Relevance of secondary compression in Venice lagoon silts

Relevánce de la compression secondaire dans le limons de la lagune de Venise

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ABSTRACT

To protect the historic city of Venice against recurrent flooding, a huge project has been undertaken, involving the design of movable gates located at the three lagoon inlets for controlling tidal flow. Selection of the gate foundations demands very careful experimental investigation and modeling of the Venice lagoon soils, composed of a prevalent silt fraction combined with clay and/or sand forming an erratic interbedding of various types of sediments. To this end two typical test sites in the lagoon area - the Malamocco and Treporti Test Site – have been selected for characterization of the silts. Some interesting results from the research carried out at the two sites concerning the mechanical behavior in secondary compression are here presented and discussed.

RÉSUMÉ

Le choix et le projet des fondations des ouvrages mobiles pour la défense de la ville de Venise des eaux hautes demande une méticuleuse analyse géotechnique des terrains qui se trouvent aux bouches de la lagune et qui présentent une combinaison chaotique de limons, de sables et d'argiles peu plastiques. A cet effet on a sélectionné dans la lagune deux zones d'essais, à Malamocco et à Treporti, dans lesquelles on a achevé l'analyse de la caractérisation mécanique des limons sablonneux et argileux. L'article ci-dessous présente d'intéressants résultats des analyses faites par rapport aux réactions du terrain en condition de compression secondaire.

1 INTRODUCTION

To protect the city of Venice against recurrent flooding, a great project has been undertaken, involving the construction of movable gates at the lagoon inlets. To properly design the gates' foundations, comprehensive geotechnical studies have been and are still being carried out to characterize the Venetian soils.

The main characteristic of these soils is the predominace of silt, combined with clay and/or sand, forming a chaotic interbedding of different sediments, whose basic mineralogy varies narrowly, as a result of unique geological origins and a common depositional environment.

These features suggested concentrating research efforts on selected test sites - namely the Malamocco Test Site (MTS) and the Treporti Test Site (TTS) - considered as representative of typical lagoon soil profiles.

Relevant results from the laboratory program carried out at MTS have been already published (Cola and Simonini, 2002). From those results it turned out that the Venice silts are characterized by very high consolidation properties, thus suggesting that secondary compression should play an important role in governing the overall time-dependent response of these silts.

To prove this and in order to study directly in situ stress-strain-time behavior, a full-scale earth-reinforced circular embankment, loading up the ground to around 100 kPa, was very recently constructed at the Treporti Test Site. Relevant ground displacements, together with pore pressure evolution, were measured both during and after construction.

The paper discusses some interesting results of the research carried out both at MTS and TTS concerning the interpretation and modeling of the secondary compression of Venice silts.

2 BASIC SOIL PROPERTIES

The soils forming the upper 50-60 m below mean sea water level (m b.s.l.) are prevalently continental sediments deposited during the last glacial period (the Würm) of the Pleistocene, when the rivers transported material down from the Alpine ice fields. The Holocene is only responsible for the shallowest lagoon deposits, about 10-15 m thick.

The Wurmian soils are slightly overconsolidated (OC) due to recent mechanical unloading or natural aging. The presence at small depths of *caranto*, a very high OC silty clay exsiccated during the last sea regression, can be observed both under the old city and locally in other areas.

Soils may be grouped into three main classes – i.e. medium to fine sand (SP-SM), silt (ML) and very silty clay (CL) – which occur in 90-95% of the profile. Only 5-10% is constituted by medium plasticity clays and organic soils (CH, OH and Pt).

Plasticity, activity and organic content are generally low: at Malamocco, Atterberg limits are $LL=36\pm9$, $PI=14\pm7$, while activity A is 0.25÷0.50 and the organic content is $O_C<4\%$.

In situ void ratio e_o lies approximately between 0.6 and 1.0, with rare values above the unity due to thin layers of OH or Pt.

Sands show two types of mineralogical composition, namely siliceous and carbonatic, the former in the form of detrital calcite and dolomite crystals. The clay minerals increase alongside variation of the grain-size distribution from sands to clays. Clayey minerals, not exceeding beyond 20%, are mainly composed of illite or muscovite.

3 THE MALAMOCCO TEST SITE

The 1st column of Figure 1 reports grain size composition profile up to a depth of about 60 m. The predominace of coarse fraction is evident, with silt sediments exceeding 50% in 65% of analyzed samples. The clay fraction rarely reaches 50%.

As depicted in the 2nd column of Figure 1, at greater depth the soil is lightly overconsolidated - except for the shallow *caranto* - with OCR in the range 1÷4.

