Dynamic properties of the Holocene age deposit in the Italian port of Ravenna

Matteo Senigagliesi[1]*, *Pierluigi* Alesiani[1], *Paolo* Ruggeri[1], *Viviene M. E.* Fruzzetti[1], *Giuseppe* Scarpelli[1]

[1] *Università Politecnica delle Marche*
Via Brecce Bianche 12, 60131, Ancona, Italia
**Corresponding author: m.senigagliesi@pm.univpm.it*

ABSTRACT

Based on the collection of many data coming from a large survey carried out in the Ravenna Port channel, this paper focuses on the dynamic properties of the 30 m thick soil deposit whose poor geotechnical characteristics make the design of infrastructures in the area particularly challenging. The study included specific seismic in-situ investigations (e.g. Seismic CPTu and CH), laboratory tests on undisturbed bored samples (e.g. Resonant Column Test) and common in-situ testing (e.g. CPTu, DMT). The main objective is the estimate of the very small strain shear modulus and its decay with strain level (i.e. curves G_0-gamma) for dynamic characterization. This is a fundamental aspect to consider for numerical modelling of geotechnical engineering problems considering soil-structure interaction under working loads and site response analysis. The availability of direct and indirect measurements of the dynamic soil properties allowed the comparison between the different estimates and an evaluation on the applicability of the correlations between the outcomes from possible in-situ investigations.

Keywords: Shear Wave Velocity (Vs), Dynamic soil properties, Eurocode 7, In-situ testing, Very small strain shear modulus, G_0-gamma

1. Introduction

The evaluation of the dynamic properties of soils represents a central aspect of geotechnical investigation for a comprehensive definition of the ground model for design of structures and infrastructures in seismic areas. The relevance of such parameters is evident if we think about their pivotal role in the site response analysis under seismic motion or in the proper evaluation of soil structure interaction under working loads.

The very small strain shear modulus (G_0), the shear modulus decay with strain increase (G-γ curve) and the damping ratio curve (D-γ curve) are the three relevant dynamic properties of the soil. The evaluation of such properties can be carried out through laboratory tests, such as Resonant Column Test (RCT), Torsional Shear Test, Dynamic Triaxial Test and Cyclic Direct Simple Shear Test. However, in addition to being expensive, these tests have the typical shortcomings of the laboratory tests, that are the limited soil volume being tested, the soil disturbance induced by sampling, the difficulty in reproducing the actual in-situ stress. For these reasons, best practice involves performing both laboratory tests on undisturbed samples to evaluate G-γ and D-γ curves and geophysical in-situ tests to measure G_0. Geophysical seismic tests are a class of in-situ investigations which use a vibratory source for the direct measurements of the wave velocity propagating in the ground, allowing the evaluation of G_0. These tests involve a large volume of soil and can be carried out from the ground surface (e.g.: Multichannel Analysis of Surface Waves - MASW, Refraction Microtremor - Re.Mi., Seismic Refraction and Reflection Methods) or in boreholes (e.g. Cross-Hole Test – CH, Down-Hole test – DH). Depending on the type of geophysical test, the velocity of compression (P-), shear (S-) or surface waves can be measured. Methods based on surface waves give a good estimation of G_0 but require experienced operators. Down-Hole and Cross-Hole tests are more expensive but give more reliable results. With recent technological progresses, the possibility of measuring the shear wave velocity in CPT and DMT has been implemented with geophone installed on the probes, adding Seismic CPT (SCPT) and Seismic DMT (SDMT) to available investigation techniques.

The high costs of geotechnical investigation for infrastructures typically drives an optimization of the investigation test list. For complex geotechnical works, a certain redundancy of the investigation is however necessary as the cross-checking between different estimates of ground properties is a requirement prescribed by the high consequence class associated with high geotechnical complexity of the works. In line with these objectives, several empirical correlations are available from the literature to estimate the dynamic properties of soils from standard in-situ tests, such as CPT and DMT. Due to intrinsic uncertainties of such correlations, any occasion in which both direct and indirect tests are available, is useful to check their reliability for estimating soil dynamic properties, as in the present case study.

After a short presentation of the main parameters needed to describe the dynamic behavior of soils, this paper presents experimental data from in-situ and laboratory tests to verify the capability of empirical correlations in estimating soil dynamic properties for practical applications.

The study refers to the soil deposit that constitutes the first 30 m of the ground in the central part of the port of Ravenna, along the Adriatic coast, north Italy. The empirical correlations to derive values of dynamic properties of the soil are those suggested by the most recent version of the new Eurocode 7 (FprEN 1997-2:2023), whose approval by the member countries is in progress.

In particular, the paper focuses on the dynamic properties of the Clayey Silt Unit, a soft cohesive layer whose peculiar behaviour is strongly influential for design of infrastructures in the port area. Geophysical test data are assumed to be representative of the actual soil behaviour and this makes possible a check on the validity of the largely employed empirical estimates of dynamic properties from CPT, DMT and physical soil properties for common practice.

