Site characterization for assessment of the seismic vulnerability of ancient buildings in the center of Macerata

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ABSTRACT: This paper illustrates the results of site investigations carried out in the center of Macerata, a town of about 40,000 inhabitants located in the vast region struck by the 2016-2017 Central Italy seismic sequence. The site investigations were planned as part of a study for the assessment of the seismic vulnerability of two ancient buildings, property of the University of Macerata. The investigation program comprised boreholes to 40-100 m depth, V_S measurements by seismic dilatometer in backfilled boreholes to 40-100 m, down-hole tests to 40 m, surface wave tests and seismic noise measurements. Laboratory tests, including cyclic/dynamic tests, were carried out on undisturbed samples. The site characterization based on in-situ investigations and laboratory test results is described in the paper. The investigation data permitted to define the input geotechnical subsoil model and related parameters for a site response analysis aimed at evaluating the seismic action on the existing buildings.

Keywords: site investigations; shear wave velocity; down-hole test; seismic dilatometer test; resonant column test

1. Introduction

During the last half century several moderate to strong earthquakes have struck many regions of Italy. In particular, major seismic sequences have struck central Italy in 1997 (Umbria-Marche), 2009 (L'Aquila), 2016-2017 (Central Italy). The last sequence culminated in various destructive main shocks on August 24, 2016 (Accumoli, moment magnitude M_w 6.0), October 10, 2016 (Castelsantangelo sul Nera, M_w 5.4 and Visso, M_w 5.9), October 30, 2016 (Norcia, M_w 6.5) and January 18, 2017 (Capitignano, M_w 5.1, 5.5 and 5.4, and Barete, M_w 5.0).

The events that hit central Italy in 2016-2017 caused significant damage over a widespread area across four regions (Marche, Umbria, Lazio, Abruzzo). In general they were accompanied by numerous series of moderate and minor shocks that often amplified previous damages. Several municipalities in the Macerata province (Marche) suffered severe damages. The earthquakes induced structural damage also in the old town of Macerata (about 40,000 inhabitants), which comprises many historic buildings. Several of these buildings are owned by the University of Macerata. Subsequently, the University of Macerata planned an ample investigation, aimed at evaluating the level of safety of these structures under seismic actions to design the necessary measures to strengthen the unsafe buildings.

Within this program an extensive soil investigation was planned and completed in two areas, the Loggia del Grano (Site 1) and Piazza Strambi (Site 2), where two university buildings are located. Both sites are close to the Northern edge of Macerata hill.

In the paper, after a brief description of the geology of the area, the results of the different in situ and laboratory tests performed at both sites are described and commented. The attention is focused on the interpretation of in situ and laboratory tests to reconstruct a subsoil model and to determine the dynamic properties of the different soil layers. Successively, these data will be used in site response analyses to estimate the effects of ground shaking on these historic constructions and suggest possible remediation measures.

2. Site characteristics and geology

The construction of the historical town of Macerata dates back to the IV-V centuries A.D., when the first dwellers retreated atop the hills to seek protection from the barbaric invasions. During the XIV-XVI centuries the town was largely expanded, becoming close to its present shape. The historic center occupies an almost square area, on the top of a hill that rises at an elevation of 300-315 m a.s.l. about 25 km West of the Adriatic Sea.

The geology of the area comprising the town is characterized by a basal formation of Pliocenic origin that extends to great depths, below sea level. This formation consists of predominantly fine-grained soils layered with sandy soils, locally cemented into a weak-soft sandstone rock. The fine-grained soils include clays, silty clays and marly clays; they include thin layers of fine to medium sand. The coarser materials consist of layered sandstone and sand with thin silty clay strata.

This formation is covered by Quaternary deposits originated by local slides and slopewash, erosion and subsequent deposition due to rain and surface waters. These deposits are mainly composed of fine silty sands and sandy silts, clayey sands and occasionally soft clays with organic matter.

The geological model of the subsoil described in the literature includes the presence of near vertical faults and associated relative vertical displacements. Hence, log of boreholes might show vertical stratigraphic differences even if drilled at close distance.

Details on the geology of the area of Macerata and other related information can be found in the documents [1] produced as part of level 3 seismic microzonation studies carried out for the reconstruction of several municipalities struck by the 2016-2017 Central Italy earthquakes. The studies were executed by professional geologists and geotechnical engineers with the scientific supervision and support of the Center for Seismic Microzonation and its applications (CentroMS, https://www.centromicrozonazionesismica.it/en/).

During the investigation performed within this study the groundwater table was not detected. It is very likely that inside the historical center of Macerata the water table remains at great depths, some hundred meters below surface. It is expected that ground seepage and water level are controlled by the hydraulic regime of the two main rivers, Potenza and Chienti, flowing through the flat lands at the base of the Macerata hill, on the North and South sides respectively. These rivers flow in the West to East direction towards the Adriatic Sea.

