# Investigation and monitoring to model the interaction between the Scrovegni's Chapel in Padova (Italy) and the underlying foundation soil

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## ABSTRACT

In Padova's historic centre lies the renowned Scrovegni's Chapel, painted by Giotto in 1303. The local subsoil primarily consists of silty sand with some layers of silt. The crypt beneath acts as a buffer against soil moisture, preventing damage to the frescoes. However, during heavy rain, groundwater rises flowing across the floor and lateral walls, therefore flooding the pavement. A pumping system is eventually activated to mitigate the pavement inundation. Several investigations including geophysical surveys, piezocone tests, and boreholes with soil sampling have been conducted to provide the subsoil geotechnical model and understand the local hydrogeological behaviour. Monitoring systems, such as piezometers, deep extensometers and optical fiber cables, track groundwater levels and long-term soil displacements.
The paper aims to characterize the subsoil's stratigraphy, mechanical properties and permeabilities to model how the environmental conditions affect the ancient Chapel and ensure its long-term stability.

**Keywords:** Historical site, CTPU and SPT interpretation, static and dynamic soil characterization.

## 1. Introduction

In the historic centre of Padova in Northern Italy there lies the Scrovegni's Chapel from the surname of the commissioner, that was painted with the fresco-technique by Giotto, one of the most famous middle-age painters, around 1303. The Chapel is lying actually in a delicate equilibrium on a subsoil mainly formed by silty sand with some layers of silt. The crypt below the Chapel acts as a sort of compensation chamber, through which the soil humidity cannot reach the upper wall and the frescoes. The crypt base, partially founded on ruins of an ancient roman arena, is located at a certain depth so that, in case of intense rains, the phreatic surface rises the groundwater flowing across the floor and lateral walls, therefore flooding the entire pavement, according to the pluvial contribution and to the water level variation in the nearby Piovego channel. A pumping system is eventually activated to reduce pavement inundation.

The recurrent oscillation of the water surface provides a continuous, even very small, vertical effective stress variation that may lead to a vertical strain accumulation into the Chapel subsoil.

In addition, the construction of a new music Auditorium, located in a surrounding area, was planned a few years ago. It would have required deep excavations with intense dewatering, down to several meters into the ground, with possible impact on the chapel equilibrium.

To investigate the subsoil and its response to effective even small stress variations, several investigations were performed as geophysical surveys, piezocone tests and boreholes with soil sampling, to carry out classification and mechanical laboratory geotechnical tests. In addition, drilling tests have been performed into the Chapel foundations, to study the interaction between the ancient masonry wall foundations and the underlying soil. A monitoring system with deep extensometers and optical fibre cables, was installed into the wells to measure, respectively, long-term soil displacements over 20 m in depth and the dynamic soil response. The groundwater regime is also monitored through several piezometers.

The paper presents and discusses the characterization of the subsoil mechanical properties with the goal of model the effect of the environmental conditions and the overall long-term equilibrium of the Chapel.

## 2. Description of the case study

### 2.1. The significance of the Scrovegni Chapel

The Scrovegni Chapel (Fig. 1a), inscribed on the UNESCO World Heritage List, is dedicated to *Santa Maria della Carità* and was realized close to the palace of the Scrovegni Family, that has been later demolished. Fig.1b shows an historical cross section of the Chapel with the crypt lying below the pavement.

The cycle frescoed by Giotto in just two years, between 1303 and 1305, unfolds over the entire interior surface of the Chapel and concludes with the majestic Last Judgment on the counter-façade (Fig 1c). This Chapel is a milestone in the history of painting because here Giotto accomplished two great revolutions; first, in the representation of space, by introducing perspective

and rendering of the third dimension that anticipate the Renaissance theories by a hundred years; second, in the innovative attention paid to the representation of man, in his physicality and emotionality, by representing with intensity the human joys and sorrows in the faces and positions of the various characters.
Several studies and restorative interventions were developed in the 1980s and 1990s, since some old lesions inside the Chapel reopened in 1976 caused by a high magnitude earthquake, despite the epicentre was at more than 150km. The interventions took into consideration both directly the pictorial cycle itself, which appeared to be ruined by air moisture and pollution, and the Chapel structure and masonry. In addition, particular attention was devoted to the geotechnical and hydrogeological characterization of the subsoil, in order to sketch a detailed geotechnical mode to understand the phreatic surface regime, since water flows across the floor and lateral walls according to the rain contribution and to the variation of water level in the nearby Piovego channel. The aim was to investigate possible effects of such porewater pressure oscillation on the long-term Chapel stability. Several piezometers have been installed in some of boreholes, to monitor the water table variations induced by the nearby channel Piovego and to the local rain infiltration. In addition to these, more recently (in 2021-2023), further investigations have been conducted in order close to the Chapel with the aim of performing deep geophysical tests and to install a soil displacement monitoring system.

a) b) c)



**Figure 1.** The Scrovegni Chapel, a) the external view, b) a cross section c) the internal view with the frescoes and the blue ceiling.

