 2015; Gori et al. 2011) pointing out that the Morrone fault represents a potential source of earthquakes with magnitude M > 6.5 with an elapsed time since the last activation in the order of 1,850 years. Indeed, in times preceding the time interval represented in CPTI15 catalogue, this fault most likely caused a strong earthquake during the 2nd century AD responsible for the destruction of Roman towns in the Sulmona basin (Ceccaroni et al., 2009; Galadini & Galli 2001; Galli et al. 2015).

Currently, the Municipality of Sulmona is included in Zone 1 both in the classification by Regione Abruzzo and basing on the Seismic Hazard Map of Italy. According to the Italian Building Code (Ministero delle Infrastrutture e dei Trasporti 2018), the peak ground acceleration (a_g) expected at Sulmona with a 10% probability of exceedance over 50 years on firm soil and free field conditions is about 0.258 g. Local subsoil conditions could also produce amplification phenomena of ground surface motion in some areas of the city with important effects on the damage to residential and monumental buildings.

4 SUBSOIL INVESTIGATION AND GEOTECHNICAL MODELLING

4.1 *Overview of available data*

In the years, the Sulmona area has been investigated by numerous *in situ* and laboratory testing surveys. Field tests include: numerous boreholes (maximum depth of 60 m); five seismic dilatometer tests, SDMT (maximum depth of 60 m); eleven down-hole tests, DH (maximum depth of 30 m), and several surface geophysical linear measurements, MASW, and ambient vibration measurements (HVSR technique). Laboratory tests were performed on disturbed and undisturbed samples collected at different depths in some of the boreholes and include grain size distribution analysis and measures of unit weight and Atterberg limits, resonant column (RC) and cyclic torsional shear (CTS) tests.

Four boreholes, performed during distinct field campaigns, are located close to the SS. Annunziata Complex. Data belongs to the 1993 restoration project of the SS. Annunziata Complex performed by the Regione Abruzzo Public Work Department, to the former campaign of microzonation studies of the area (Di Capua et al. 2009; Scarascia Mugnozza 2007; Totani et al. 2009), and to the most recent testing campaign performed in 2018 for the Top-down FISR 2016 project (Ciani et al. 2021) to better explain the seismic behaviour of the Annunziata Complex. Figure 4(a) shows the location of the investigated verticals closest to the SS. Annunziata area: S1_1993 (S1 in the following), close to the front of the building, drilled up to 40 m of depth; S3c_SDMT2006 (S3 in the following), located SE of the SS. Annunziata at a distance of about 60 m, advanced up to 60 m of depth; S11_SDMT2018 (S11 in the following), located close to the back of the SS. Annunziata, 37 m deep, and S12_SDMT2018 (S12 in the following), located behind the main church, drilled up to 50 m of depth. Seismic dilatometer tests were performed in boreholes S3 (2006), S11 and S12 (both in 2018).

Based on the data from the geological surveys and from the four investigated verticals above mentioned, the following soil units can be identified in the area of the monumental Complex, from the top to the bottom: backfill (R), gravel (G), silty sand (S), clayey silt (L), lacustrine clay (A). Clayey silt represents the transition material between fluvial (above) and lacustrine (below) deposits. Overall, the stratigraphy is quite heterogeneous and significant differences were also found in soil profiles located at a short distance from each other, especially in the first tens of meters. In borehole S1, close to the front of the Complex, a silty sand layer is detected within the first 2 m, followed by gravel up to about 22 m and by the transition clayey silt layer below this depth up to the end of the borehole. Boreholes S3, S11, S12 show a shallow backfill layer of about 2-3 m-thick. Below this layer, silty sand lenses are framed within gravel banks at shallow depths in boreholes S3 and S11, while in borehole S12 a silty sand layer is detected between 5.4-6.3 m in depth, followed by a continuous gravel layer up to ≈ 30 m. Transition alluvial-lacustrine clayey silts are found starting from 28, 23, and 30.3 m in S3, S11 and S12, respectively, interrupted by gravel lenses. Lacustrine clay is only detected at deep (starting from 41.6 m) in S3, and at the bottom of S12 (5 m-thick layer from 45 m below ground) where a gravel lens between L and A materials is also found.