2. Dynamic soil properties: definitions

The very small strain shear modulus (G_0), the shear modulus decay with strain (G- γ) and the damping ratio (D - γ) curves are the main parameters needed to describe the dynamic behaviour of a soil.

G_0 is the value of the elastic modulus measured at shear strain less than 10^{-5}. It is also called initial shear modulus and it represents the maximum value of the elastic modulus of a soil as well as the slope at the origin of the stress-strain backbone curve.

G-γ degradation curve or decay curve of soil stiffness represents the variation of the shear modulus with shear strain. It is often represented in a normalised form of G/G_0 versus shear strain γ.

D is a measure of the dissipative response of the soil and is defined as the ratio between the amount of energy dissipated during a load cycle and the maximum elastic energy reached during the same cycle. The well-known representation of a loading cycle in the plane shear stress vs shear strain of Figure 1 shows the graphic evaluation of the damping ratio.

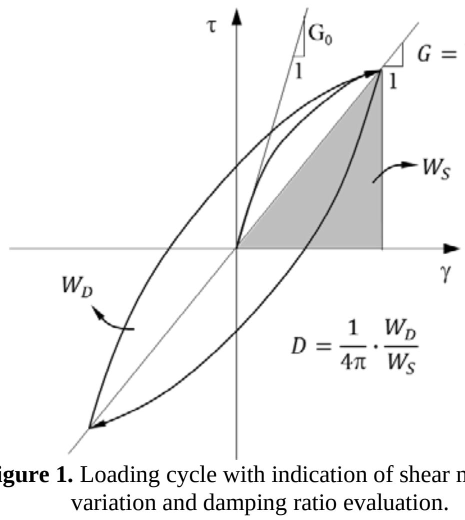

Figure 1. Loading cycle with indication of shear modulus variation and damping ratio evaluation.

Depending on the level of strain, a soil subjected to cyclic loading exhibits 3 typical behaviours:

- A - when the strain level is very low, the closed loop shows a pseudo-linear behaviour that means very little amount of energy dissipated;
- B - when the strain level increases, the closed loop is stable, but an area is enclosed, that means an amount of energy is dissipated (hysteretic loop);
- C – when the strain level is large, the closed loop shows a non-linear unstable behaviour, that means a large amount of energy is dissipated and the soil degrades progressively reducing its stiffness until failure.

In Figure 2 these behaviours are schematically represented together with a normalised shear stiffness degradation curve. Threshold strain values at the transition among behaviours depend both on the soil type and stress level.

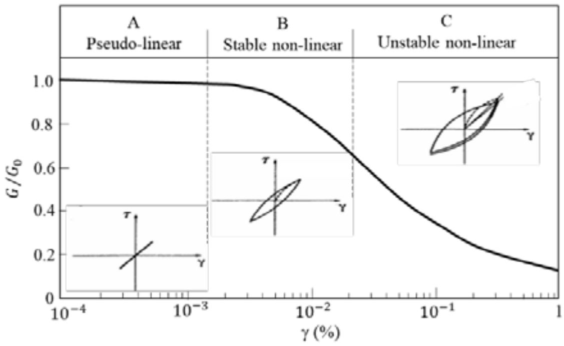

Figure 2. Normalized G/G0-g curves with the indication of typical behavior of cyclic loading at different level of strain: pseudo-linear (A), stable non-linear (B), unstable non-linear (C) (modified from Crespellani and Facciorusso, 2010).

3. Holocene deposit of the Port area

The port area of Ravenna has long been the object of research studies at the Marche Polytechnic University. This is because it is an area largely investigated from the geotechnical perspective to allow the development of a relevant public infrastructure in a challenging environmental context characterized, among others, by soils of poor mechanical properties.

A description of the soil stratigraphy characterizing the area can be found in Ruggeri et al. (2021a) resulting from boreholes, static piezocone penetrometer (CPTu) and flat dilatometer (DMT) and the geological model provided by Amorosi and Marchi (1999) and Battaglio et al. (1986).

A recently implemented major project for the port area of Ravenna gave the opportunity to build a comprehensive database from old surveys where the results from many geotechnical investigations with values of relevant geotechnical properties are collected (see also Ruggeri et al., 2021b; Alesiani and Ruggeri, 2024). The geological setting of the Port channel, characterized by the horizontal layering of the recent soils, gives the opportunity to designers to profit from the organized database to build their geotechnical models for design.

Here, the geotechnical investigations carried out at the Port channel in its central area of about 500,000 m^2 are considered. The representative stratigraphic sequence for the first 35 m from ground level is shown in Figure 3. Four Geotechnical Units can be identified.

Starting from the ground level an anthropic landfill is found, formed by the pavement and the artificial landfill of coarse-grained composition, with thickness of some meters. Below there is a layer of Silty Clay of lacustrine origin with relatively small thickness (1-2 m).