3. Site investigation

The investigation program has comprised drilling of four boreholes with total soil recovery (S1, S2, S3, S4), flat dilatometer testing with seismic module inside two backfilled boreholes (SDMT1, SDMT2) and through ground in the vicinity of these boreholes (SDMT1bis, SDMT2bis), shear wave velocity measurements via down-hole testing in two boreholes (DH-S1, DH-S2), recording of ambient noise at two locations (HVSR1, HVSR2), the execution of multichannel surface wave tests along three alignments (MASW1, MASW2, MASW3), the retrieval of 17 soil samples for static and cyclic/dynamic laboratory tests. The location of the site investigations is shown in Fig. 1.

Within Site 1 boreholes S1 and S4, to depths of 40 m and 100 m respectively, were drilled. Borehole S1 was equipped for the down-hole test DH-S1. In the 100 m deep borehole S4 V_S measurements were obtained with the seismic dilatometer (SDMT2) by pulling the probe upward, while the hole was progressively backfilled with clean fine-medium gravel, keeping the probe embedded. Measurements were taken at depths from 2.5 m to 99.5 m.

This procedure, with minor differences, was introduced by Totani et al. [2] and has been largely employed in the area of L'Aquila after the 2009 earthquake, as described by Monaco et al. [3]. In this procedure the SDMT probe is inserted and advanced into a pre-drilled backfilled borehole by use of a push rig and V_S measurements are taken every 0.50 m of depth as in the usual SDMT testing [4], but without DMT measurements (meaningless in the backfill). In this way 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 [2]. 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.

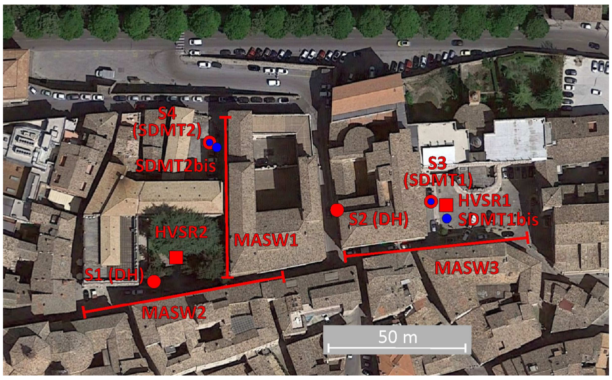

Figure 1. Plan layout of site investigations.

Figure 2. Execution of V_S measurements by seismic dilatometer (SDMT2) in the backfilled borehole S4 using a special heavy hammer as seismic source at ground surface.

The above V_S measurements were obtained by use of an "enhanced" seismic source, specifically designed and tested at the University of L'Aquila in previous investigations [5] to improve the quality of the signals and reduce the uncertainty in the interpretation of V_S measurements by SDMT in deep backfilled boreholes. This "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.

In the vicinity of the same hole the SDMT2bis test was also performed by pushing the blade directly through the ground; however measurements were taken only to a depth of 2.4 m, after an obstacle stopped the blade to advance.

Investigation at Site 1 comprised also HVSR2, MASW1 and MASW2. Geophones to record surface waves were aligned and fixed on the pavement of two perpendicular streets along the North-South (MASW1) and East-West (MASW2) directions. Ambient noise was recorded using commercial instruments.

At Site 2 the remaining S2 and S3 boreholes were drilled to the same depth of 40 m. S2 was equipped for the DH-S2 down-hole test. Instead S3 was used to perform the seismic SDMT1 test with the probe pulled upward following the same procedure described above. The seismic SDMT1bis test was located near S3, with the blade pushed through soil from ground surface; here the test reached the depth of 11.4 m.

Ambient noise recording HVSR1 was performed in the vicinity of borehole S3. Geophones for the MASW3 were aligned on the street in the direction East-West, parallel to MASW2.

The soil samples retrieved during drilling (17) were sent to a geotechnical laboratory to determine physical and mechanical properties. The experimental program had to be modified from its original plan to account for the available material. In fact, due to the specific soil conditions only 5 samples were retrieved using a thin tube sampler; 7 samples were retrieved using a Mazier sampler; the remaining 5 were retrieved from the cored material. Most samples had limited length, varying between 0.2-0.5 m, mostly 0.3-0.4 m.

Physical properties have been determined for all samples; these include unit weight, natural, dry and saturated, water content, specific gravity of soil particles, Atterberg limits, grain size distribution, degree of saturation and void ratio.

Mechanical testing included 9 oedometer tests (OEd), 9 resonant column tests (RC), 2 cyclic torsional shear tests (CTS).