According to the available measurements, the historical centre of Sulmona is characterized by a significant shear wave velocity inversion located in the transition zone between fluvial and lacustrine deposits. From SDMT measurements, the shear wave velocity (V_s) of the backfill is around 230 m/s in S3 and 500 m/s in S11 and S12. For gravel, V_s shows a great variation with depth and borehole, ranging from ≈ 285 m/s in S3 to > 1000 m/s in S3, S11 and S12 due to a denser state. For clayey silt, V_s is around 280-510 m/s, with occasional spikes to 689 m/s (S11) and > 1400 m/s (S12). In silty sand and lacustrine clay, V_s ranges between 400-600 m/s, generally increasing with depth. None of the boreholes reached the calcareous bedrock. By combining the available V_s data with the microtremor measurements performed close to the monumental Complex (Pizzi et al. 2014), the bedrock depth was estimated, resulting in ≈ 270 m, in agreement with previous studies (Di Buccio et al. 2017; Di Filippo & Miccadei 1997; Manuel 2007).

4.2 *Geotechnical modeling of analyzed soil profiles*

For the purposes of this study, numerical 1D ground response analyses have been performed on the S11 and S12 soil profiles that are located respectively close to one side and to the back of the monumental Complex where the greatest damage was observed during the 2009 L'Aquila earthquake (Figure 4(a)). The two boreholes are almost 60 m far from each other and result significantly different between 7 to 30 m depth, where many thin layers of silty sand alternate with thicker layers of gravel in S11 profile, while in S12 profile the layer of gravel extends continuously, as found in S1 borehole close to the front of the Complex.

Given the data discussed in the previous sections, the following criteria were adopted for the geotechnical modeling of the two analyzed S11 and S12 profiles. The layering of each profile was directly obtained from the survey results; the lithological unit identification was based on the visual observation of the boreholes cataloging boxes combined with the results from classification laboratory tests performed on the disturbed samples, when pertinent. The shear wave velocity of each lithological unit, at a given depth, was obtained as the average of the SDMT measurements from S3, S11 and S12 locations at the same depths. Considering that S11 ends at 37 m, S12 at 50 m and S3 at 60 m, litho-stratigraphic profile from S12 (with V_s averaged values from S12 and S3) was adopted also for S11 between 37 m to 50 m (S11 and S12 are very close and the same soil unit is encountered at 37 m in both S11 and S12 borehole), while the litho-stratigraphic profile obtained from S3 (with associated V_s values) was adopted for both S11 and S12, from 50 m to 60 m. The lacustrine clay soil unit was assumed from 60 m to the top of the bedrock, estimated at a depth of 270 m (Di Buccio et al. 2017). Due to the lack of direct measurements, V_s values below 60 m of depth up to 270 m for lacustrine clays were inferred from a power regression ($V_s = a \cdot z^b$, with z depth, a=53.125 and b=0.572 determined from regression) of the available experimental