The above ground rests over a more relevant layer of Silty Sand sedimented during the last marine regression. In the area of interest, the Silty Sand Unit has a thickness of about 6 m and is characterized by a maximum grain size D_{90} = 0.08 mm, a D_{60} = 0.1-0.2 mm, an effective size D_{10} = 0.005-0.001 which means a uniformity coefficient U = D_{60}/D_{10} = 20-40, that is a well-graded soil. The fines (D < 0.42 mm) are non-plastic and the typical range for the friction angle is 34-36°.

The Silty Sand lays on a 15 m thick layer of fine-grained soil sedimented in marine environment from 7,000 to 2,000 years old. Its particle size distribution indicates a 60-70% of silt, 20-30% of clay and 0-10% of fine sand, that is a Clayey Silt. The Clayey Silt has a plasticity index from 10 to 30 and, due its geological history, is a normal consolidated deposit (i.e. OCR = 1). Its composition, plasticity and stress history indicate a soft soil with a high compressibility, low undrained shear strength, relatively high effective friction angle. Laboratory tests confirm these findings giving an undrained cohesion from 30 to 50 kPa but an effective friction angle between 29° and 31°.

Below the Clayey Silt Unit a thin layer of Sand, sedimented during the last transgressive marine cycle, is encountered. Then, a continental deposit formed at the end of the Pleistocene (when the sea level was 100 m lower than now) is found up to large depth. This Unit is made of an alternance of coarse-grained and fine-grained layers.

Together with the soil stratigraphy, basic data from some CPTu and DMT are represented in Figure 3. It is worth noting that the profiles from all in-situ testing clearly detect main soil Units in the investigated area.

From a design perspective, the mechanical behavior of the Clayey Silt Unit, with its low stiffness, strongly conditionate the behavior of geotechnical constructions as well as the site response analysis in the Port area. In Figure 4, geotechnical properties of the Clayey Silt are presented: particle size distributions, Atterberg limits on the Plasticity Chart and the Soil Type resulting from CPT and DMT. It is worth noting that the identification from CPT and DMT falls on the trend line proposed by Robertson (2009).

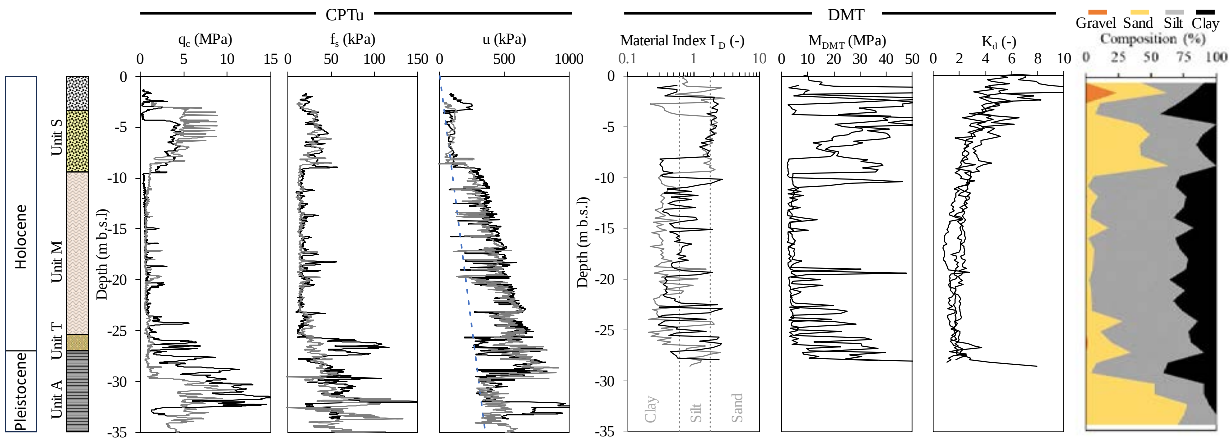

Figure 3. Soil Units with typical trends of properties.