## 2.2. Geotechnical site characterization

Firstly, the already available data from previously performed on site investigations have been collected, consisting in some boreholes equipped with piezometers as well as in numerous standard CPTs, within the restoring and retrofitting interventions (in 1953, 1963 and 1995, 2001).
In addition to these, the following investigations performed 2011 - 2012 in the area just on the other side of the channel Piovego (area B in Fig.2a):

- n.9 boreholes with SPTs and Lefranc hydraulic conductivity tests (maximum depth 60m), including 7 equipped with piezometers at various depths (in particular, Pz3 and Pz6 are indicated in the map);
- n.12 CPTUs down to a maximum depth of 30m (indicated as P1-P12);
- geotechnical laboratory tests on 18 undisturbed samples;
- an additional borehole equipped to monitor the Piovego canal water level (indicated as W).

Fig.2a reports the locations of the principal investigations previously performed, together with the Chapel location and the channel, while Fig. 2b reports the additional more recent wells drilled in the vicinity of the Scrovegni Chapel, than equipped with extensometers and optical fibre cables to monitor the long-term soil displacements over 20 m in depth and the dynamic soil response.

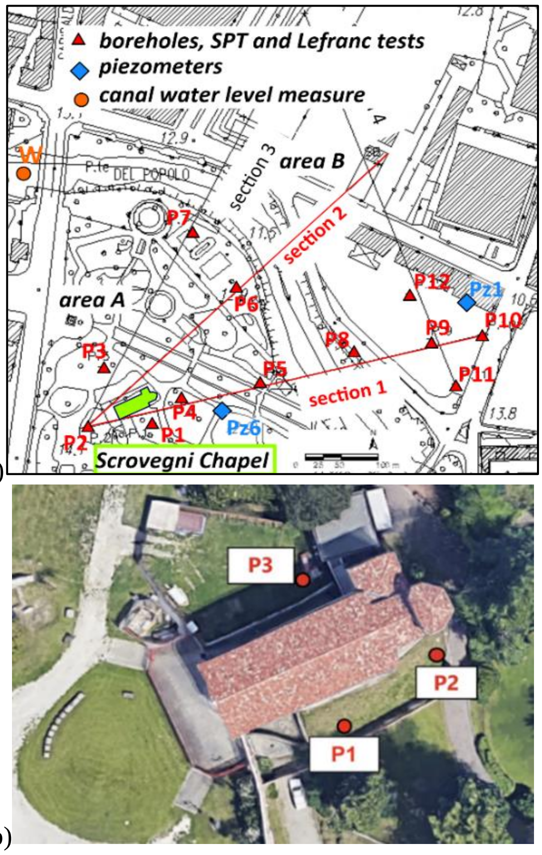
a) b)



**Figure 2.** a) The principal investigations previously performed; b) location of the monitoring boreholes equipped with extensometers and optical fiber cables.

The data acquired from the previous investigations have allowed the reconstruction of the soil profile in the entire area. Continuously present, although with slightly variable thicknesses from point to point, in the Scrovegni area (*area A* in Fig 2a) down to a depth of 20 m are five layers, as reported in Table 1. This stratigraphy is also confirmed by the more recent investigations.

**Table 1.** Stratigraphic profile down to 20m

| Depth [m] | Layer n. | Layer description |
|---|---|---|
| **0-1.30** | 1 | Bricks, mortar, and rubble in a sandy silt matrix (backfill) |
| **1.30-5.00** | 2 | Sandy-silty clay with bricks |
| **5.00-12.50** | 3 | Slightly silty sand, finer in the upper part and coarser at the bottom |
| **12.50-16.50** | 4 | Alternating clayey silt with sandy silt and silty clay with some sandy layers at variable depth |
| **16.50-20** | 5 | Medium-fine sand, coarser at the bottom |

In addition, the already available data acquired from on-site investigations performed on the other side of the channel (indicated as *area B* in Fig.2a) provide a broader framing of the issue from the hydrogeological point of view. The succession present beneath the Chapel extends continuously also northward. The investigations confirmed the horizontal continuity of the layers identified beneath the Chapel and showed that their thickness varies, with fluctuations of about +/- 2 meters: in some zones Layer 2 is absent, leaving Layer 3 in direct contact with Layer 1. Boreholes drilled to greater depths have also identified a further alternation of sandy deposits of significant thickness and clayey-silt layers down to 60m.