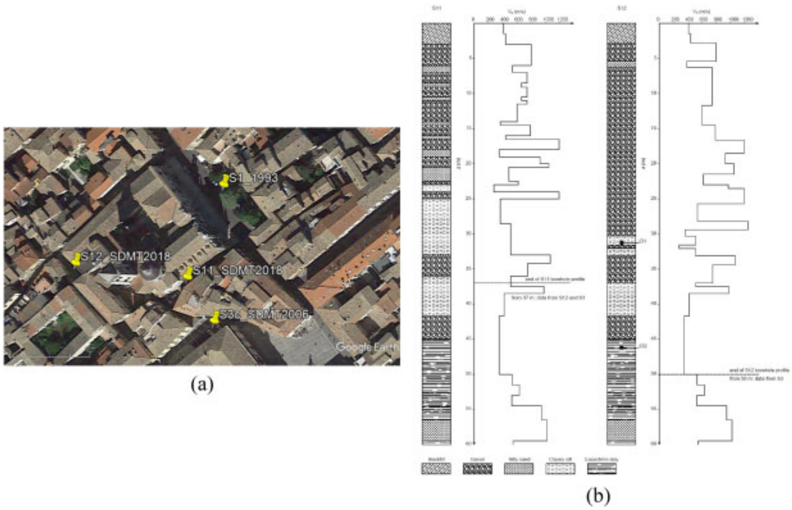

Figure 4. Location of the boreholes around the SS. Annunziata Complex (a); subsurface profiles with location of retrieved samples and associated shear-wave velocity profiles (b) at S11 and S12 sites.

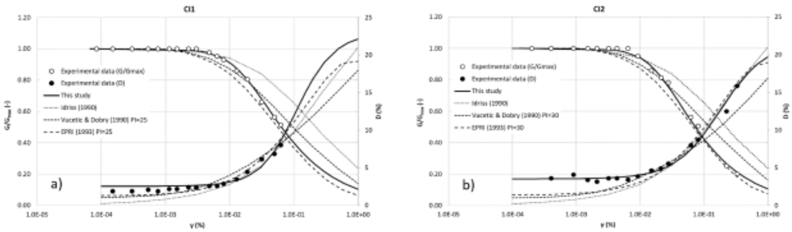

Figure 5. G/G_{max} and D experimental data for samples CI1 (a) and CI2 (b) and fitting curves compared with other literature curves.

measurements in this soil unit. Figure 4(b) shows the analyzed soil profiles of S11 and S12, with the associated V_s profiles, up to 60 m.

To describe the non-linear soil response in ground response analysis, data obtained from resonant column tests were used for the estimation of shear modulus decay and damping ratio curves for some soil units; for others, in case of any available data, literature correlations were used. Figure 5 shows the experimental results from resonant column tests performed on two specimens collected from borehole S12, namely samples CI1 (31.0-31.6 m) and CI2 (46.0-46.4 m), in terms of normalized shear modulus (G/G_{max}, being G_{max} the maximum shear modulus) and damping ratio, D, against shear strain, γ. The sample CI1 (Figure 5(a)) belongs to clayey silt and it was characterized by plasticity index PI = 24%; the sample CI2 (Figure 5(b)) belongs to lacustrine clay with PI = 31%. Figure 5 also shows the normalized shear modulus reduction and damping curves that best fit the experimental data (Ramberg-Osgood model, this study) compared with some well-established literature curves (EPRI 1993; Idriss 1990; Vucetic & Dobry 1991).

As it can be seen, the experimental shear modulus decay data are well matched by the adopted models for both CI1 and CI2; for the damping, a more satisfactory data matching is achieved for sample CI2. For both materials, the experimental shear modulus decay data are well within the range suggested by literature curves for similar PI, while the same does not hold in general for the damping data. Table 1 shows the soil parameters used in numerical analysis. The unit weight γ_n was estimated from laboratory tests on disturbed samples for all soil types, except for the calcareous bedrock. For the latter, a linear viscous-elastic behavior was assumed, with D = 0.5%, V_s = 1200 m/s and γ_n = 24kN/m^3 (Di Buccio et al. 2017).

Table 1. Soil parameters for numerical analyses.

Lithotype	γ_n (kN/m^3)	G/G_{max} model	D model
Backfill	20.36	Rollins et al. (1998)	Rollins et al. (1998)
Gravel	21.30	Modoni & Gazzellone (2010)	Modoni & Gazzellone (2010)
Silty sand	20.03	Amoroso et al. (2015)	Amoroso et al. (2015)
Clayey silt	20.53	see Figure 5	see Figure 5
Lacustrine	clay 21.63	see Figure 5	see Figure 5

5 NUMERICAL ANALYSIS

Numerical 1D ground response analyses were performed on the two soil profiles S11 and S12 using the well-known STRATA computer program (Kottke & Rathje 2009). It performs linear-equivalent site analysis in the frequency domain, assuming the soils behave as viscous-elastic materials (Kelvin-Voigt model). Two sets of real time-domain input motions were used in the analysis for each soil profile (see Section 5.1), assuming a maximum frequency of 20 Hz for the discretization of the soil layers, according to the Lysmer and Kuhlemeyer (1969) criterion. The results are described in terms of peak ground acceleration (PGA) and maximum shear strain (γ_{max}) profiles, as well as of pseudo-acceleration (S_a) response spectra.