Except for two OEd tests which have been pushed to a maximum applied effective vertical stress of 6400 kPa, the remaining 7 samples were subjected to a maximum vertical stress of 3200 kPa.

Dynamic tests (RC, CTS) were performed applying a consolidation pressure close to the estimated values of the in situ average effective stress p'. Values of p' were estimated using the relationship $p' = (1 + 2 K_0) (\sigma'_v) / 3$ assuming $K_0 = 1$ and absence of groundwater.

4. Results of the in situ tests

The material recovered from the four boreholes drilled at Sites 1 and 2, was closely examined and described in four borehole logs. Data from these logs are consistent with the geological model of the subsoil within the area of Macerata; they are briefly described below. To simplify this description, and for purpose of clarity, three soil units are defined: A, B and C. Unit A includes all fine-grained clayey and silty soils; they exhibit very similar dynamic responses; Units B and C include the coarser sandy and silty soils and the cemented sandstone, respectively.

The four borehole logs show that the natural deposits are covered by a superficial layer of manmade fill. It has variable thickness, comprised between 0.7 m and 2.7 m, typically close to 2 m. Very likely this fill is encountered throughout the town.

The fill covers the Quaternary deposits which have been encountered to variable depths at the two sites, 5.7 m and 8.0 m at Site 1, and 5.3 m and 5.5 m at Site 2. These geologically recent deposits are mainly composed of clayey silts (A) and silty and clayey sands (B). In addition, a layer of fat organic clay and silty clay with inclusion of clayey peat was encountered in borehole S3 only, at depths 2.7-5.3 m underneath the manmade fill.

The Quaternary deposits cover the marly-clay Pliocenic formation, whose base was not reached within this investigation (S1-S4).

In the upper 40-50 m, all borehole logs show interbedded layers of fine and coarse soils; the sequence begins with the finer materials on top, right under the Quaternary deposits. The maximum and minimum thickness of each layer varies between 8.2-15.2 m and 0.9-3.0 m.

Logs of the four boreholes indicate that the layers of Unit A soils have maximum thickness of 11.7 m (S1), 9.0 m (S2), 8.2 m (S3), 11.0 m (S4). The layers of Unit B have maximum thickness of 5.4 m (S1), 15.8 m (S2), 13.5 m (S3), 12.5 m (S4). The thickness of the sandstone layers (Unit C) is uncertain; due to disturbance caused by drilling and coring, combined with a variable degree of cementation, this weak or lightly cemented rock is frequently retrieved in disks and bits; the maximum length of the intact fragments is 120 mm. The rock disks and bits are interbedded with thin layers of dense sands, fine silty sands and more rarely silty clay. The thickness of these clayey inclusions reaches 50-70 mm.

The color of Unit A soils is typically brown, becoming grey at variable depths in the four boreholes, 12 m, 28 m, 27 m, 37 m (S1-S4). The color of Unit B and Unit C is typically brown to light yellow to greater depths, reaching 30 m (S2) and 37 m (S1).

At depths below 35-52 m (S2, S4) the subsoil stratigraphy becomes slightly different. From the log of borehole S4, it can be inferred that at depths greater than 50 m the silty clays and clayey silts within the marly-clay formation are frequently interbedded with levels of fine silty sands, fine clayey and silty sands, sandy and clayey silts. The thickness of these coarser inclusions is limited, within 20-50 mm. The color is predominantly grey, locally dark or light grey. The clayey fraction appears to be stiff or very stiff becoming hard with depth.

To obtain a rough estimation of the undrained resistance of the clayey and silty soils, many pocket penetrometer tests were performed on the freshly retrieved cores. In the upper 20 m, most values of this resistance varied between 0.4-0.6 MPa; locally, however, values of 0.6-0.9 MPa were also measured, even at shallow depths (5-12 m). At depths of 30-40 m data range within 0.5-0.9 MPa, although values greater than 1.0 MPa, corresponding to the full scale range of the penetrometer, are also indicated. Below 40 m the full scale range was generally reached; the lowest values of resistance vary between 0.65-0.95 MPa. These data indicate a general increase of the undrained resistance with depth; in addition a localized change might be recognized at depths of 40-50 m.

The main results obtained from the boreholes, the in-situ seismic measurements and the seismic dilatometer tests are summarized in Figs 3, 4, 5, 6 and 7. Each of these figures refers to a distinct borehole/test location and shows the schematic soil stratigraphy derived from the borehole log, as well as the profiles with depth of the shear wave velocity V_S measured in the same borehole by down-hole tests or seismic dilatometer tests (V_S-only measurements) in backfilled boreholes.

In particular, Fig. 3 shows the schematic soil stratigraphy obtained from the borehole S1 and the corresponding profile of V_S measured by down-hole (DH-S1) to a depth of 40 m, compared with the profiles of V_S obtained from the interpretation of the nearest surface wave tests (MASW1, MASW2).