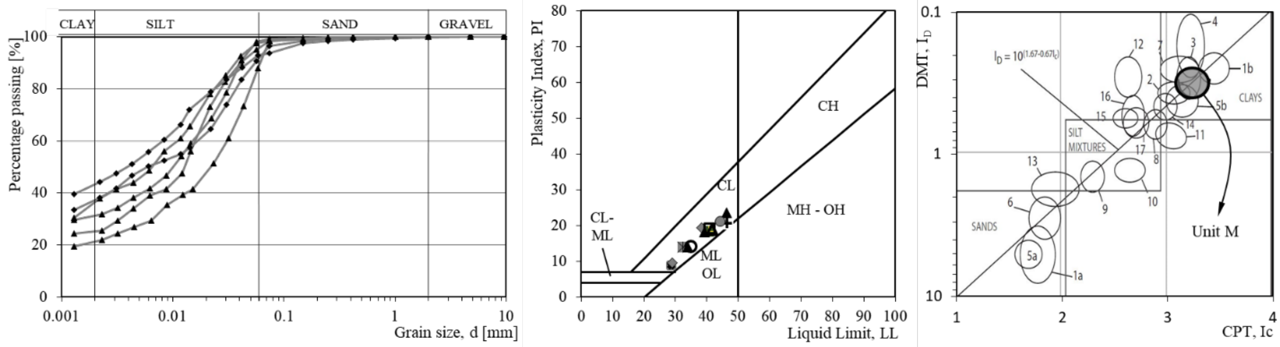

Figure 4. Clayey Silt: particle size distribution, soil classification according to Casagrande Chart and through CPT index Ic and DMT index I_D.

4. Direct measurements on the Holocene age deposit

Dynamic properties of soils at very small strain levels are usually evaluated by geophysical seismic tests. These tests, which operate at strain levels below 0.001%, investigate the pseudo-linear soil response and allow the determination of the very small strain shear modulus G_0 from direct measurement of propagation velocity of waves in the ground. Geophysical seismic tests have the advantage of detecting the response of relatively large volume of soil in the in-situ conditions avoiding disturbance related to sampling. Some geophysical tests are performed from the ground surface while others require one or more conditioned boreholes. The tests performed from the ground surface are less expensive and not time-consuming but require non-trivial post processing of the recorded signals to evaluate the profile of the wave velocity with depth. On the contrary, tests performed in boreholes to be conditioned with a liner are expensive but a profile of wave velocity in the ground may be obtained.

For the present case study, a selection of some geophysical tests was considered; specifically, tests include: 1 cross-hole test (CH), 9 Seismic CPTu (SCPTu), 4 Refraction Microtremor (ReMi) and 1 Multichannel Analysis of Surface Waves (MASW). All these tests have provided a profile of the shear wave velocity of the first 30-35 m of depth from the surface.

Resulting profiles of the shear wave velocity are shown in Figure 5, both from boreholes and surface tests. The good match between all the profiles confirms the regularity of soil layers in the area. The following aspects emerge from a careful analysis of the profiles:

- the shear wave velocity generally increases with depth, from 120 m/s to 280 m/s between the ground level and -35 m from see level;
- in the upper Silty Sand Unit Vs = 150-180 m/s;
- In the Clayey Silt Unit Vs increases with depth, with values ranging between 140-160 m/s at the top and 200-230 at the bottom of the layer;
- at transition between the Silty Sand and the Clayey Silt a reduction of shear wave velocity of about 30 m/s can be observed;
- Re.Mi. measurements give values in good agreement with those resulting from CH and SCPTu profiles, but the change of the values at the Silty Sand-Clayey Silt transition is not captured;
- the Shear wave velocity profile from MASW test agrees quite well with the other profiles up to 20 m of depth; beyond this depth the shear wave velocity appears overestimated.

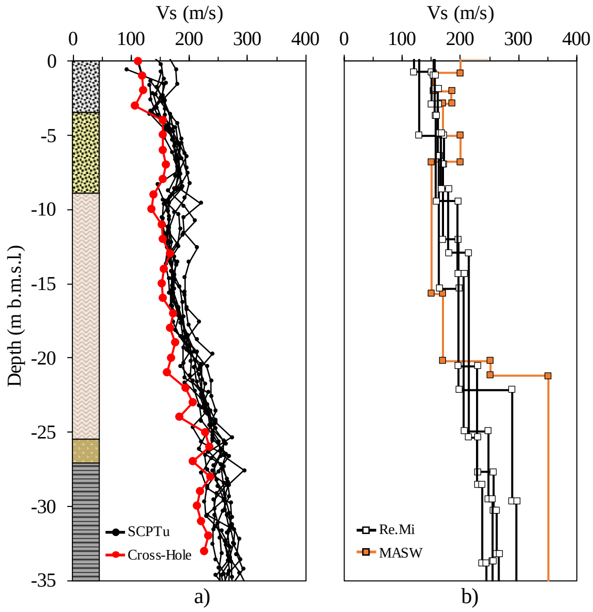

Figure 5. Vs from geophysical tests: CH and SCPTu (a); Re.Mi. and MASW (b).

On the base of these findings, the ground model resulting from direct measurements is considered strongly reliable, therefore it can be adopted as reference model when comparing the shear wave velocity estimates from empirical correlations, soil physical properties and CPT and DMT probing.

5. Focus on dynamic properties of Clayey Silt Unit

The dynamic properties of the Clayey Silt Unit have a great relevance on the seismic response of the deposit and on the behaviour of infrastructures. These properties are analysed with some details in the following.