5.1 *Reference input motions*

To investigate the effects of soil non-linearity on ground motion amplification with varying the earthquake-induced strain levels, two sets of real acceleration time-histories recorded on outcropping rock have been used in the analysis. Each one included 7 different motions and was on average spectrum-compatible with a design acceleration response spectrum of the site (target spectrum). Two different return periods (Tr) were considered, namely 30 and 475 years, obtaining a set of 'weak motions' and a set of 'strong motions', respectively, The records were selected using the software Rexel v. 3.5 (Iervolino et al. 2010), within the European Strong-Motion Database, to match the target spectrum with upper and lower tolerance of 30 and 10%, respectively, in the period (T) range 0.1–2.0 s. The accelerograms were selected based on their peak ground acceleration (PGA), to fall within the range $0.5a_g < PGA < 2a_g$, being a_g the peak ground acceleration expected at the site for the two different Tr; the signals were not scaled. Among the different motion combinations returned by Rexel, the selection was based on the fault mechanism (prevalently normal and strike slip) and on magnitude (M) and epicentral distance (R) of each signal, to be as close as possible to the mean M-R couples obtained from the a_g disaggregation. Figure 6 shows the pseudo-acceleration elastic spectra for the two selected motions' sets, together with the average and target spectra (note different ordinate scale).

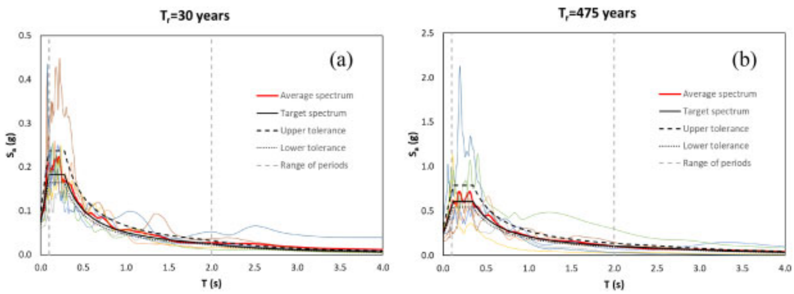

Figure 6. Pseudo-acceleration spectra of weak motions (a) and strong motions (b) used as input in the numerical analysis and corresponding average spectrum compared with the target spectrum at Sulmona for frequent ($T_r = 30$ years) and rare ($T_r = 475$ years) earthquake.

5.2 *Results*

Figure 7 shows the pseudo-acceleration (S_a) elastic response spectra (5% of critical damping) at ground surface against period (T) for S11 (Figure 7(a)) and S12 (Figure 7(b)) profiles. In Figure 7, the results for Tr = 30 years are in light grey, the results for Tr = 475 years are in darker grey, and the average spectra are in black (dashed/solid lines). As can be seen, the average elastic spectra are similar for both S11 and S12 soil profile, for each of the two considered return periods. Thus, at ground surface, significant differences are not expected, in terms of spectral acceleration, between the two sides of the SS. Annunziata Complex, where S11 and S12 boreholes are located. This result points out that the effect of the thin silty sand layers frequently encountered in the S11 profile (Figure 4(b)) is negligible. Little differences between S11 and S12 profiles could also be found in the PGA profiles (Figure 8(a)), while the maximum shear stress profiles (Figure 8(b)) show a slightly bigger variation, due to the soil types layering, with spikes corresponding to significant changes in initial V_s between adjacent layers.