The 3rd and 4th columns of Figure 1 collect values of the compression indexes $C_c=\Delta e/\Delta\log\sigma'_v$ and $C_\alpha=\Delta e/\Delta\log t$, determined at the in-situ effective stress from 1-D laboratory compression tests. Note that, according to Mesri and Godlewski (1977), C_c is here defined as the local slope of the e-$\log\sigma'_v$ curve independently from the stress state.

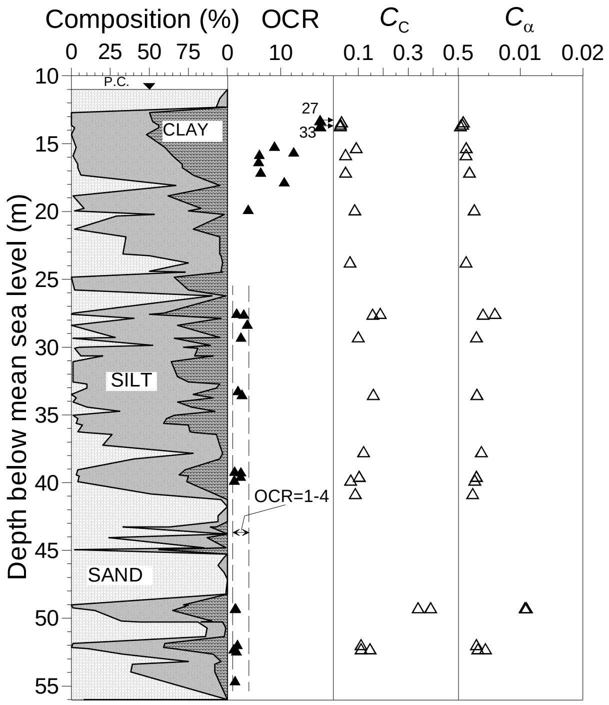

Figure 1. Soil composition and some properties profile in Malamocco.

Despite the tests have been carried out on all types of soils, C_c and C_α do not exhibit great variations and, except for the highest values C_c =0.390 and C_α =0.011, determined on a CH specimen at about 49 m b.s.l., the two indexes seem to be more affected by the stress history rather than from the grain-size composition. The lowest values C_c =0.027 and C_α =0.0054 were obtained for a *caranto* sample, drawn up at 13.6 m b.s.l.

Independence from grain-size distribution can be noticed from data reported in Figures 2 and 3, where the index C_α estimated in laboratory is plotted, respectively, against the effective stress and the compression index C_c. Different symbols are used for the four classes of soils.

For vertical stress σ'_v up to 500 kPa, C_α < 0.006. Values above this limit may be reached at higher stress levels or in more plastic soils.

According to the Mesri's compression law, the ratio C_c/C_α is independent from the stress level or from the material density, but for the Venetian soils this ratio appears also independent from the grain-size composition (Figure 3). The best fit provides C_c/C_α=0.028 with negligible differences between the classes CL, ML and SP-SM. A higher average value equal to 0.031 is obtained for the CH-OH soils, even if the difference is very small.

The prevalently silty composition of Venetian soils seems to find another confirmation from the experimental values of C_c/C_α, which are intermediary between the two limits of 0.02 and 0.04 suggested by Mesri for sandy and clayey soils, respectively.

4 THE TREPORTI TEST SITE

In order to measure in-situ the stress-strain-time properties of Venice lagoon soils, a comprehensive research program has been very recently undertaken and partially carried out. Details on the research can be found elsewhere (Simonini, 2004).

The research program was concerned with the construction of a full-scale earth-reinforced embankment over a typical soil profile in the Venice lagoon – carefully characterized through laboratory and site testing (Mayne and McGillavry, 2002, Marchetti et al., 2004, Gottardi and Tonni, 2004) - and with the measurement of relevant displacements of ground together with pore pressure evolution.

At the selected test site, referred here as Treporti Test Site (TTS), the approximate ground sequence consists of:

A) 0-2 m: soft silty clay;
B) 2-8 m: medium-fine silty sand;
C) 8-20 m: clayey silt with a sand lamination between 15 and 18 m, covering 270° in plan between North and East. This layer constitutes the fine-grained deposit that gave rise to most part of the vertical displacements;
D) 20-23 m: medium-fine silty sand;
E) 23-45 m: alternate layers of clayey and sandy silt;
F) 45-55 m: medium-fine silty sand.

Laminations of peat are present below 25 m, in layers E and F.

To measure relevant quantities, the following devices were installed: 7 settlement plates plus one GPS antenna and 12 bench marks to measure surface vertical displacements; 8 borehole rod extensometers plus 4 special multiple micrometers (capable of measuring displacements at 1 m intervals with an accuracy of 0.03 mm/m) to measure deep displacements and deformations; 3 inclinometers; 5 Casagrande as well as 10 vibrating wire piezometers; 5 load cells to measure total vertical stress beneath the loading embankment. Figure 4 shows a schematic soil profile together with the installed instruments.

