Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1037

The Treporti test site: Exploring the behaviour of the silty soils of the Venetian lagoon

Le site test à Treporti: Etude du comportement des sols limoneux de la lagune de Venise

G. Gottardi & L. Tonni
DISTART, University of Bologna, Bologna, Italy

ABSTRACT

In order to gain a better understanding of the Pleistocene silty sediments underlying the Venice lagoon, a comprehensive research programme on a representative test site was launched. After having carried out an extensive geotechnical characterisation of the subsoil using several high-quality insitu and laboratory tests, a full-scale 6.7 m high, 40 m diameter, vertical-walled cylindrical test bank was progressively built and continuously monitored. Analysis of the very large amount of data, with special emphasis to piezocone tests, provides interesting information on the geotechnical properties of such intermediate soils. Back-analysis from the load bank performance proves to be especially useful both for the validation of usual methods for the evaluation of compressibility and consolidation characteristics and for the reliable determination of the operational parameters of the Venetian silts.

RÉSUMÉ

Afin d'améliorer la connaissance du comportement des sédiments limoneux du Pléistocène qui constituent le sous-sol de la lagune de Venise, on a mis au point un long programme expérimental déroulé auprès d'une station d'essai placée à Treporti. Après avoir realisé une reconnaissance géotechnique détaillée du sous-sol à l'aide de nombreux essais en place et en laboratoire, on a construit un remblai expérimental à parois verticales de 6.7 m de hauteur et 40 m de diamètre. Lors de la construction du remblai, plusieurs dispositifs de contrôle ont été mis en place. L'ensemble des nombreuses données, particulièrement celles provenantes des essais de pénétration statique (CPTU), a apporté des informations précieuses sur les propriétés mécaniques des matériaux du sous-sol. L'exploitation des mesures enregistrées a permis de bien cerner la précision des méthodes usuelles pour la détermination des paramètres de compressibilité et consolidation, sur la base de calculs à rebours.

1 INTRODUCTION

The shallow Pleistocene sediments underlying the Venice lagoon have already been relatively well investigated. First, in the seventies, in relation to the regional subsidence (Ricceri and Butterfield, 1974), and then, in the nineties, following the extensive site investigation programme related to the foundation design of the submersible gates intended to protect Venice against flooding (Ricceri, 1997; Simonini and Cola, 2000).

They turn out to be highly heterogeneous and stratified, in an endless alternation of slightly overconsolidated silty sediments, from fine silty sands to silty clays (Cola and Simonini, 2002).

In order to gain a better understanding of such intermediate soils, neither clearly coarse-grained nor fine-grained, a comprehensive and ambitious research programme, coordinated by the University of Padova (Italy), with the collaboration of other two Italian Universities (Bologna and L'Aquila), was launched. The aim was to locate a representative test site and to carry out an extensive geotechnical characterisation of the subsoil using several in-situ tests (piezocone and flat dilatometer), boreholes and undisturbed sample extraction in conjunction with a high-quality laboratory test programme. Thereafter, a full-scale 6.7 m high, 40 m diameter, vertical walled cylindrical test bank was progressively built in order to load the area uniformly up to about 100 kPa, with the corresponding surface settlements, subsoil strains and stresses, pore water pressures, continuously monitored. Penetrometer tests, with both a mechanical Begemann-type tip and a Delft Geotechnics piezocone equipment, with 200 kN of nominal thrust, were performed solely for research purposes, with unusual care and accuracy in comparison with standard commercial testing. Details can be found in Righi et al. (2003).

Herein, selected representative piezocone data are presented and discussed within the context of the research programme, together with their preliminary interpretation based on back-analysis of the test bank performance.

