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Preliminary findings on the experimental investigation of the small-strain behaviour of Pizzoli silty sand

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ABSTRACT

The dynamic properties of soils play a crucial role in solving many geotechnical problems with special attention to earthquake engineering. In particular, the small-strain soil behavior should be accurately reproduced in geotechnical modelling to allow quantifying of the earthquake-induced site response. If the determination of the small-strain shear modulus can be easily inferred from in-situ measurements of shear wave velocity, the small-strain damping ratio of soils is rarely obtained from in-situ tests and it is commonly defined through cyclic or dynamic laboratory tests.

This paper describes preliminary findings obtained from a laboratory investigation performed to measure the small-strain dynamic properties of the silty sand deposit of the Pizzoli site (L'Aquila, Italy). Due to the remarkable seismic hazard of the considered area, demonstrated by several seismic events, such as recently the 2009 L'Aquila and the 2016-2017 Central Italy earthquakes, and in the past, the 2 February 1703 earthquake, a specific investigation program including boreholes, geophysical and geotechnical in-situ tests was carried out. Resonant column tests have been also performed at the Geotechnical Laboratory of the University of L'Aquila in both forced and free vibration modes. The interpretation of the results has been used to identify the small-strain shear modulus and damping ratio. The shear modulus as obtained from the laboratory has been compared with that obtained via the existing in-situ shear wave velocity measurements. In contrast, the damping ratio has been compared with the value estimated with a literature relationship proposed for soil deposits of Central Italy.

Keywords: Resonant column test; Small-strain soil properties; Integrated site characterization; Damping ratio.

1. Introduction

The high seismic risk of Italy, particularly in the regions affected by recent destructive earthquakes, urges an understanding of the soil properties under seismic loading. In particular, when the shear strains are lower than the linear elastic threshold shear strain, the soil exhibits quasi-elastic behavior, at which the shear modulus is practically constant as well as the damping ratio. Both parameters of the small-strain soil behavior are key factors in the quantification of the earthquake-induced site response and liquefaction evaluation. Extensive researches have been carried out to study the small-strain modulus of granular soils through the bender element (BE) or resonant column (RC) tests (among others, Youn et al. 2008; Sood et al. 2022; Liang et al. 2022).

However, if the determination of the small-strain shear modulus can be easily inferred from in-situ measurements of shear wave velocity, the small-strain damping ratio of soils is rarely obtained from in-situ tests and it is commonly defined through cyclic or dynamic laboratory tests (Lo Presti et al. 1997; d'Onofrio et al. 1999, 2019; Senetakis et al. 2015; Senetakis and Payan 2018).

This paper describes preliminary results obtained through a laboratory investigation performed to measure the small-strain dynamic properties of the silty sand deposit of the Pizzoli site (L'Aquila, Italy). The site is located in an area characterized by remarkable seismic hazard, as demonstrated by several seismic events, such as recently the 2009 L'Aquila and the 2016-2017 Central Italy earthquakes, and in the past, the 2 February 1703 earthquake.

A specific investigation program including boreholes, geophysical and geotechnical in-situ tests was carried out at the Pizzoli site. A brief description of the case study and investigation program is reported in section 2.

Dynamic resonant column tests have been also performed at the Geotechnical Laboratory of the University of L'Aquila in both forced and free vibration modes (section 3). The interpretation of the results is described in section 4 and it has been used to identify the small-strain shear modulus and damping ratio. This latter has been defined through two different approaches.

Thanks to experimental data coming from in-situ and laboratory testing, the shear modulus as obtained from the laboratory has been compared with that obtained via the existing in-situ shear wave velocity measurements, while the damping ratio has been compared with the value estimated with the literature relationships proposed by Ciancimino et al. (2020) for the soil deposits of Central Italy and Darendeli (2001).

The final discussion and open questions of the ongoing research are reported in section 5.

2. Case study and investigation program

The site investigated is located in the municipality of Pizzoli (Central Italy), 20 km far from the city of L'Aquila. The selected site experienced recently the 2009 L'Aquila and the 2016-2017 Central Italy earthquakes and was affected by many events in the past, such as the 2 February 1703 earthquake. Ground failure phenomena observed after that specific event are reported by some historical chronicles. For this reason, the site has been selected for site investigation (Chiaradonna et al. 2022).

The field investigation included boreholes, geotechnical in-situ tests (standard penetration test - SPT, piezocone penetration test - CPTU, flat dilatometer test - DMT), piezometer measurements, in-hole, and surface geophysical tests (down-hole test - DH, surface wave tests - MASW, seismic refraction surveys). Figure 1 shows the plan view of the field investigation performed.