All the data acquired during the on-site investigations have been elaborated to yield the two sections depicted in Fig. 3a along the traces indicated in red in Fig. 2a.

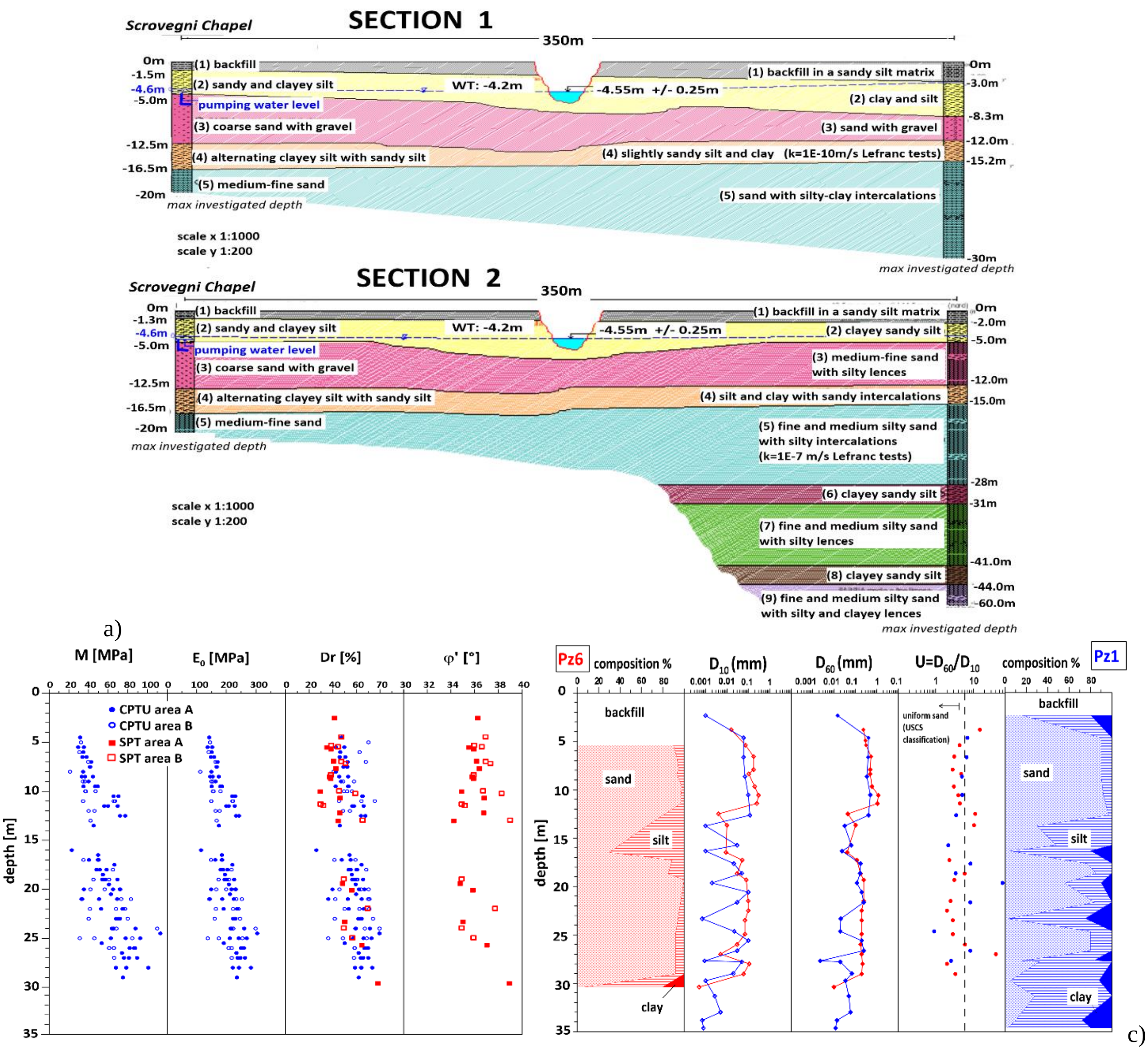



**Figure 3.** a) Stratigraphic sections along the lines indicated as 1-2 in Fig.2a; b) Vertical profiles of the main mechanical parameters acquired from the conducted CPTUs and SPT; c) vertical profiles of the granulometric composition in Pz1 and Pz6.