5.1. G and D from laboratory tests

Dynamic properties of the Clayey Silt Unit were obtained from Resonant Column Tests (RCT) on 4 undisturbed samples. In Table 1, applied effective isotropic confining stress, initial and final void ratio, Plasticity Index and G_0 on each specimen are given. Resulting values of G_0 fall in the range of 68 - 144 MPa for mean effective pressures in the RC tests between 130 and 247 kPa, that is greater than the in-situ confining stresses.

The normalized G-γ curves and the D-γ damping curves from the tests are shown in Figure 6. Note that for all samples the pseudo-elastic threshold appears at a shear strain of about 10^{-4} %. The G-γ decay curves match those proposed by Vucetic and Dobry (1991) for Plasticity Index between 15 and 30.

Table 1. RCT on Clayey Silt samples

Test code	σ'_0 (kPa)	e_0 (-)	e_f (-)	I_P (-)	G_0 (MPa)
RCT1	152	1.00	0.90	21	68
RCT2	247	0.80	0.68	13	144
RCT3	130	1.05	0.88	19	74
RCT4	186	1.06	0.84	39	81

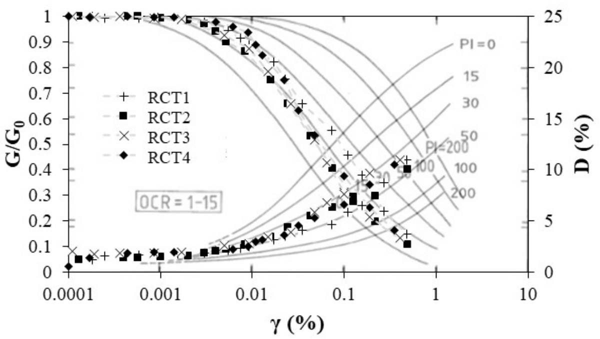

Figure 6. Normalized G-γ and damping curves for Clayey Silt samples from RC tests plotted on the graph proposed by Vucetic and Dobry (1991).

5.2. G_0 from empirical relationship

Soil stiffness at very small strain level depends on many parameters among which void ratio, particle size and shape, effective stress, fabric and particle arrangement. Many empirical relationships have been proposed to estimate G_0 from some relevant parameters. For example, Hardin (1978) proposed a well-known relationship between G_0 and stress state, void ratio and stress history. For the interested reader a comprehensive presentation of the subject can be found in Clayton (2011).

In line with the most recent findings, the draft of the new Eurocode 7 (FprEN 1997-2:2023) suggests the following formulation to estimate the very small strain shear modulus:

$$\frac{G_0}{p_{ref}} = \frac{k_1}{(1+e)^{k_2}}\left[\frac{p'}{p_{ref}}\right]^{k_3} \tag{1}$$

where e is the void ratio, p' is the mean effective stress, p_{ref} is a reference pressure, k_1, k_2, k_3 are constants depending on the soil type.

For the Clayey Silt Unit, the variation of the void ratio with depth was estimated from the water content of several samples taken during the boring, assuming saturated conditions and specific gravity G_s of 26.5. The resulting profiles of the water content and void ratio with depth are shown in Figure 7. The void ratio data points are well fitted by a logarithmic trend line that is taken for deriving the G_0 values from the Eq. (1). Following the indication of Eurocode 7 two set of parameters k_1, k_2, k_3 can be selected for fine-grained soils: according to Vardanega and Bolton (2013) k_1 = 20.000±5.000, k_2 = 2.4, k_3 = 0.5 and p_{ref} = 1 kPa; according to Viggiani and Atkinson (1995), k_1 = 2.100, k_2 = 0, k_3 = 0.6-0.8 and p_{ref} = 1 kPa.

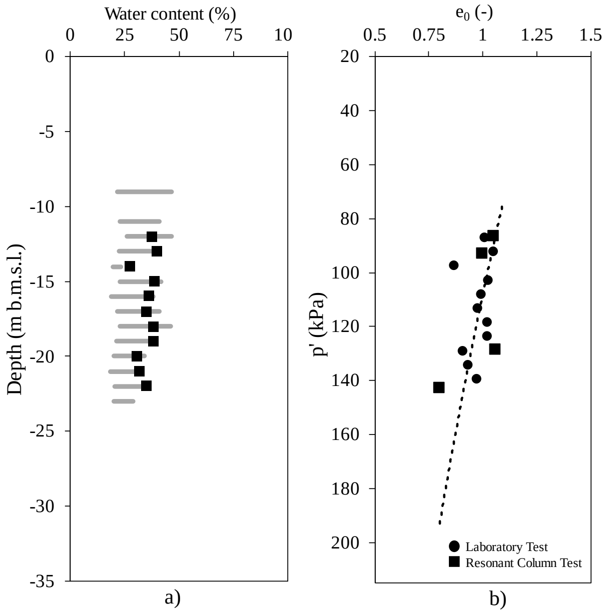

Figure 7. Water content (a) and corresponding void ratio (b) with depth or mean effective stress for the Clayey Silt.