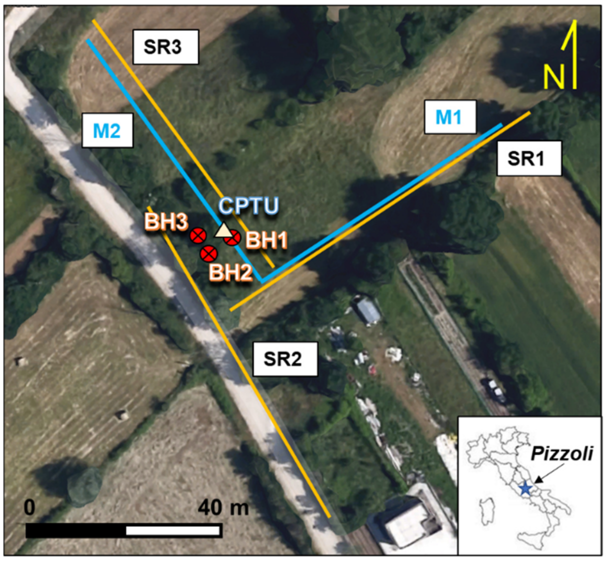


Figure 1. Plan view of the field investigation at the Pizzoli site. BH = borehole; M = MASW; CPTU = cone penetration test; SR = seismic refraction survey.

The stratigraphic logs of boreholes BH1, BH2, and BH3 indicate the predominance of coarse-grained materials in the shallowest portion of the soil deposits at the site, down to the maximum investigated depth of 21 m. The soil profile is mostly composed of alternating layers of dense gravel and sand with gravel, particularly in the upper 6–7 m, while sand layers are also encountered below this depth.

Piezometer measurements were carried out in boreholes BH1 and BH3 during the various investigation phases. The groundwater table was found to be quite variable during the year (Chiaradonna et al. 2022). The value of about 7.3 m measured in November 2020 has been adopted in the calculations.

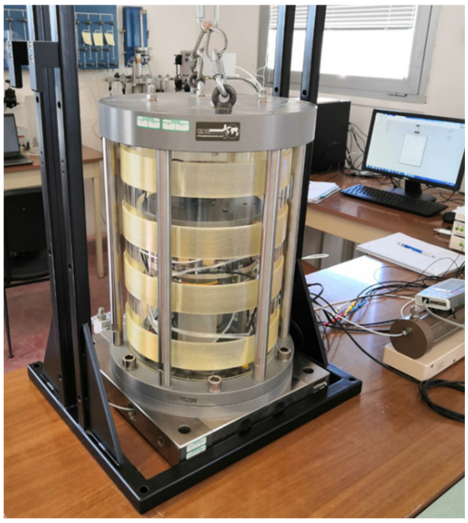
During the execution of the continuous core borehole BH1 to 21 m depth below the ground surface, two undisturbed samples were recovered at depths 9.00–9.30 m and 14.50–15.00 m, in predominantly sandy layers.

3. Laboratory testing: experimental apparatus

The Resonant Column (RC) / Torsional Shear (TS) apparatus used in this study (Fig. 2) was made available by the Geotechnical Laboratory of the Department of Civil, Construction-Architectural Engineering of the University of L'Aquila.

The apparatus is a modified version of the first free-fixed type machine designed at the University of Texas at Austin (Isenhower 1979) and is equipped with a computer-controlled data acquisition system.

The bottom of the cylindrical soil specimen is on a fixed base, while a driving system capable of applying a torquing excitation is attached to the cap of the top free specimen end. The soil specimen and excitation device are installed in a compressed air cell (Fig. 2a), even though the soil specimen is submerged in water.



(a)

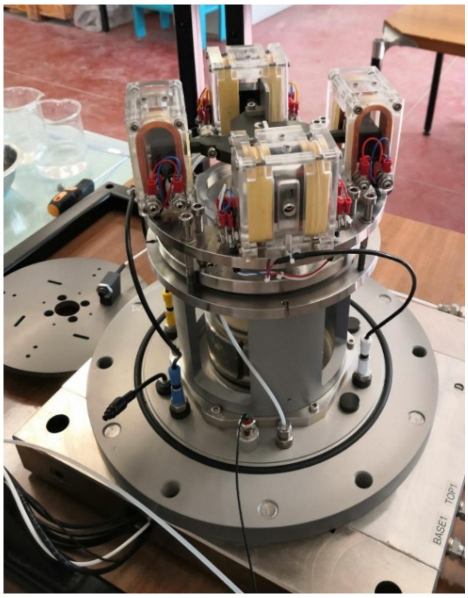


Figure 2. Resonant column / Torsional shear apparatus available at the Geotechnical Laboratory of the University of L'Aquila: compressed air cell (a) and pedestal, specimen, and driving system (b).