The vertical profiles of the main mechanical parameters obtained from the conducted CPTUs and SPTs in the areas A and B are reported in Fig. 3b down to 20m depth. The relative density $D_r$ has been estimated based on CPTUs values by applying the formulation proposed by Baldi et al. (1986), while the SPT have been elaborated following Skempton's formulation (1986). The friction angle has been estimated by applying Schmertmann's correlation (1978). In the vertical profile in Fig. 3b, the $D_r$ estimations gained from SPT appear lower than that acquired from CPTUs, usually considered more robust and reliable.

Additionally, while drilling the boreholes for installing piezometers Pz1 and Pz6 (refer to their locations in Fig. 2a), we collected disturbed samples from the cores at 1m intervals for laboratory geotechnical classification. Fig. 3c reports the vertical profiles of the grain size composition, summarizes the trend of $D_{10}$ and $D_{60}$, the uniformity coefficient $U$, and the percentage granulometric composition along the depth in Pz1, Pz6.The stratigraphy mainly consists in sand, with two aquifers separated by a silty layer around 12-17m. The shallow aquifer, whose typical oscillation does not yearly exceed 1m, is fairly uniform up to 10 meters, consisting of medium sand ranging from weakly silty to silty, and exhibits, only in the Scrovegni area, a layer of coarser sand between 10 and 13 m. This characteristic also translates into greater penetration resistance measured by the piezocone and SPT. The deep aquifer, however, shows greater variability and is composed of finer sand, ranging from weakly silty to silty. The fine percentage is significantly higher in the *area B* (on the other side of the river) compared to the Scrovegni area.

In the finer layers several undisturbed samples have been collected, classified trough the Atterberg Limits (Fig. 4) and tested to obtain the oedometric modulus M. The trend of the modulus with effective vertical stress is shown in Fig. 5. The values range from 3 to 12 MPa within the stress range that can be reached in the field. Higher values are obtained for non-plastic samples with high percentages of silt and sand.