2 TREPORTI TEST SITE

The Venice lagoon is underlain by 800 m of Quaternary deposits, alternatively originated from continental and marine sedimentation, as a consequence of marine regressions and transgressions over the last 2 million years. In particular:

- from ground level to 5-10 m below m.s.l., the sediments are due to the present lagunar cycle (Holocene);

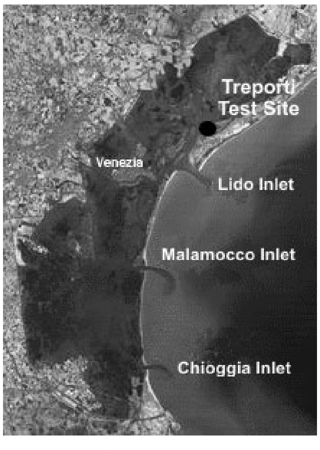

Figure 1. Satellite view of the Venetian Lagoon, with location of the Treporti test site.

- ☐ from 5-10 m to 50-60 m below m.s.l., there is a chaotic interbedding of continental deposits, occurred in the last glacial Pleistocenic period (Würm). Such sediments are predominantly characterized by a silty fraction, combined with sand and/or clay, with small quantities of peat.

A representative test site of such subsoil was eventually located outside Treporti, an old fishermen village on the Cavallino coast line, facing the North Eastern lagoon (Fig. 1). The initial site investigation campaign – carried out only by piezocone tests - was aimed at detecting the most compressible layers within the rather heterogeneous selected area, in order to develop as large settlements as possible (Gottardi and Tonni, 2004).

The penetration device is a standard cone, with a net area ratio a = 0.82. The equipment enables continuous measurement of the cone resistance q_c, the sleeve friction f_s and the induced pore pressure u at the cylindrical extension of the cone (position 2). Test procedure and reporting of test results are in agreement with the latest recommendations (ISSMGE, 1999).

The water table was easily found to be very close to the ground level, consistent with the nearby canal height and also subjected to local tidal excursions, about ± 0.5 m twice a day.

Such preliminary results confirmed the presence of a highly stratified subsoil, with a well-defined top layer of silty sand, 6-7 m thick, and then a rather dense alternance of sandy to clayey silts. The pore pressure u rarely followed up the hydrostatic level, often fell below it, but never developed high values, typical of pure clays. Occasionally, but consistently throughout the tests, rather large friction ratio values showed the presence of thin layers of peat and organic soil.

3 IN-SITU TESTING

The in-situ testing programme for the geotechnical characterisation of the subsoil concerned by the loading bank, consisted of 10 piezocone and 10 flat dilatometer tests (Marchetti et al., 2004), 2 standard mechanical CPT tests and 4 60 m-deep boreholes, all within a circular area of 45 m diameter. In addition, three seismic cone tests as well as three seismic dilatometer tests were subsequently carried out (McGillivray and Mayne, 2004). CPTU and DMT tests were located in the same positions, numbered from 11 to 20 (Fig. 2), and were pushed as deep as possible, depending on the maximum available thrust, typically to about 42 m.

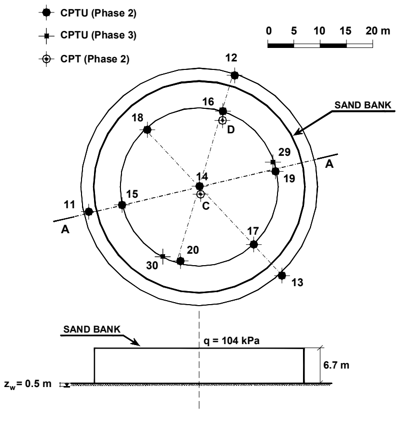

Figure 2. Loading sand bank and location of in-situ tests.
A: Very soft silty clay;
B: Medium-fine silty sand;
C: Silt with thin layers of sandy to clayey silt;
D: Dense clean sand;
E: Silty sand;
F: Alternate layers of silty sand, sandy silt and clayey silt, with occasional presence of peat.

Figure 3 reports data from CPTU No. 14, in terms of cone resistance q_t, friction ratio *FR* and pore pressure parameter B_q, on the classification charts proposed by Robertson et al. (1986). Relevant points mainly fall in zones 4 to 9, thus confirming that the typical Venetian lagoon subsoil is composed of a complex mixtures of clayey silts, silty sands and clean sands.