After the preparation and installation of the sample on the cell, a latex membrane is placed and sealed with O-rings on the pedestal and on the top cap, where the driving system is positioned. The soil specimen can be then saturated using a back-pressure process by the drainage in the base pedestal.

The device can perform both cyclic torsional shear and dynamic resonant column tests.

For the purpose of this paper, only the resonant column tests performed on the recovered undisturbed sample at depths 14.50–15.00 m are illustrated in the subsequent sections.

4. Laboratory testing: results and interpretation

4.1. Soil sample properties

The tested soil is an undisturbed silty sand sample retrieved at a depth of 14.50–15.00 m. The grain size distribution (Fig. 3) has been assessed on both the undisturbed sample and the material retrieved from the borehole at the depth immediately before the sampling, by leading substantially to the same results.

The main soil parameters are summarized in Table 1. The tested soil is a silty sand with a fines content, FC (grain size smaller than 0.075 mm) equal to 35%.

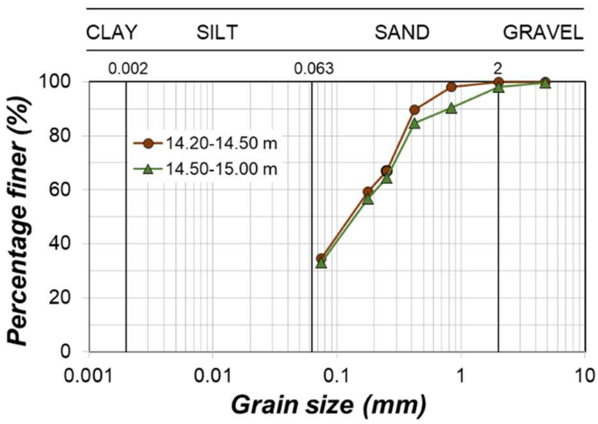


Figure 3. Grain size distribution of the tested soil.

Table 1. Main soil properties

Soil	d_{50} (mm)	d_{60} (mm)	FC (%)
Pizzoli silty sand	0.15	0.2	35

4.2. Resonant column test procedure

The specimen has been gradually saturated and then subjected to an initial effective confining pressure of 148.8 kPa, which is closer to the mean effective stress of the sample on site (147 kPa). After the end of the consolidation phase, the cylindrical specimen has a height, *H*, of 108.8 mm and a diameter, *d*, of 49.69 mm. The mass of the specimen, *m*, is 476.11 g.

Resonant column tests were performed at the small strain level of 1.41 x 10^{-4}% in both forced and free modes.

The driving system consists of four magnets attached to the free end that are excited by eight fixed coils (Fig. 2b).

In the forced vibration test, the soil response at the applied loading is reported in terms of peak voltage as a function of the applied frequency (Fig. 4). The soil response curve has been used to estimate the small-strain shear modulus, G_0 (as described in the next section 4.3.), and the small-strain damping ratio, D_0 (as described in section 4.4.). In the free vibration test, the free decay soil response has been performed to have a second determination of D_0 (as described in section 3.2.).

The soil response curve has been used to detect the resonance frequency of the tested specimen, which is equal to 122.5 Hz (Fig. 4).

The small-strain shear modulus has been then estimated by solving the frequency equation coming from the dynamic equilibrium of the system:

$$\frac{I}{I_0} = \mathrm{F} \tan \mathrm{F} \tag{1}$$

where I is the polar moment of inertia of the specimen (I=m x $d^2/8$), I_0 is the polar moment of inertia of the driving system and F is the frequency factor (F=$2\pi f_r H/V_S$), depending on the resonance frequency f_r and on the shear wave velocity V_S.

The polar moment of inertia of the driving system has been measured through a calibration procedure, using three different aluminum bars, and it is equal to 36.45 kg cm^2.

From the resolution of Eq. (1), a shear wave velocity of 417 m/s has been obtained. The small-strain shear modulus, G_0, can be then calculated as:

$$G_0 = \rho\, V_S^2 \tag{2}$$

where ρ is the soil density, calculated as the ratio between the mass, m, and the volume of the specimen, V (V= $\pi d^2/4$ * H). The obtained G_0 is equal to 395 MPa.