Fig. 4 shows the schematic soil stratigraphy obtained from the borehole S2 and the corresponding profile of V_S measured by down-hole (DH-S2) to a depth of 40 m, compared with the profile of V_S obtained from the interpretation of the nearest surface wave test (MASW3).

Fig. 5 shows the schematic soil stratigraphy obtained from the borehole S3 and the profiles of V_S measured by seismic dilatometer in the same backfilled borehole (SDMT1) to a depth of 41 m and by the normal SDMT procedure in the virgin soil, at about 6-8 m distance, to a depth of 11.40 m (SDMT1bis). Such profiles are compared with the profile of V_S obtained from the interpretation of the nearest surface wave test (MASW3).

The profiles with depth of parameters obtained from the SDMT1bis results using common DMT interpretation formulae [6] are illustrated in Fig. 6. These results clearly detect the presence of soft fine-grained materials at depths between about 2.5 and 6 m, corresponding to organic clay in borehole S3 (Fig. 5). The mechanical properties of the soil increase below 6 m.

Fig. 7 shows the schematic soil stratigraphy obtained from the borehole S4 and the profiles of V_S measured by seismic dilatometer in the same backfilled borehole (SDMT2) to a depth of 100 m and by the normal SDMT procedure in the virgin soil, at about 2 m distance, to a depth of only 2.40 m (SDMT2bis). Such profiles are compared with the profile of V_S obtained from the interpretation of the nearest surface wave test (MASW1).

The comparisons in Figs 3, 4, 5 and 7 show that, in general, the V_S profiles obtained by different techniques (down-hole tests, seismic dilatometer tests in backfilled boreholes and in natural soil, surface wave tests) are broadly in agreement, and they are reasonably consistent with the soil stratigraphy.

At all test locations V_S generally increases with depth, showing higher values in correspondence of fine sand (Unit B) or sandstone (Unit C) layers, where values of V_S > 800 m/s may be encountered. For instance in the deepest borehole S4 (Fig. 7) the V_S obtained by SDMT2 are about 200-300 m/s in the upper ≈ 20 m, increase to about 700-800 m/s between ≈ 20 m and 40 m, then reduce to about 400 m/s and below 40 m increase almost linearly with depth to about 600-700 m/s at the maximum investigated depth of 100 m.

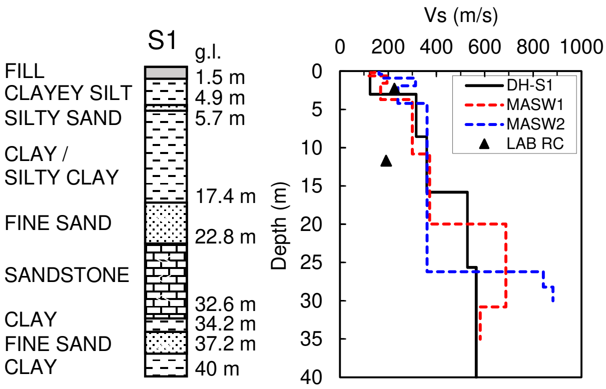

Figure 3. Borehole S1: schematic soil stratigraphy and profiles of V_S from down-hole and MASW.

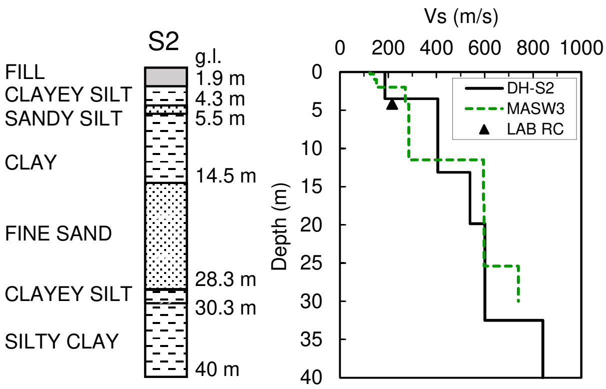

Figure 4. Borehole S2: schematic soil stratigraphy and profiles of V_S from down-hole and MASW.

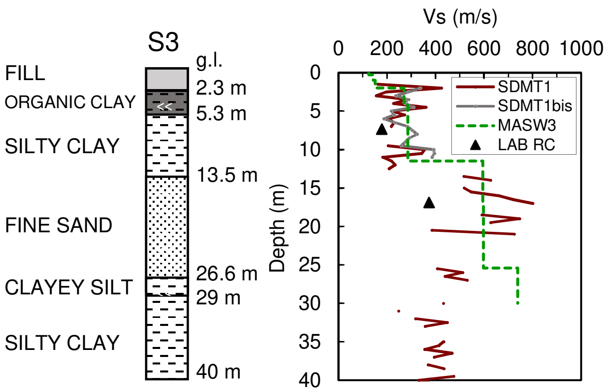

Figure 5. Borehole S3: schematic soil stratigraphy and profiles of V_S from SDMT in backfilled borehole and MASW.