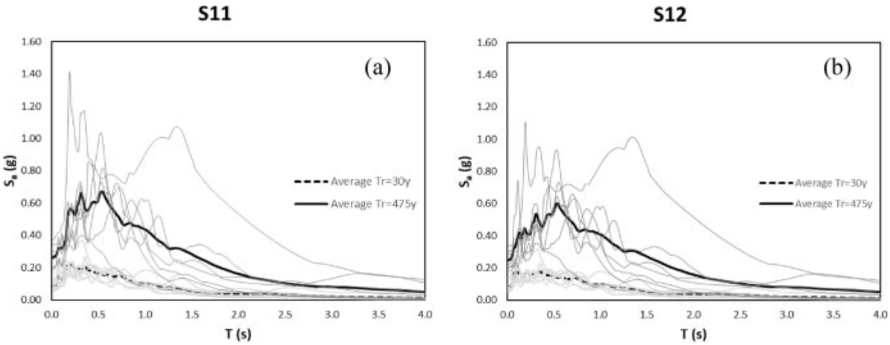

Figure 7. Pseudo-acceleration response spectra of ground surface motions at S11 (a) and S12 (b) sites for weak motions (light grey lines and dashed black line) and strong motions (dark grey lines and solid black line).

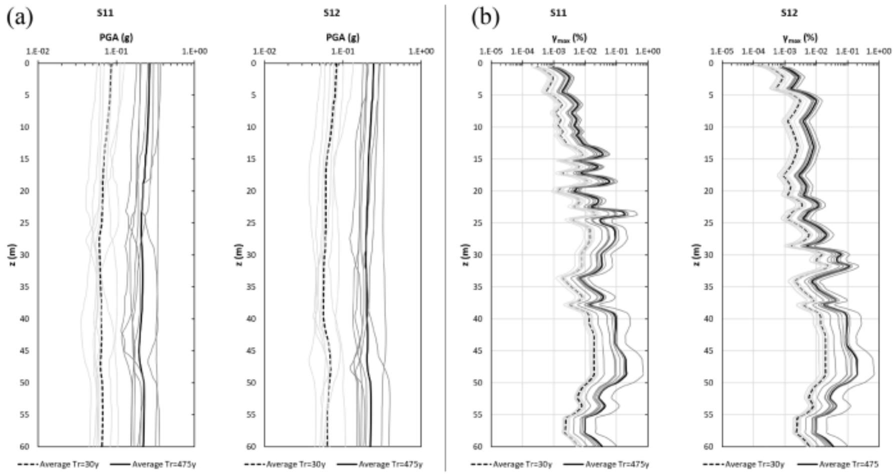

Figure 8. Peak ground acceleration (a) and maximum shear strain (b) up to 60m depth at S11 and S12 sites for weak motions (light grey lines and dashed black line) and strong motions (dark grey lines and solid black line).

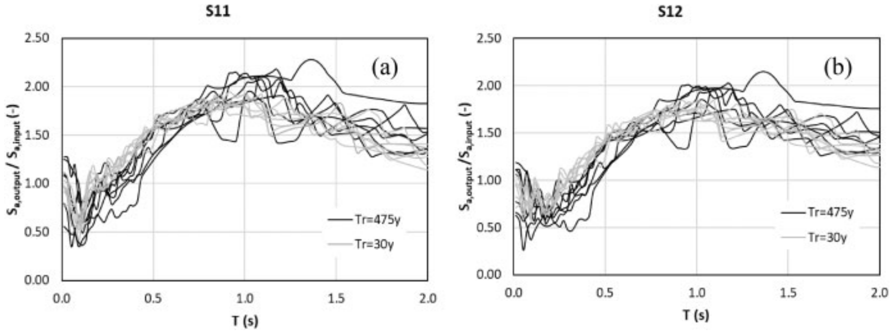

Figure 9. Spectral pseudo-acceleration ratio between ground surface motion and bedrock outcrop motion at S11 (a) and S12 (b) sites for weak motions (light grey lines) and strong motions (black lines).