The cylindrical sand bank construction started on September, 12th, 2002 and ended on March, 10th, 2003. The bank is formed by 13 geogrid-reinforced layers with a 0.5 m thickness. Figure 5 shows the loading sequence and corresponding vertical settlement at the centre of the embankment.

The high values of the consolidation coefficient, let us suppose that primary consolidation should have been quite rapid

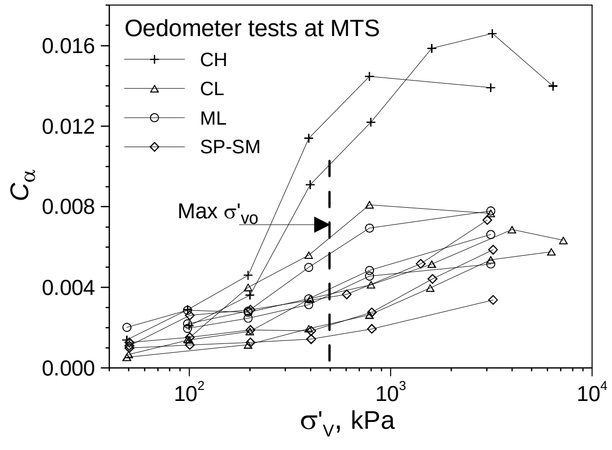

Figure 2. Secondary compression index from oedometer test.

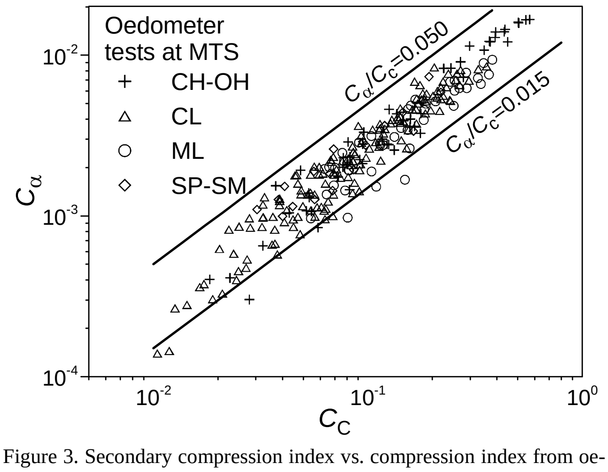

Figure 3. Secondary compression index vs. compression index from oedometer tests at MTS.

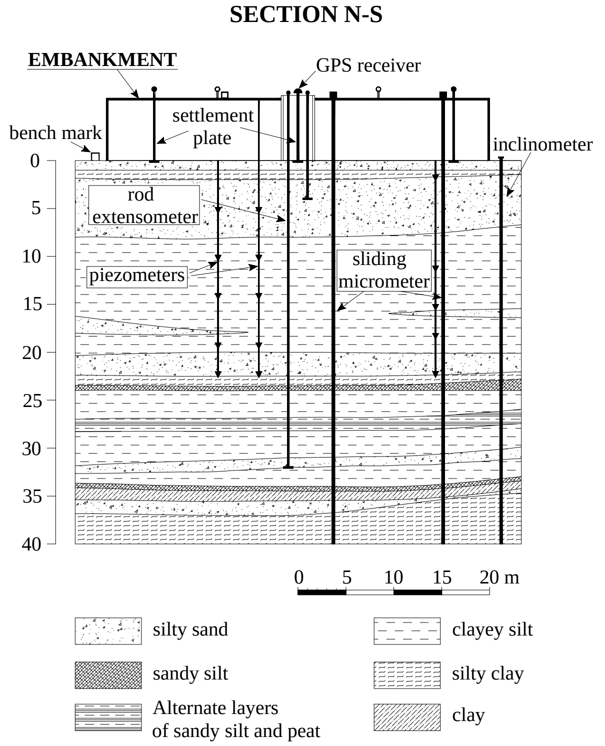

Figure 4. Cross-section of embankment with soil profile and monitoring devices.

along with bank construction. This hypothesis was confirmed by the application of the theory of consolidation under a linearly increasing load (Olson, 1977), then corroborated by the piezometer readings which gave no detectable pore pressure increase in any layer up to and beyond bank completion.

4.1 *Vertical displacements and deformations*

Comparing the vertical and horizontal displacements throughout the loading process, it appeared that the total vertical displacement is one order of magnitude greater than the maximum horizontal displacement, that is, the deformation process developed prevalently in the vertical direction.