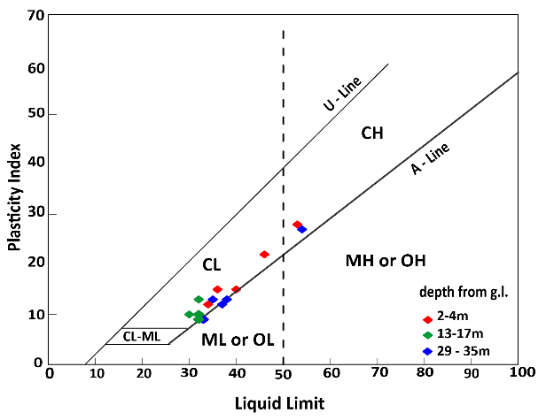


**Figure 4.** Casagrande Plasticity Chart.

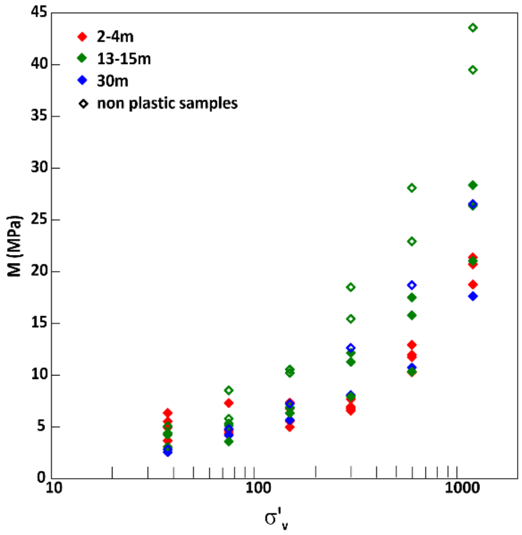


**Figure 5.** Oedometric modulus trend with effective vertical stress.

## 2.3. Hydraulic conductivity and hydrogeological regime

The coefficient of vertical consolidation $c_v$ has been derived from the consolidation curves by using the Taylor method. Finally, for each specimen, three variable-head hydraulic conductivity tests were conducted under conditions corresponding to three different stress states to determine the coefficient of vertical hydraulic conductivity. The hydraulic conductivity coefficient was calculated according to ASTM D 5084 (*Method B*). The tests were performed at the end of the load steps approximately corresponding to stresses of $0.5\sigma_{v0}'$, $\sigma_{v0'}$, and $2\sigma_{v0}'$, where $\sigma_{v0}'$ is the effective geostatic stress. The values of the vertical consolidation coefficient $c_v$ and the horizontal consolidation coefficient $c_h$, obtained respectively from the oedometer compression tests and the dissipation tests with the piezocone, are shown in Fig. 6a. It can be observed that the values of the horizontal coefficient are generally higher than those of the vertical one, with a ratio between the two around 10.

Fig. 6b compares the values of vertical hydraulic conductivity obtained from the oedometer compression tests ($k_v$) with those derived from the variable-head tests and those of the horizontal hydraulic conductivity determined with the piezocone. The indirectly determined values of both vertical and horizontal conductivity appear more uniform, while those calculated directly, which are more reliable, vary by several orders of magnitude.

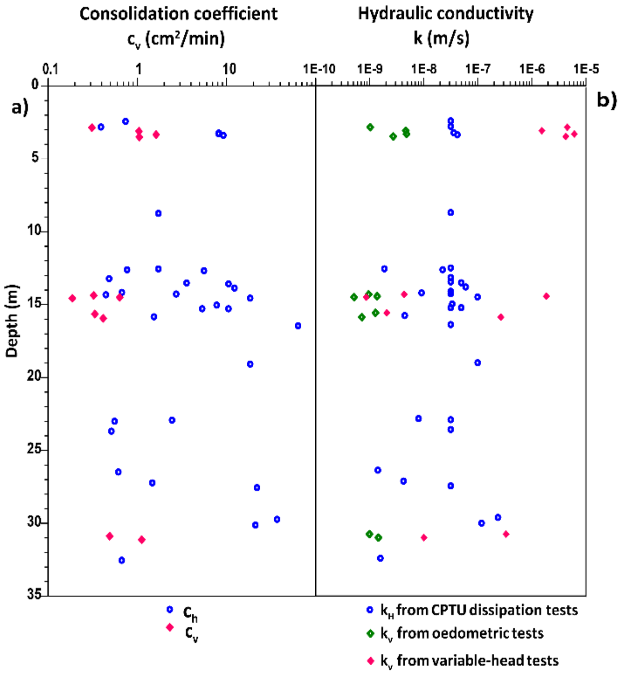



**Figure 6.** a) Vertical profiles of $c_v$ and $c_h$, obtained respectively from the oedometer compression tests and the dissipation tests with the piezocone

The hydraulic conductivity of the superficial fine layer (2-4m) is much higher than that of the other layers. Despite initially being visually classified as silty clay or clayey silt, and this classification being confirmed by the Atterberg limits (see Fig. 4), its hydraulic conductivity is more similar to that of silt, probably due to the presence of sand in its grain size distribution. Also, from the interpretation of the piezocone tests, the superficial layer appeared to be composed of silt.

Between 4 and 13 m, there is a layer of weakly silty sand with spatially quite uniform grain size characteristics. Hydraulic conductivity varies between $10^{-5}$ and $10^{-4}$ m/s. At depths ranging from 12 to 17 m, the layer of sandy silt/clayey silt/silty clay of several meters thickness which divided the two aquifers is characterized by significant sandy intercalations therefore the hydraulic conductivity varies over a wide range ($10^{-9}$<k<$10^{-6}$ m/s). Between approximately 17 and 28 m below ground level, there is another important deposit of sand, where the grain size is spatially more variable; it consists of fine sand, in some points very silty, especially in *area B*. It hosts the second aquifer with a hydraulic conductivity varying between $10^{-6}$ and $10^{-5}$ m/s.

## 2.4. Recent investigations around the Scrovegni Chapel

As already introduced, further investigations have been performed in the last two years, in order to deepen the knowledge of the subsoil strictly around the Chapel and to install deep extensometers and optical fiber cables to measure long-term soil displacements and the dynamic soil response. Therefore, further 3 boreholes have been drilled down to 20m, in the locations already indicated in Fig.2b. In addition, two surface wave tomography measurements campaigns have been performed in the vicinity of the Chapel. As described in Barone et al. (2022, 2023), they provided the image of several ancient buried features, among which possible remains of radial walls of the adjacent Roman amphitheater as well as structures belonging to a medieval convent, located at a depth of few meters.