With the aim of proposing an operational simplification of such dense alternation, the following units were sequentially identified, from top to bottom:

In particular, unit F is quite heterogeneous, but being commonly located at depths greater than 24 m, its further refinement is of reduced engineering interest for settlement prediction. With reference to such schematization, Figure 4 shows a stratigraphic section, drawn along one of the selected diameters (A-A in Fig. 2), with the corrected cone resistance q_t from CPTU tests No. 11, 15, 14 and 19. It is interesting to observe that unit D, made up of clean sand of medium-high density, tends to progressively reduce its thickness and then disappears.

Taking into account the stratigraphic sections drawn along the two other diameters (not reported here), it can be seen that only a quarter of the loaded circular area is without unit D, thus producing a rather marked asymmetry of the subsoil response. Figure 5 is a three-dimensional representation of the whole stratigraphic model below the inner circle of tests (Gottardi and Tonni, 2004).

Finally, several dissipation tests were performed in order to estimate the consolidation characteristics of fine-grained soils. Such silty sediments are typically characterised by high values of the horizontal coefficient of consolidation which, together with the limited layers thickness, provide rather short consolidation times.

4 LOADING BANK

The instrumentation installed for the monitoring of the foundation subsoil following the loading bank construction included: Casagrande and vibrating wire piezometers, load cells, inclinometers, fixed embankment and borehole extensometers, advanced sliding deformeters, GPS system as well as traditional surveying methods (Simonini, 2004).

The cylindrical sand bank construction started on 12th September 2002 and ended on 10th March 2003. It was carried out in 13 steps of 0.5 m each. When completed, the sand bank was covered with 0.2 m of gravel, thus giving a total height of 6.7 m above the original ground level and an estimated, uniform, total stress increase of 104 kPa.

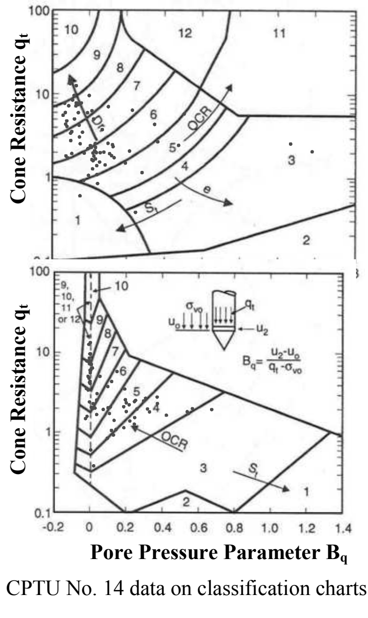

Figure 3. CPTU No. 14 data on classification charts.

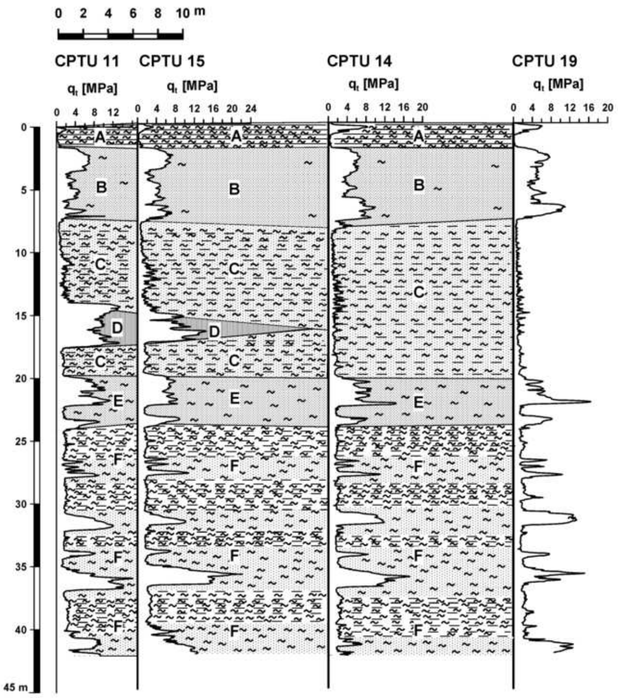

Figure 4. Stratigraphic section A-A across the loading bank.