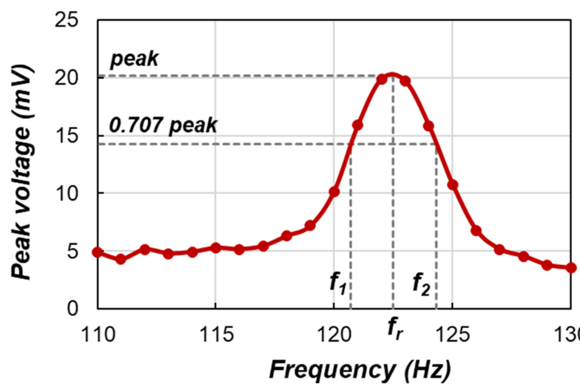


Figure 4. Soil response curve as obtained by the resonant column test.

The shear wave velocity obtained through the interpretation of the resonant column test has been compared to the measured value during the DH test (Chiaradonna et al. 2022). Figure 5 shows the shear wave velocity of the soil along the depth and the interpreted profile (continuous line).

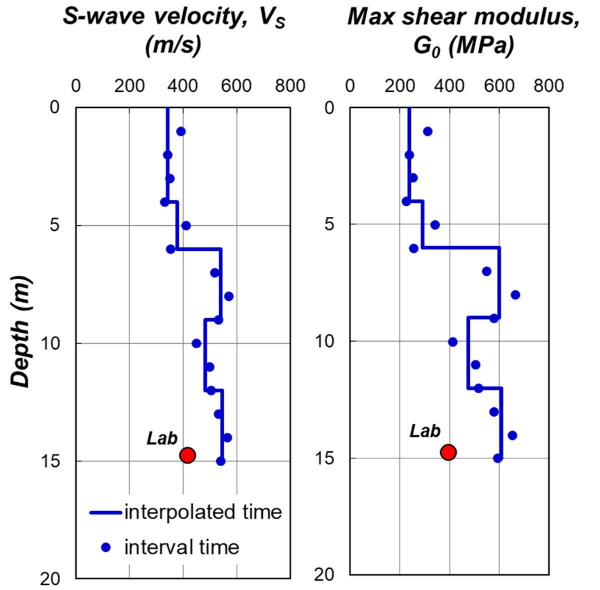


Figure 5. Shear wave velocity profile as measured by DH test and related small-strain shear modulus profile compared with the values obtained in the laboratory (redpoint).

Similarly, the shear modulus, G_0, has been inferred from Eq. (2). The shear modulus measured in situ is 1.5 higher than that obtained from the laboratory test.

As expected, the soil shear modulus determined in the laboratory is lower than that inferred from the in-situ test due to the disturbance induced in the soil by the sampling operations.

4.3. Damping ratio

The small-strain damping ratio, D_0, has been estimated according to two different approaches. The first estimation has been performed on the soil response curve (Fig. 4), according to the half-power method. This method is based on the measurement of the width of the frequency response curve around the resonance peak, specifically f_1 and f_2 which are the frequencies at which the amplitude is √2/2 times the maximum amplitude (Fig. 4). The small-strain damping ratio is then calculated as:

$$D_0 = \frac{f_2 - f_1}{2 f_r} \tag{3}$$

The obtained D_0 value is equal to 1.47%.

The second considered method consisted in the assessment of the logarithmic decrement as obtained in a free decay test (Fig. 6a).

The sample has been excited initially at the resonance frequency, f_r, for 2 seconds, then, the input current is switched off to perform a free-vibration test. The amplitude decay has been recorded with time by the accelerometer (Fig. 6a). The peak amplitude has been determined for each cycle and then the value of logarithmic decrement, δ, has been defined as the steepness of the peak amplitude-number of cycles curve in the natural logarithmic scale (Fig. 6b).