Once again, one disturbed sample was from the cores from the cores at 1m intervals laboratory geotechnical characterization. Comparing the grain size curves and parameter values, it's clear that sandy material predominates in all three boreholes (in most samples, it comprises over 70%), with variable and sometimes significant percentages of silt. There is minimal coarser material, observed in P1 at depths of 5-6m and from 10 to 13m, and in higher percentages in P2 at the same depths. The highest percentage of finer material is found in P1 at a depth of 18m and in P2 at a depth of 16-18m, indicating a single finer (silty) layer.

The local geotechnical model derived from the borehole analysis aligns with the broader previous model, revealing a predominantly sandy stratigraphy. It features a shallow, coarser aquifer starting at a depth of 5m, directly interacting with the Chapel's crypt. The aquifer is closed at the bottom by a silty layer at the depth around 15m. The detailed representation is provided in Fig.7.

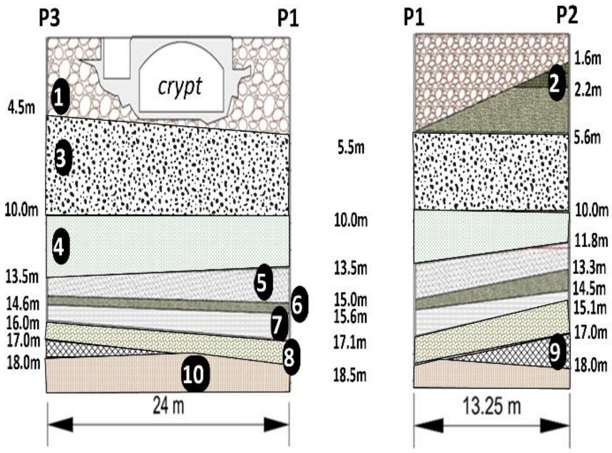



**Figure 7.** Layers identified in the local geotechnical model of the subsoil of the Scrovegni Chapel: 1) backfill, 2) medium sand with coarse sand and fine sand, 3) medium sand, 4) medium sand with coarse sand, fine sand and traces of fine gravel, 5) medium sand with fine sand and traces of coarse sand, 6) fine sand with medium sand and silt, 7) silt with fine-medium sand, 8) fine-silty sand, 8) medium sand with fine gravel.

During the drilling operations, several SPT tests were performed down-the-hole to characterize the friction angle of the sandy layers. First, the $N_{spt}$ values have been elaborated to estimate the relative density $D_r$ by applying the Skempton relationships (1986):

$$D_r = \sqrt{\frac{C_N \cdot N_{SPT}}{60}} \quad \text{(Eq. 1)}$$

where: $$C_N = \frac{2}{1+\frac{\sigma'_{v0}}{p_a}} \quad \text{for fine sands} \quad \text{(Eq. 2)}$$

$$C_N = \frac{3}{2+\frac{\sigma'_{v0}}{p_a}} \quad \text{for coarse sands} \quad \text{(Eq. 3)}$$

Afterward, the friction angle $\varphi'$ was derived from each value of $D_r$ by applying the Schmertmann's correlation (1978), which varies with soil grain size as here indicated:

$$\varphi' = 28 + 0.14D_r \quad \text{(Eq. 4)}$$

for uniform fine sand

$$\varphi' = 31.5 + 0.115D_r \quad \text{(Eq. 5)}$$

for homogeneous medium sand and well graded fine sand

$$\varphi' = 34.5 + 0.1D_r \quad \text{(Eq. 6)}$$

for homogeneous coarse sand and well graded medium sand

$$\varphi' = 38 + 0.08D_r \quad \text{(Eq. 7)}$$

for sand and slightly silt gravel

In all the layers, we applied the formulation proper for homogeneous medium sand and well graded fine sand. In Table 2 the averaged values of relative density (with the standard deviation) and the estimated friction angle for each layer are listed.

**Table 2.** Averaged value of $D_r$ and $\varphi'$ for each layer.

| Layer n. | $D_r$ (average value) | St. Dev.(%) | $\varphi'$ |
|---|---|---|---|
| 2 | 0.63 | 4 | 38.7 |
| 3 | 0.65 | 10 | 39.0 |
| 4 | 0.69 | 10 | 39.5 |
| 5 | 0.65 | 2 | 38.9 |
| 8 | 0.53 | 5 | 37.6 |
| 9 | 0.64 | 6 | 38.8 |
| 10 | 0.68 | 9 | 39.4 |

High values of friction angle are obtained (all around 38°), suitable for mostly medium sands characterized by a relatively high relative density (around 60%), with the maximum value reached in correspondence to the sand with traces of gravel, constituting Layer 4 ($\varphi'$ = 39.5°). The lowest value of $D_r$ is the one characterizing the layer 8, around the depth of 16m.