In Figure 6 the integral vertical displacement at various depths with time is reported for the sliding deformeter No. 3, located at the centre of the loading bank. It is clearly noticeable the greater compressibility of fine-grained units, namely the soft shallow silty clay (unit A) and the central silty unit C; on the other hand, contribution of soil layers deeper than 32 m appears negligible, also in relation to the rapid reduction of the total stress increment with depth.

The maximum total vertical settlement of the centre of the loading bank has been, after two years, of almost 475 mm. Secondary settlements clearly play an important role: a rough estimate from the logarithmic plot of Figure 6 would allocate the initial 418 mm to primary consolidation settlements, completed after 228 days from the start of the loading bank construction.

5 SOIL COMPRESSIBILITY

The 1D constrained modulus *M* can be easily back-calculated every meter from the sliding deformeter measurements dated 18-04-03 and the standard elastic stress distribution increment under a circular uniform surface load (Fig. 7a). *M* values at greater depths may not be significant because of the tiny measured deformation. Therefore, the following analysis of soil compressibility is limited to the upper 32 m.

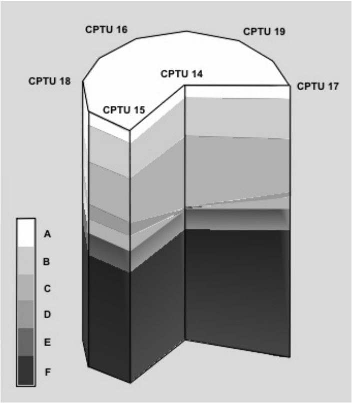

Figure 5. 3D view of the stratigraphic model below the loading bank.

From CPTU No. 14, *M* can be estimated with the well-known and widely used relationships:

$$M = \alpha\cdot q_c = 4\cdot q_c \tag{1}$$

$$M = \beta\cdot(q_t-\sigma_{vo}) = 8.25\cdot(q_t-\sigma_{vo}) \tag{2}$$

proposed respectively by Lunne and Christophersen (1983) for coarse grained soils and by Kulhawy and Mayne (1990) for fine grained soils (Fig. 7b). Both methods tend to substantially overestimate *M* and, consequently, underestimate the relevant vertical strain. In Figure 7c, the local vertical settlements measured by the sliding deformeter are compared to those computed with such *M* values and the standard 1D integral of deformation:

$$\Delta H = \int_L \varepsilon(z)dz = \sum_i \frac{\Delta\sigma_z(z_i)}{M_i(z_i)}\cdot\Delta z_i \tag{3}$$

In order to increase accuracy in settlement predictions, average site-specific coefficients α and β for (1) and (2) were then determined from sliding deformeter data, introducing a soil unit dependency. Results are summarized in Table 1 and plotted in Figure 8.

Table 1: Site specific coefficients for relationships (1) and (2)

Soil Unit	α	β
A	3.52	3.75
B	2.06	2.19
C_0	1.63	2.20
C_1	2.50	4.80
E	1.71	1.93
F	5.96	8.45

With this purpose, unit C was divided into two sub-units, namely C_0, mostly sandy silt, and C_1, mostly clayey silt. Unit D is not present under the centre of the loading bank.

Site specific coefficients α and β tend of course to be generally smaller than those provided by Lunne and Kulhawy and some difference between coarser and finer fractions is detectable. Values for unit F, the most heterogeneous, appear to be higher due to the limited stress increment at greater depths in slightly overconsolidated soils. However it is rather difficult to find a unique criterion within this empirical framework and an alternative approach for such intermediate soils should be used. Back calculating the total settlement via eq. (3) and coefficients of Table 1, “Lunne modified” gives 381 mm, “Kulawy modified”