The various trends of G_0 resulting from Eq. (1) with the two different sets of parameters k_1, k_2, k_3 are shown in Figure 8 together with values from Cross-Hole and Resonant Column tests. The best estimate for G_0 is the one obtained with k_1 = 25.000, k_2 = 2.4, k_3 = 0.5 and p_{ref} = 1 kPa, according to Vardanega and Bolton (2013).

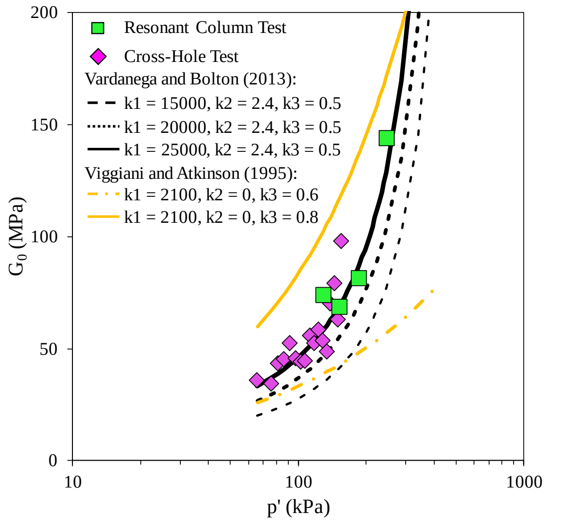

Figure 8. Comparison between G_0 from direct in-situ and laboratory measurements and empirical correlations suggested by Eurocode 7.

5.3. G/G_0 decay from empirical relationship

Eurocode 7 (FprEN 1997-2:2023) suggests the use of the formulation proposed by Darendeli (2001) to evaluate the G/G_0 decay curve for fine-grained soil. This is given by Eq. (2)

$$\frac{G}{G_0} = \left[1 + \left(\frac{\gamma_{cyc}}{\gamma_{ref}}\right)^{\alpha}\right]^{-1} \tag{2}$$

in which γ_{ref}, the reference value of the engineering shear strain at which G/G_0=0.5, is given by Eq. (3)

$$\gamma_{ref}(\%) = (\phi_1 + \phi_2 I_P OCR^{\phi_3})\left(\frac{\sigma'_0}{p_{atm}}\right)^{\phi_4} \quad (3)$$

and γ_{cyc} is the cyclic shear strain, $\alpha = \phi_5$ is a curvature coefficient, I_P is the Plasticity Index, OCR is the overconsolidation ratio, σ'_0 is the mean effective stress. The formulas for the constants $\phi_1, \phi_2, \phi_3, \phi_4, \phi_5$ can be found in the Annex G of Eurocode 7.

Assuming OCR = 1, α = 0.9190, I_P and σ'_0 as listed in Table 1, the decay curves of Figure 9 are obtained. Note that the estimated curves well fit the experimental data points.

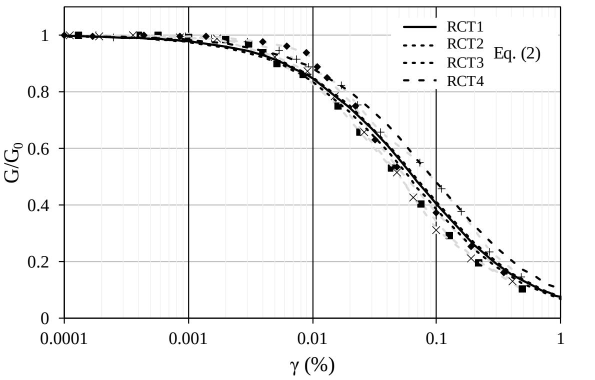

Figure 9. Comparison between estimated and measured G/G_0 decay curves for Clayey Silt.

6. Estimation from CPT and DMT

Although direct measurement of Vs is preferable, several correlations have been proposed to derive the shear wave velocity from the results of CPT and DMT probing. This is justified considering that indirect methods may be used to obtain estimates of Vs when resources for ground investigation do not allow direct testing for Vs, as for geotechnical works classified with low consequence and complexity classes. In this section those suggested in the draft of the new Eurocode 7 are tested against the direct measurements presented before.

6.1. Vs and G0 from CPT

To estimate Vs from piezocone tests the formulation proposed by Robertson (2009) is used for the Holocene-Pleistocene coarse-grained soil:

$$V_S = \sqrt{10^{(0.55 I_C + 1.68)}\,\frac{q_{t-\sigma'_v}}{p_a}} \quad (\mathrm{m}/\mathrm{s}) \quad (4)$$

where I_c is the Soil Behavior Type index, q_t is the corrected cone resistance, σ'_v is the vertical effective stress. Even though the Eq. (4) was originally developed for coarse-grained soils, a more generalized use of the formula is allowed through the index I_c, to be cross checked against direct measurements. For this reason, in the following, Eq. (4) has been used to estimate Vs up to the depth investigated by in situ testing.