The relative density values obtained during this second SPT campaign appear slightly higher than those derived from the previous SPTs. Some differences can be attributed to the fact that the first campaign covered a wider area with only a few SPT tests performed at each location. In contrast, the current campaign focused on three wells located approximately 10 meters apart, specifically around the Scrovegni Chapel, with tests conducted every 1.5 meters in depth. The $D_r$ values obtained from the current campaign fall within the higher range identified by the previous CPTU results. Consequently, the derived friction angle values appear to be higher than those estimated previously.

## 2.5. Resonant column experimental tests

Given the possible dynamic actions induced by earthquake or even traffic nearby, 5 reconstructed samples of sands extracted from P1 core have been subjected to the resonant column test in order to characterize the dynamic response of the silty sand and to determine the shear stiffness modulus at small shear deformation, crucial for seismic soil analysis. Through the resonant column tests, the shear modulus G, as the slope of the tangent to the stress-strain curve passing through the origin, was estimated. In addition, the test provides also the damping *D*, representing the decrease in oscillation amplitude over time. The cylindrical samples (with 30-70mm diameter and 70-140mm height) undergo isotropic consolidation before testing, allowed by a porous stone at the base. Magnets apply cyclic torsional loading, to measure the resonance frequency and the rotation of the sample, thus deriving the shear wave velocity $v_s$ to obtain *G* (see Eq.8), and the torsional deformation $\gamma$. Finally, observing the decrease in oscillation amplitude over time provides the damping D.

$$G = \rho\left(2\pi \cdot l \cdot \frac{f_n}{\beta}\right) \quad \text{(Eq. 8)}$$

where $\rho$ is the material density, $l$ is the sample height, $f_n$ is the natural frequency, and $\beta$ is a coefficient related to the shear wave velocity and the natural pulsation.

The 5 samples were collected from the depths of 6.00-7.00 m, 7.00-8.00 m, 9.00-10.00 m, 10.00-11.00 m and 14.00-15.00 m and tested under a load corresponding to the geostatic stress.

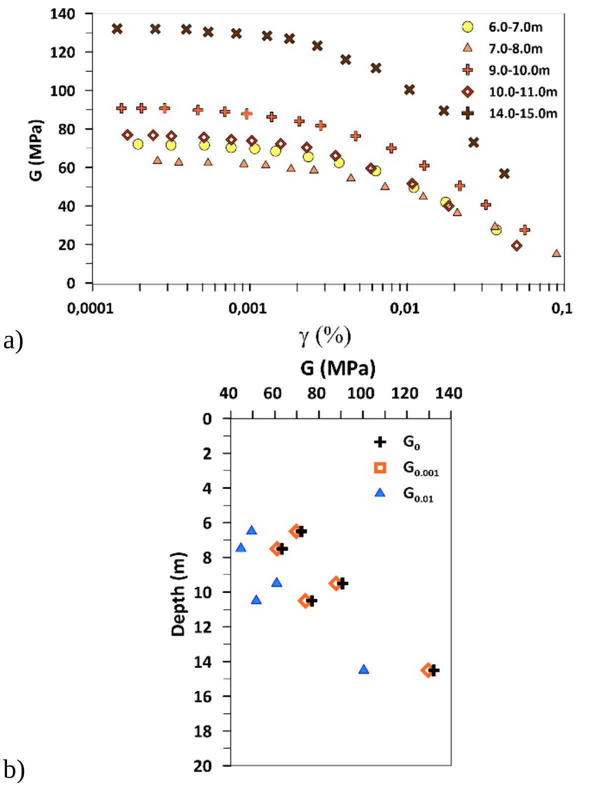



**Figure 8.** a) Trend of *G* with the angular strain obtained for the 5 samples, corresponding to different depths; b) Vertical profiles of $G_0$, $G_{0.001}$ e $G_{0.01}$

In Fig. 8a the $G$-$\gamma$ curves obtained from all the specimens are compared to determine the variation of shear stiffness with depth. The values obtained for $G$ are consistent with those typical for sands characterized by medium to high levels of density, in agreement with the previous observations.
$G$ values correlate relatively well with shear wave velocity ($v_s$) distribution derived from geophysical data by Barone et al. (2022, 2023) for the shallower layers (max 10m); unfortunately, geophysical investigation depth limitations preclude further comparison.