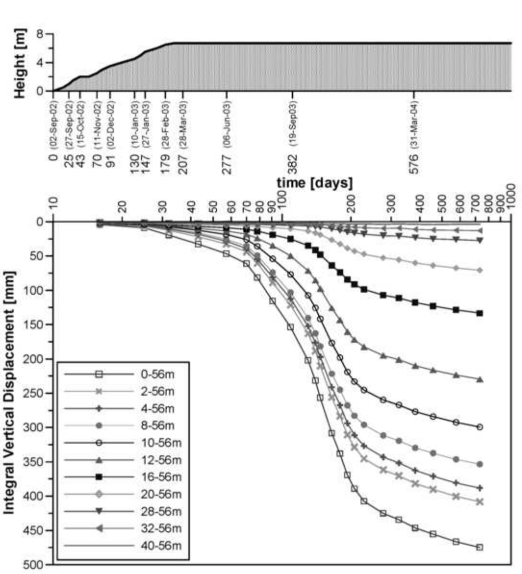

Figure 6. Integral vertical settlement at various depths with time.

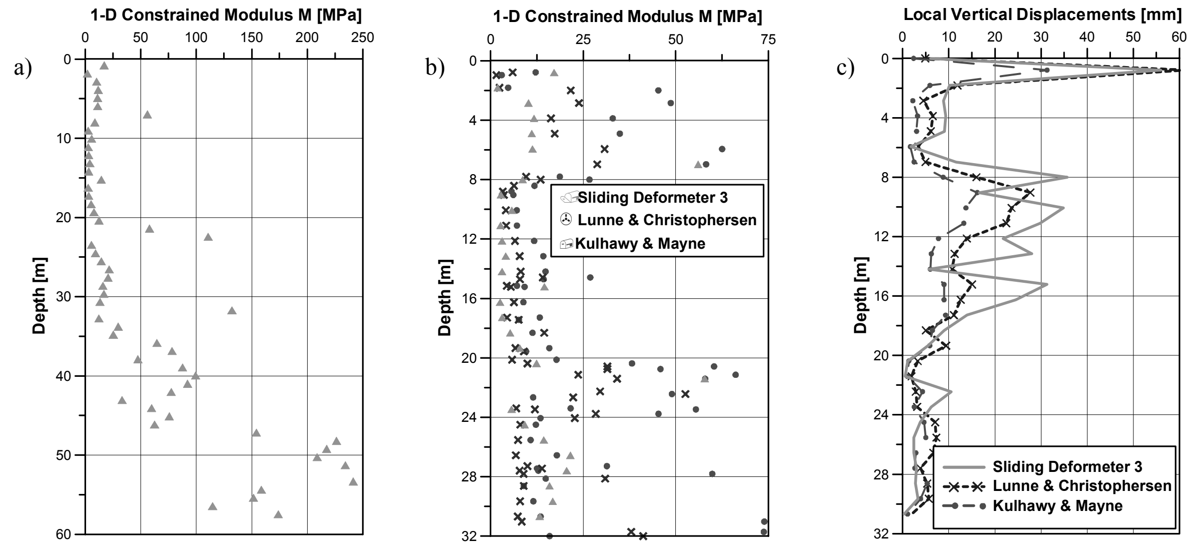

Figure 7. Comparison between back calculated and estimated M-values.

390 mm, whereas the sliding deformeter to 32 m provided 406 mm.

6 FINAL REMARKS

The Treporti test site represented a unique opportunity, not only for the definition of a reliable geotechnical model aimed at the foundation design of the submersible gates intended to protect Venice and its lagoon environment against flooding, but also for the investigation of the potentials of in-situ testing. Thanks to an extensive comparison among geotechnical parameters, independently determined from a full-scale and long-lasting loading experiment, commonly accepted relationships and charts can be verified and calibrated for a highly stratified, rather complex, silty subsoil, whose behaviour is not clearly typical of coarse grained materials nor of fine-grained materials.

Thus, their partially drained response under penetrometer testing is of difficult interpretation within a unique simple relationship. In addition, time rate consolidation turns out to be very high, comparable with the loading bank construction time in this case. Therefore, secondary settlements - which play a very important role - can not be clearly separated from primary component.

A deeper insight into the behaviour of the silty soils is currently under development, by means of an existing constitutive model within the framework of Generalized Plasticity Theory, which has already proved to be suitable for natural frictional materials.