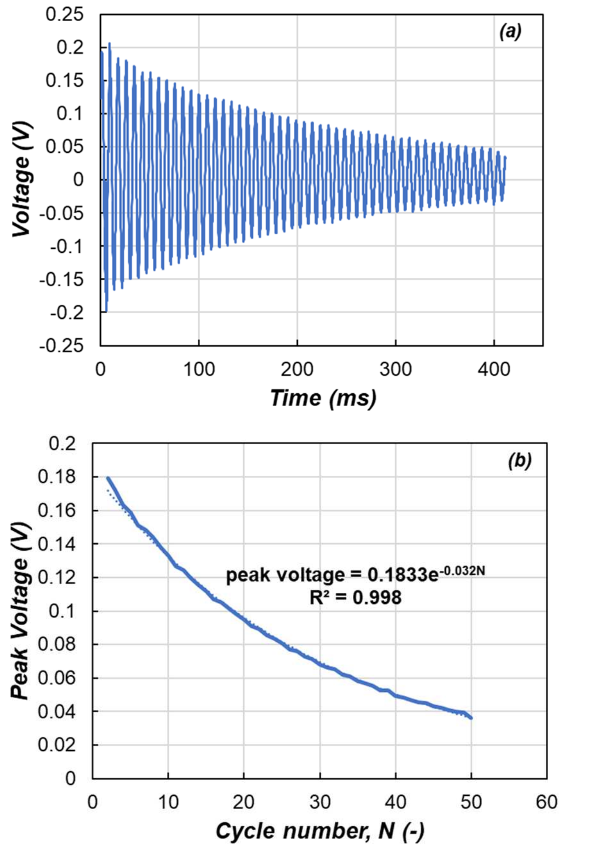


Figure 6. Time history of free vibrations during the free decay test (a) and peak amplitude decreasing with the number of cycles (b)

Ascribing the soil response to the damped free vibrations of a single degree of freedom system, the damping ratio can be then calculated as (Kramer 1996):

$$D_0 \cong \frac{\delta}{2\pi} \tag{4}$$

The logarithm decrement is equal to 0.032, to which corresponds a damping ratio of 0.51%.

The value obtained by the half-power method is about 3 times higher than that determined by the assessment of the logarithmic decrement.

Ciancimino et al. (2020) preferred free-vibration method data to data from the half-power bandwidth method because, if the input current is switched off, the resulting material damping ratio is less affected by the use of the electromagnetic driving system for providing the torsional excitation, which is a recognized source of error in RC measurements (Wang et al. 2003; Meng and Rix 2003).

4.4. Comparison of test results with predictive relations

Since no experimental determination of the small-strain damping is available from in-situ tests, a comparison of the D_0 values obtained in the laboratory has been performed with the predicted values according to Ciancimino et al. (2020). This predictive model is based on a large database of experimental data collected after the 2016–2017 Central Italy Earthquake sequence, within the framework of the seismic microzonation studies of the most damaged municipalities.

The predicted relationship by Ciancimino et al. (2020) provides soil nonlinear curves as a function of the plasticity index, *PI*, mean effective confining stress, σ'_m, and loading frequency, *f*. The small-strain damping has the following functional form:

$$D_0 = (\varphi_1 + \varphi_2 \cdot PI) \cdot \sigma_m'^{\varphi_3} \cdot [1 + \varphi_4 \cdot \ln(f)] \qquad (5)$$

where *PI* is expressed in percentage, σ'_m is in atm, and *f* is in Hz. The model parameters are: φ_1 = 1.2808, φ_2 = 0.0361, φ_3= −0.2740, and φ_4= 0.1340.

For the considered depth and a plasticity index of 15%, the adopted relationship leads to a damping ratio of 1.02%. This latter value is in the range of the two values obtained from the laboratory tests.

Additionally, the predicted relationship proposed by Darendeli (2001) has been also adopted. This relationship for D_0 considers the influence of the overconsolidation ratio, *OCR*, in addition to *PI*, σ'_m, and *f*, as follows:

$$D_0 = (0.8005 + 0.0129 \cdot PI \cdot OCR^{-0.1069}) \cdot \sigma_m'^{-0.2889} \cdot [1 + 0.2919 \cdot \ln(f)] \qquad (6)$$

where *PI* is expressed in percentage, σ'_m is in atm, and *f* is in Hz.

For the considered depth and *OCR*=1, this second relationship leads to a damping ratio of 2.14%, which is almost two times higher of the previous predicted value. However, this result is in line with the findings obtained by Ciancimino et al. (2023), where measured and predicted small-strain damping ratios D_0 are compared for a comprehensive database of cyclic and dynamic laboratory tests conducted on natural Italian soils.

5. Conclusions

This paper presents preliminary laboratory results performed on an undisturbed sample of silty sand retrieved at the Pizzoli (Central Italy) site.

Integrated results from in-situ and laboratory tests have allowed a better insight into the determination of the small-strain soil properties. The small-strain shear modulus has been compared with that inferred from DH test and it is 1.5 times lower.

The small-strain damping ratio has been evaluated through two different methods and it ranges between 0.51% and 1.47%. In absence of in-situ determination, the laboratory results have been compared to the prediction provided by the Ciancimino et al. (2020) relationship which was specifically defined on the soil deposits of Central Italy. The predicted value is included in the range of values obtained from the resonant column test.

Further laboratory tests are in progress to measure the small-strain properties with cyclic torsional shear tests and check the repeatability of the obtained results. Moreover, further tests will be performed for defining the nonlinear soil behavior of the Pizzoli silty sand from the small to the large shear strains.

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