## 3. On-going monitoring outputs

The piezometric measurements conducted for several years by means of the installed monitoring system, indicated the main characteristics of the local piezometric regime. The piezometric levels measured in *area A* are generally higher than those in *area B*, indicating a slight natural slope of the aquifer towards the North East. During the examined period the level of the Piovego canal, that is artificially controlled, is consistently lower than the groundwater levels, that remains almost stable around -4.2m. The two identified aquifers respond quickly and appreciably to pluvio-meteorological contributions and need significant time to rebalance. Due to the Piovego level variations, the oscillations of the shallow aquifer are slightly less pronounced than those of the deeper one. Finally, the two identified aquifers result always in a weak disequilibrium of a few centimetres, with the lower displaying a slight pressure. However, there is a significant variability in the piezometric response, indicating marked heterogeneity in the hydraulic properties of the formations.

As for the soils displacements, the monitoring system composed by deep extensometers and optical fibre cables, was installed into the 3 wells realized just around the Chapel to measure, respectively, long-term soil displacements over 20 m in depth and the dynamic soil response.
The extensometer consists of a bar made of INVAR, a metallic alloy of iron, nickel, chromium, and carbon characterized by a very low coefficient of thermal expansion (about $10^{-6}$ $K^{-1}$) to ensure high measurement precision. It is inserted into a plastic casing that allows vertical movement. The bar is equipped with a displacement transducer LVDT at the top, and fixed to the INVAR bar anchored at a depth of 20 m. The extensometer measures the distance variation between the two ends and thus the total deformation of the soil it traverses along its entire length. The settlements are indicated by negative changes relative to the initial value. The system started working on the month of August 2022, and the first year of measurements is shown in Fig. 9.

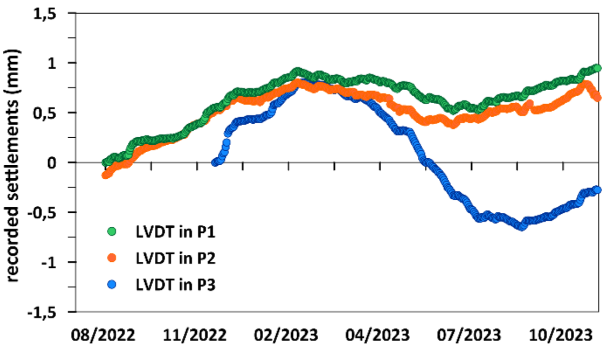


**Figure 9.** Ground surface deformations recorded around the Scrovegni Chapel through the monitoring system (settlements are indicated as <0).

Since installation, the sensors have recorded ground level variations of less than 1mm, which vary with the seasons. From the conducted measurements, a picture of substantial stability emerges regarding the first 20 meters of the Chapel's subsurface, with very limited oscillations, around 1-1.5 mm, comparable to those generated by the seasonal fluctuation of the local water table (up to a maximum of 40 cm). This confirms the significant stability of the Chapel's subsurface, primarily composed of medium to high-density sandy material with high stiffness and shear strength.

## 4. Conclusions

The study showed the main results of the geotechnical investigations carried out so far for the characterization of the subsoil of the Scrovegni's Chapel in Padua. The delicate equilibrium together with the preciousness of the Giotto's frescoes, an annual destination for thousands of visitors, prompted the detailed investigation of the ground beneath the Chapel and surrounding area, with the aim to formulate a comprehensive geotechnical model of the foundation soil. This, in order to assess whether the small but frequent excursions of the water table, which give rise to continuous flooding of the crypt that is of major concern to the City of Padua, could have a long-term impact on its long-term stability, with the occurrence of small settlements that may damage the frescoes.

Continuous monitoring through the deep extensometers shows clear stability of the Scrovegni's Chapel subsurface, providing displacement measurements of the ground level relative to the base at 20 meters depth of less than 1 mm. The sandy nature of the soil down to considerable depth seems to rule out this possibility, although there is compressible soil at depth that could be affected by any lowering of the water table beyond the normal limits of oscillation causing minor subsidence.
The investigation was an opportunity to also carry out a dynamic characterization in order to perform, in the future, a three-dimensional dynamic FE analysis of the Chapel-soil interaction.

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