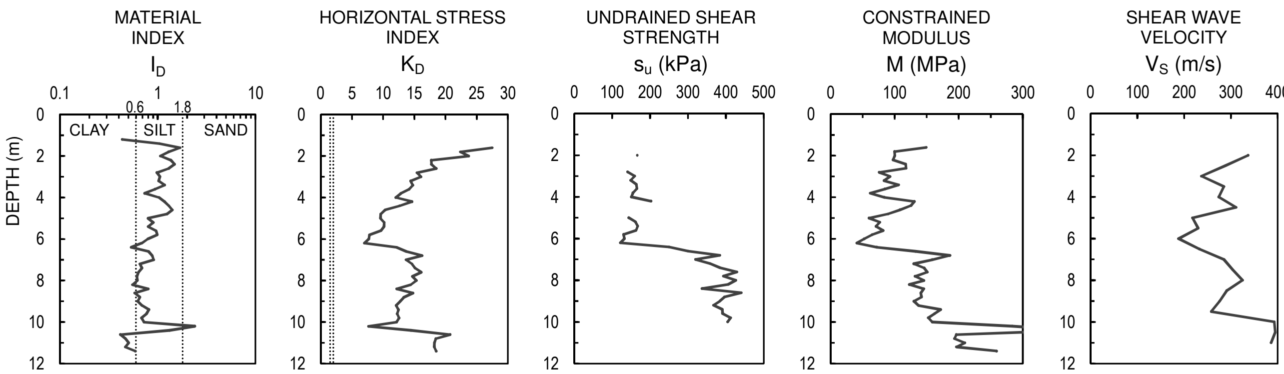

Figure 6. Results of interpretation of SDMT1bis.

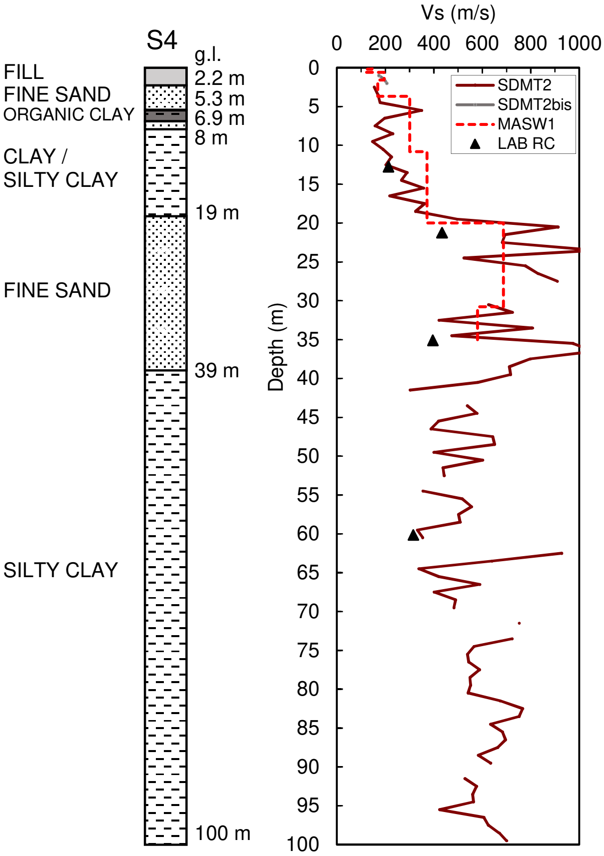

Figure 7. Borehole S4: schematic soil stratigraphy and profiles of V_S from SDMT in backfilled borehole and MASW.

5. Results of laboratory tests

As indicated before, the laboratory investigation comprised the determination of the physical properties of all samples, including natural dry and saturated unit weight, water content, specific gravity, Atterberg limits, grain size distribution, degree of saturation, void ratio, the execution of 1D consolidation tests (9) and of dynamic tests, RC (9) and CTS (2).

Available data of physical properties are summarized in Table 1.