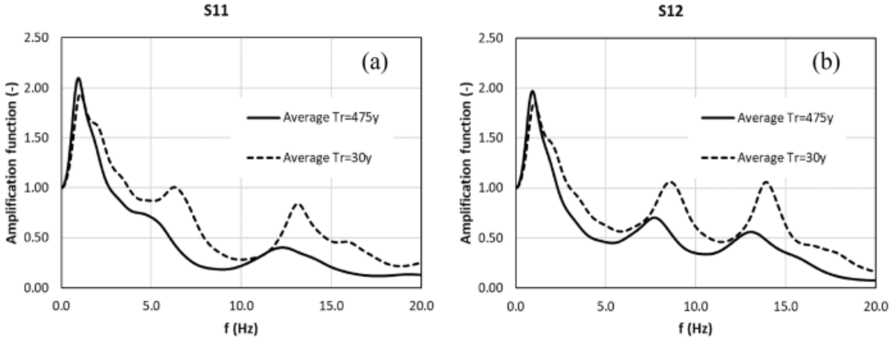

Figure 10. Amplification functions at S11 (a) and S12 (b) sites for weak motions (dashed line) and strong motions (solid line).

As it can be noted from Figures 7 and 8, the trend of the soil response under weak and strong motion inputs has a similar shape (although the amplitude of the parameters is significantly different). This is even more clear by looking at Figure 9, which shows the ratio between the spectral pseudo-acceleration at ground surface ($S_{a,output}$) and the spectral pseudo-acceleration at bedrock outcrop ($S_{a,input}$), against T, for all input signals. Within the period range 0.0-0.5s, the spectral ratio curves associated to Tr = 30 years generally lie above those associated to Tr = 475 years; for 0.5s < T < 1.0s the curves are interlocking; for higher periods, the spectral ratio curves associated to Tr = 475 years lie prevalently above those associated to Tr = 30 years. When 'strong motion' inputs are used, the natural frequencies of the deposit are expected to be lower than the natural frequencies corresponding to 'weak motion' signals, because of the reduction of the shear modulus associated to the greater shear strain level, as confirmed by the amplification function trend (Figure 10). Consequently, a greater amplification is expected for higher periods (lower frequencies) for Tr = 475 years, while greater amplification is expected at lower periods (higher frequencies) for Tr = 30 years, as it results from numerical output shown in Figure 9 and discussed above.

6 CONCLUSIONS

Preliminary 1D ground response analyses were performed on two vertical profiles in the area of the of the SS. Annunziata Complex, which is the most important historical monument in Sulmona. The main purpose of this study was to investigate the influence of the different stratigraphic conditions on local ground amplification which may have caused significant damage to the back of the Complex during the last seismic events. Due to the lack of local recordings on outcropping rock, two different sets of input motions were selected from databases of real recordings, associated to different earthquake-induced shear strain levels (corresponding to 'weak motions' and 'strong motions'), to evaluate the influence of non-linear behaviour of soil. For each of the two signal sets, the obtained results showed that there is no significant difference in the 1D response at the ground surface for the two analyzed soil profiles. More specifically, the ground surface response does not seem to be affected by the presence of numerous sandy-silty lenses intercluded within a thick layer of fluvial-lacustrine gravel that characterizes one of the two vertical profiles. Therefore, the different amount of damage observed in the different parts of the Complex following the recent earthquakes appears to be ascribable to structural reasons rather than to the different seismic shaking at the basement. However, further research is needed to verify if significant 2D amplification effects may be induced by topography and/or by the pronounced horizontal heterogeneity associated to the presence of the sandy-silty lens within the layer of fluvial-lacustrine gravel.

ACKNOWLEDGEMENTS

Special thanks to Studio Prof. Marchetti (Italy) for kindly providing the SDMT apparatus, to FISR 2016 project to fund the 2018 site investigations and to the Municipality of Sulmona and the Casa Santa dell'Annunziata to providing the access for the site campaign.

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