The profiles for Vs derived from 16 CPTu in the Port area are shown in Figure 10. Values of Vs fall in a relatively narrow band around the average, that is the blue profile in the figure, and the very good match between the average profile and the Cross-Hole measurements is observed. Also, the comparison between the G_0 profile obtained for Clayey Silt by means of Eq. (1), Cross-Hole measurements and average trend from CPT's shows a good agreement between the available estimates.

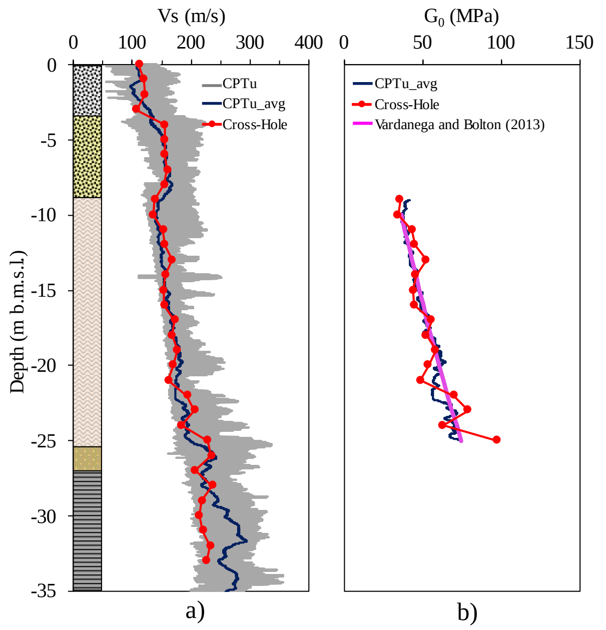

Figure 10. a) Vs average profile estimated from CPTu compared with Cross-Hole; b) comparison of G_0 for Clayey Silt from CPTu, empirical correlation from Eurocode7 and Cross-Hole.

6.2. Vs and G0 from DMT

According to draft of the new Eurocode 7 the very small strain shear modulus G_0 can be obtained from the results of flat dilatometer testing by means of the following equation, originally proposed by Monaco et al (2009):

$$G_0 = k_1 {K_D}^{-k_2} M_{DMT} \quad (5)$$

In the above formulation, K_D is the horizontal stress index, M_{DMT} is the dilatometer modulus, k_1, k_2 are constants depending on the material index I_D. The formulation assumes that the ratio G_0/M_{DMT} is influenced by the soil type in a range 0.5-20. The shear wave velocity may then be obtained from the relationship $G_0 = \rho\, Vs^2$ where ρ is the soil density.

Profiles of the shear wave velocity obtained from the 6 DMT tests (grey lines) and their average trend (green line) are represented and compared with Cross-Hole profile in Figure 11. The variability of the single profile spans between 100 and 200 m/s for Clayey Silt, but the average trend is stable. A good match between the average profile and the data from Cross-Hole testing is also observed. Finally, the G_0 profile obtained applying Eq. (1) for Clayey Silt is compared with Cross-Hole's and average trend from DMT; a good match among the three profiles can be appreciated.

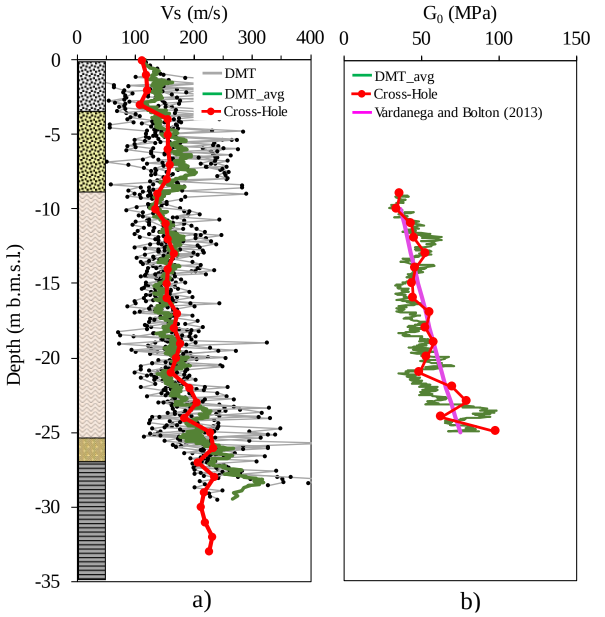

Figure 11. a) Vs average profile estimated from DMT and compared with Cross-Hole; b) comparison of G_0 for Clayey Silt from DMT and empirical formula from Eurocode 7 and Cross-Hole.

7. Discussion

Profiles of G_0 for the Clayey Silt Unit derived from empirical correlations between CPT and DMT logs and soil physical properties are presented in Figure 12. Values of G_0 range from 40 and 70 MPa with good agreement with those obtained from Cross-Hole tests.