As can be observed the Quaternary fine soils (Unit A1), clayey silts and clayey silts and sands, have unit weight in the range 17.6-20.6 kN/m^3 and 16.5-17.3 kN/m^3 with the lower values registered for the two samples of organic clays (Unit A2). The unit weight of the solid particles ranges 26.2-27.1 kN/m^3. The void ratio is relatively low, comprised between 0.53-0.89, with the exception of the fat clays having e = 1.53-1.19. Similarly, the natural water content varies in the ranges 16.3%-22.9% (Unit A1) and 44.1%-53.6% (Unit A2). The degree of saturation varies between 69%-81% and reaches 97% and 100% for the organic clays. The plasticity index varies in the range 16%-26% for Unit A1 soils and is equal to 23%-29% for the organic clays (Unit A2). Based on the grain size distribution samples can be described as silts and clays with sand or moderately sandy. The amount of fines ranges between 23%-44% clay and 50%-52% silt; the sand content ranges 18%-35% with a minimum value of 4%, while gravel is nearly absent at 1%-6%. The variability of the grain size distribution is coherent with the geology of these relatively young deposits.

Data from the Pliocenic fine soils appear less variable. Measures of the in situ unit weight range 20.1-22.0 kN/m^3 and are generally close to 21.1-21.4 kN/m^3. The unit weight of the solid particles ranges 26.2-26.9 kN/m^3. The void ratio has dropped to the range 0.46-0.57, with the minimum e = 0.38 for the sample at greatest depth (60.0-60.3 m). Similarly, the natural water content varies in the range 16.3%-18.7% with the minimum 13.9% for the deepest sample. The degree of saturation varies between 89%-100%; available data are not sufficient to explain the saturation of near surface and deep samples. With the exception of one sample, having PI = 30%, the plasticity index varies little and remains in the range 24%-26%. With the exception of the deepest sample the grain size distribution can be described as silts and clays with very little sand. The amount of fines ranges between 36%-52% clay and 46%-57% silt; the sand content ranges 2%-8%. For the sample retrieved at depth of 60.0 m the sand content prevails at 51%; silt and clay reach 32% and 17% respectively. No gravel was detected in any sample.

The three coarser samples (Unit B and B-C) have unit weight between 14.5-21.7 kN/m^3, unit weight of the solid particles ranging 26.2-26.3 kN/m^3, void ratio between 0.51-0.68, natural water content ranging 14.5%-21.7%, degree of saturation within 77%-98%. All samples are non plastic. The grain size analyses yielded a sand content ranging 51%-68% and silt and clay contents ranging 20%-32% and 11%-17% respectively. Hence these soils classify as clayey and silty sands.

Table 1. Summary of physical properties of soil samples.

Sample	Depth (m)	Soil unit	γ (kN/m^3)	γ_s (kN/m^3)	e	S (%)	w_n (%)	w_l (%)	w_p (%)	PI (%)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)
S1-C1	2.15-2.45	A	20.57	26.97	0.527	85	16.3	45	19	26	44	52	4	0
S1-C2	11.50-11.90	A	21.11	26.84	0.482	93	16.3	49	19	30	52	46	2	0
S1-C3	25.00-25.50	C	18.45	---	---	---	18.5	---	---	---	---	---	---	---
S1-C4	39.80-40.00	A	21.08	26.91	0.515	99	18.5	42	18	24	41	55	4	0
S2-C1	4.00-4.40	A1	17.06	26.23	0.893	69	22.9	38	19	19	27	34	35	4
S2-C2	8.00-8.30	A	21.37	26.52	0.467	100	18.0	45	21	24	45	50	5	0
S2-C3	12.00-12.30	A	21.24	26.51	0.456	98	16.5	44	19	25	44	50	6	0
S2-C4	32.60-33.00	A	21.27	26.42	0.456	100	17.0	39	19	25	36	57	7	0
S3-C1	7.10-7.60	A	20.09	26.54	0.571	89	18.7	45	19	26	42	54	4	0
S3-C2	3.00-3.50	A2	16.49	27.14	1.534	97	53.6	57	33	25	23	44	27	6
S3-C3	4.50-5.00	A2	17.34	26.30	1.189	100	44.1	56	28	28	29	50	18	3
S3-C4	16.70-17.10	B	19.99	26.30	0.509	77	14.5	---	---	---	11	29	60	0
S4-C1	5.00-5.50	A1	19.14	26.33	0.650	81	19.7	33	17	16	26	50	23	1
S4-C2	12.50-13.00	A	20.97	26.19	0.467	99	17.2	45	19	26	44	48	8	0
S4-C3	21.00-21.50	B	20.08	26.23	0.593	98	21.7	---	---	---	17	32	51	0
S4-C4	35.00-35.20	B (C)	18.88	26.33	0.676	79	19.9	---	---	---	11	20	68	1
S4-C5	60.00-60.30	A	21.95	26.61	0.383	99	13.9	38	18	20	41	56	3	0

γ = natural unit weight; γ_s = unit weight of solid particles; e = void ratio; S = degree of saturation; w_n = natural water content; w_l = liquid limit; w_p = plastic limit; PI = plasticity index

For the single rock sample, Unit C, only the unit weight (18.5 kN/m^3) and the natural water content (18.5%) were determined.