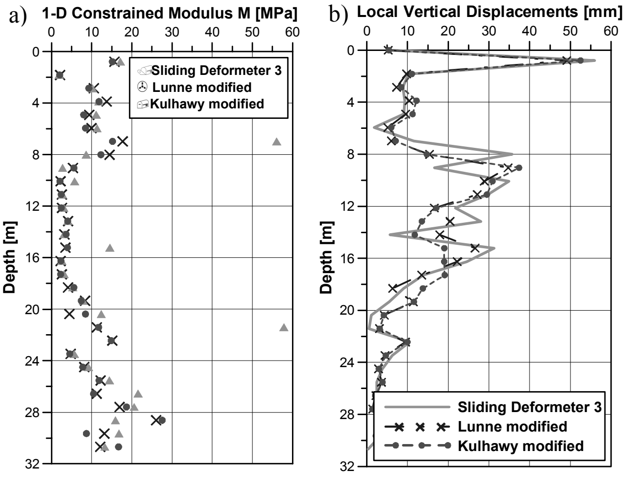

Figure 8. M-values from site specific relationships.

REFERENCES

Cola, S. and Simonini, P. 2002. Mechanical behaviour of silty soils of the Venice lagoon as a function of their grading characteristics. *Canadian Geotechnical Journal*, 39, 879-893.

Gottardi G. and Tonni, L. 2004. Use of piezocone tests to characterize the silty soils of the Venetian lagoon (Treporti test site). *Proc. ISC-2 on Geotechnical and Geophysical Site Characterization*. Porto, Portugal, 19-22 September 2004, 2, 1643-1650.

ISSMGE 1999. International Reference Test Procedure for the Cone Penetration Test (CPT) and the Cone Penetration Test with pore pressure (CPTU). *Report of the ISSMGE, TC16, Proceedings XII ECSMGE*, Amsterdam, 7-10 June 1999, 3, 2195-2222.

Kulhawy, F.H. and Mayne, P.H. 1990. Manual on estimating soil properties for foundation design. *Electric Power Research Institute, EPRI*, August 1990.

Lunne, T. and Christophersen, H.P. 1983. Interpretation of cone penetrometer data for offshore sands. *Proc. of the Offshore Technology Conference*, Richardson, Texas, Paper No. 4464.

Marchetti, S., Monaco, P., Calabrese, M. and Totani, G. 2004. DMT-predicted vs. measured settlements under a full-scale instrumented embankment at Treporti (Venice, Italy). *Proc. ISC-2 on Geotechnical and Geophysical Site Characterization*. Porto, Portugal, 19-22 September 2004, 2, 1511-1518.

McGillivray , A. and Mayne, P.W. 2004. Seismic piezocone and seismic flat dilatometertests at Treporti. *Proc. ISC-2 on Geotechnical and Geophysical Site Characterization*. Porto, Portugal, 19-22 September 2004, 2, 1695-1700.

Ricceri, G. 1997. Geotechnical problems for the barriers. *Symposium on "Venice and Florence: a complex dialogue with water"*, 24 May 1997, Florence, Italy.

Ricceri, G. and Butterfield, R. 1974. An analysis of compressibility data from a deep borehole in Venice. *Géotechnique*, 24 (2), 175-192.

Righi, P.V., Gottardi, G. and Tonni, L. 2003. Le indagini in sito mediante piezocono in località Treporti (VE) finalizzate alla definizione del modello geotecnico del sottosuolo. *Internal Report No. 92*, DISTART, University of Bologna, 110 p. (in Italian).

Robertson, P.K., Campanella, R.G., Gillespie, D. and Greig, J. 1986. Use of piezometer cone data. *Proc. of the ASCE Specialty Conference In Situ '86*, 1263-1280.

Simonini, P. 2004. Characterization of the Venice lagoon silts from in-situ tests and the performance of a test embankment. *Proc. ISC-2 on Geotechnical and Geophysical Site Characterization.* Porto, Portugal, 19-22 September 2004, 1, 187-207.

Simonini, P. and Cola, S. 2000. Use of piezocone to predict maximum stiffness of Venetian soils. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 126 (4), 378-382.