Considering the G_0 trend line from Eq. (1), a correction of the G_0 values from RCT must be applied to account for the difference in the stress level between laboratory and in-situ testing. Such corrected values of G_0 falls very close to the G_0 Cross-Hole profiles, so confirming the importance of confining pressure range for laboratory testing.

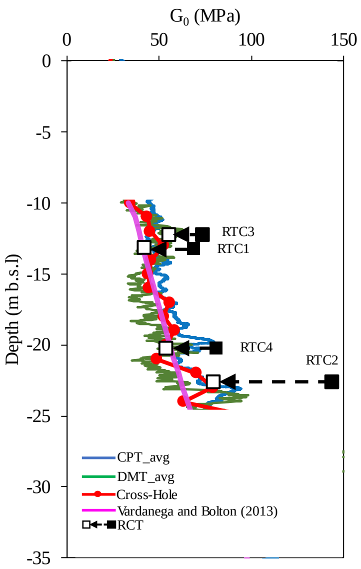

Figure 12. G_0 from in situ and laboratory tests for Clayey Silt. Values from RC are corrected to account for the stress level.

When observing the shear wave velocity from DMT represented in Figure 11, some variability in the superimposed profiles was observed. To better investigate these findings, two single DMT profiles are analyzed in Figure 13. Focusing on the Clayey Silt Unit the oscillation of G_0 in the DMT profiles disappears with averaging (see the green line in Figure 11) and the comparison with the Cross-Hole turns out to be good. This comparison allows us to argue that due the presence of little sand layers in the Clayey Silt Unit, the local oscillation of the values is representative of the real layering which cannot be detected by the Cross-Hole test. This layering affects the values of the single profile and raises the values of G_0 in the average trends of the Clayey Silt Unit.

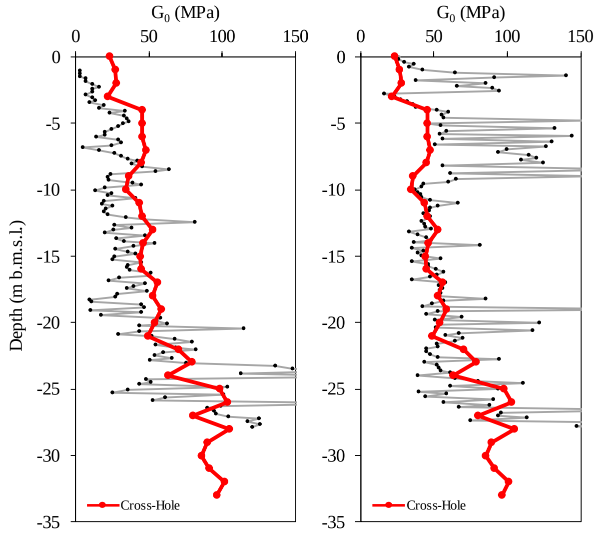

Figure 13. Variability in single DMT profiles against direct measurement from CH.

8. Conclusions

Based on the formulations suggested in the new draft of Eurocode 7, this paper explored the reliability of indirect methods for evaluating soil dynamic properties, namely G_0 and G/G_0 decay curve, of the Holocene age deposit in the central area of the Channel port of Ravenna. The case study resulted very useful because some direct measurements of those properties were also available, allowing a solid comparison between empirical evaluation of properties and their actual values.

Focusing on the Clayey Silt Unit, the following are the most relevant findings:

- empirical correlations to derive G_0 from void ratio, mean effective stress and soil type indexes gave reliable results even though the estimate of the initial void ratio and the variability of the soil type indexes render the assessment of G_0 only approximate if direct measurements of dynamic properties are not available;
- the empirical correlations suggested by Eurocode 7 to estimate the G/G_0 decay curve from Plasticity Index, overconsolidation ratio and mean effective stresses gave good prediction;

- the correlation proposed for the evaluation of shear wave velocity from CPT profiles based on Soil Behaviour Index and vertical effective stress, gave very good results if the best fit of G_0 from more profiles is considered;
- the correlation proposed for the evaluation of shear wave velocity from DMT profiles based on material index, horizontal stress index and dilatometer modulus, gave a very good prediction if the best fit of G_0 from more profiles is considered.

Estimates of dynamic properties from individual CPT and DMT profiles are not aligned with results from direct testing probably for the presence of thin lenses of sand in the Clayey Silt that may locally influence the single determination; the influence of such non-homogeneities is masked by averaging trend from several profiles.

This case study indicates the likelihood of a good assessment of soil dynamic properties from common in-situ tests, when several testing profiles are available and the estimate may derive from an average between many different probing. On the other hand, this study also shows that the direct evaluation of the very small strain shear modulus through geophysical tests is not straightforward and relies on the quality of the execution and experience of operator. Therefore, the investigation of dynamic properties from common in-situ tests may either support the results from direct measurements by geophysical methods or may suggest the opportunity of an in-depth investigation in case of divergencies.

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