The oedometer tests performed on samples of Unit A yielded values of the compression and swelling coefficients within the intervals 0.11-0.15 and 0.04-0.06 respectively. The reduced compressibility exhibited by these fine soils is related to the overconsolidation induced by geological tectonic stresses, as can be inferred from the relatively low void ratios.

The two tests performed on samples of Unit B yielded the two pair of values for the compression and the swelling coefficients of 0.047 and 0.015 (S4-C3) and of 0.133 and 0.020 (S4-C4). These differences may be interpreted considering that these sandy soils are often slightly or moderately cemented and tend to behave as soft sandstone rocks.

The results obtained in the laboratory from resonant column (RC) tests are summarized in Fig. 8, in terms of variation of the shear modulus G, normalized to its small strain value G_0, and of the damping ratio D as a function of the shear strain γ. The experimental curves obtained on samples retrieved from the same soil unit are grouped together, respectively in Fig. 8a for Unit A (silty clay), in Fig. 8b for Unit A1 (clayey silts and sands) and in Fig. 8c for Unit B (silty and clayey sands).

It can be noted that the $G/G_0 - \gamma$ and $D - \gamma$ curves determined on different samples belonging to Unit A (Fig. 7a) and Unit B (Fig. 7c) are quite similar.

The values of V_S obtained in the laboratory from RC test results, using the relation $G_0 = \rho V_S^2$ (where ρ is the soil density), are compared to the corresponding in-situ V_S values in Figs 3, 4, 5 and 7. As a first approximation, the depths of the laboratory V_S datapoints plotted in Figs 3, 4, 5 and 7 correspond to the average depths at which the samples were retrieved, although such depths should be properly related to the consolidation stress p' applied in the RC test for each sample. However, considering that such p' values are very similar to the mean in-situ effective stress at the sampling depth, the difference is negligible. The laboratory V_S values are generally similar of slightly lower than the corresponding in-situ V_S values.

Fig. 9 shows the variation of the small strain shear modulus G_0 as a function of the mean effective consolidation stress p' determined from RC tests on samples taken in Unit A (silty clay) at depths varying between 2.15-2.45 m and 60.00-60.30 m below the ground surface. The best-fit correlation expressing the dependence of G_0 on p' is also indicated in Fig. 9.

6. V_S profile and identification of the seismic bedrock

One critical issue emerging from the analysis of the results of the site investigation described in the previous sections is related to the fact that, despite the significant depth (100 m) reached by borehole S4 and the corresponding V_S measurements obtained from SDMT2, neither the geologic or the "seismic" bedrock (characterized by V_S > 800 m/s) was detected.

It is also worth noting that the ambient noise records (HVSR1, HVSR2) were of little help in determining the position of the bedrock. In fact both records indicate possible impedance variations at depths in the order of 40-60 m (HVSR1) and 35-55 m (HVSR2), thus in the upper 50 m of the Pliocenic formation. Instead shear wave velocity measurements by SDMT2 in borehole S4 indicate that the V_S = 800 m/s threshold indicating a "seismic" bedrock had not been reached at the maximum test depth of 100 m.

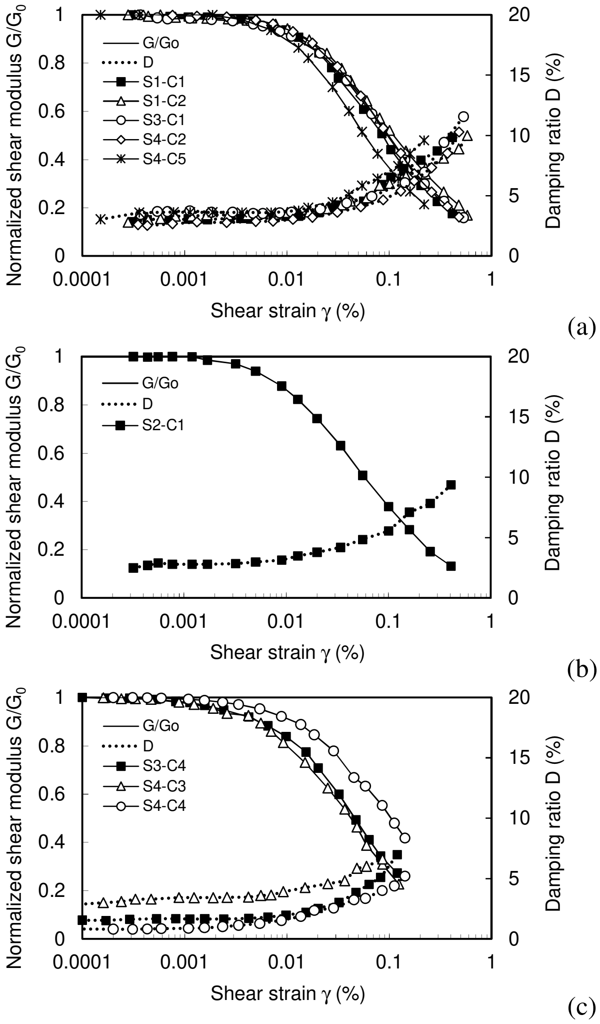

Figure 8. Normalized shear modulus G/G_0 and damping ratio D vs. shear strain γ from RC tests: (a) Unit A (silty clay); (b) Unit A1 (clayey silts and sands); (c) Unit B (silty and clayey sand).

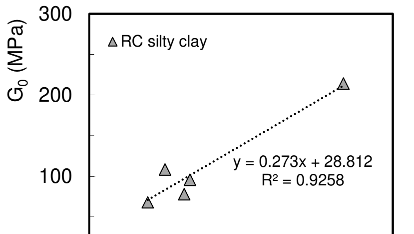

Figure 9. Variation of the small strain shear modulus G_0 as a function of the mean effective stress p' in Unit A (silty clay) from RC tests.

Therefore, considering that this information is essential for reconstructing a reliable subsoil model for site response analyses, the depth of the "seismic bedrock" was tentatively estimated from the available information from laboratory and in situ test data.

The $G_0 - p'$ relationship in Fig. 9, determined from RC laboratory test data for Unit A (silty clay), was tentatively used to extend the in-situ V_S vs. depth profile obtained from SDMT2 (borehole S4) to a depth at which V_S > 800 m/s. Such depth would be assumed as the "seismic bedrock" in future ground response analyses. For this purpose, the values of p' were converted into corresponding depths by assuming a constant value of the at-rest lateral earth pressure coefficient K_0 = 1 (a reasonable assumption in such overconsolidated deposits). The resulting trend line is shown in Fig. 10, compared to the interpolation line obtained as best-fit of V_S values measured in situ by SDMT2 in Unit A, to a maximum depth of 100 m. The two laboratory and in-situ interpolation lines indicate that $V_S \approx 800$ m/s is reached at depths comprised between about 115 m and 130 m below the ground surface.

7. Conclusions

This study illustrates the main results of a comprehensive investigation program, extended to great depths, in the city center of Macerata. Such results allowed reconstruct a reliable subsoil model for future site response analyses.

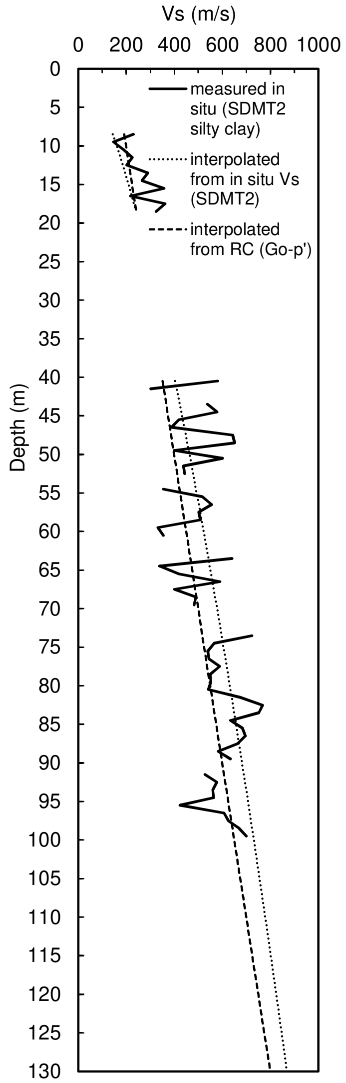

Figure 10. Extension of the in-situ V_S vs. depth profile in silty clay obtained from SDMT2 (borehole S4) to a depth at which V_S > 800 m/s, based on best-fit interpolation of laboratory RC test data and V_S measured in situ.

Under relatively uniform geological conditions, as in the case of Macerata, it is necessary to extend the investigations to significant depths to determine the position of the "seismic bedrock" (V_S > 800 m/s).

The study illustrates that, under these conditions, the SDMT proves as an effective and reliable tool to obtain V_S measurements to significant depths. In this respect, a notable feature is that the seismic module of the SDMT is equipped with a signal amplifier to provide a clear record of the waveforms. When combined with a specifically designed heavy hammer, capable to deliver high energy, this feature allows to extend measurements at depths larger than usual, up to 100 m and more.

Laboratory resonant column tests are a very reliable and effective mean to determine soil properties for dynamic analyses. However when testing very stiff soils and samples retrieved at great depths, the representativity of the test may be affected by the limit of the testing equipment to apply a consolidation pressure close to the in-situ mean stress.

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