The total settlement at the bank completion was about 36 cm, including, besides immediate and consolidation settlements, the secondary settlement that also occurred during the construction. Until march 2004, an additional secondary settlement of 12 cm was measured, thus giving a total settlement of 48 cm. Note that the secondary settlement is 25% of the total settlement measured so far.

The interpretation of the displacement readings given by the multiple sliding micrometers provided the trend for vertical strains as a function of stress increments and/or time. The strains measured during load application at increasing depth with the micrometer close to the bank centerline were related to the stress increments, the latter estimated using an elastic finite element analysis. Figure 6 depicts the stress-strain responses for some 1-m thick layers: note the much stiffer response at the beginning of the loading phase before a yielding point, beyond which the soil behaves much softer.

Hypothesizing that consolidation occurred along with the loading phase, the sharp variation of curvature has been interpreted in terms of yielding stress σ'_Y and compared with the overburden stress σ'_{vo}, to estimate preconsolidation trends with depth. It turned out that the soil is mechanically NC with a small OCR (1.1-2.0 for layers B, C, D and E), probably due to the influence of secondary compression over centuries. No diagenetic effect seems to be present at TTS.

4.2 *Primary and secondary compression*

The stress-strain behavior for layers up to a depth of 30 m (beyond 30 m no relevant deformation occurred) has been interpreted, whenever possible, in terms of a virgin compression index $C_c^* = (1+e_0)\cdot CR^*$, as shown in Figure 6. The asterisk denotes that the deformation process under the bank approaches but does not coincide with the 1-D condition. It is interesting to note that a virgin compression index has been estimated even for SP-SM materials: this index represents only the current slope of the virgin compression line beyond the yielding stress.

For all the layers, the strain-time trend is characterized by the *S-type* shape, being the final part fitted in the ε_z-log$t$ plane by a straight line whose slope is $C_{\alpha\varepsilon}^*$. The slope of this line is assumed to represent a secondary compression index $C_\alpha^*=(1+e_0)\cdot C_{\alpha\varepsilon}^*$ where the asterisk denotes, again, the occurrence of a 3-D deformation condition.

Figure 7 reports the soil profile with OCR, C_c, C_α, estimated from laboratory tests in the NC range as well as C_c^* and C_α^* determined as explained above. The comparison may be, of course, criticized, since the in-situ stress and deformation condition is different from that occurring in 1-D compression tests. To note, in Figure 7, the very large variation of compression indexes even within the same type of formation.

In-situ secondary compressibility is generally higher than that measured in the laboratory, but no definitive conclusion can be established due to the limited number of laboratory data from

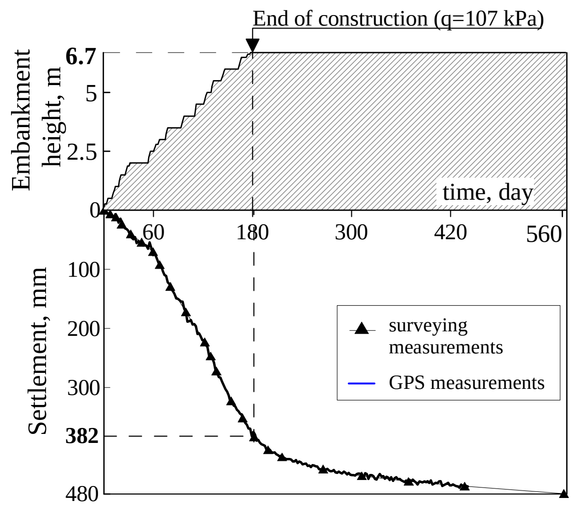

Figure 5. Evolution with time of ground settlement under the embankment centerline.

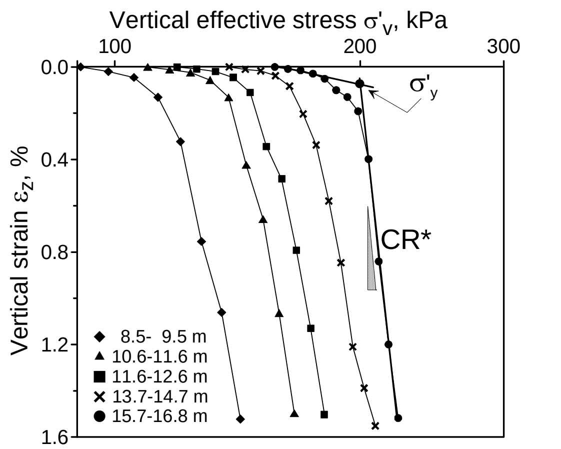

Figure 6. Vertical strain of the most compressive strata, developed during construction.

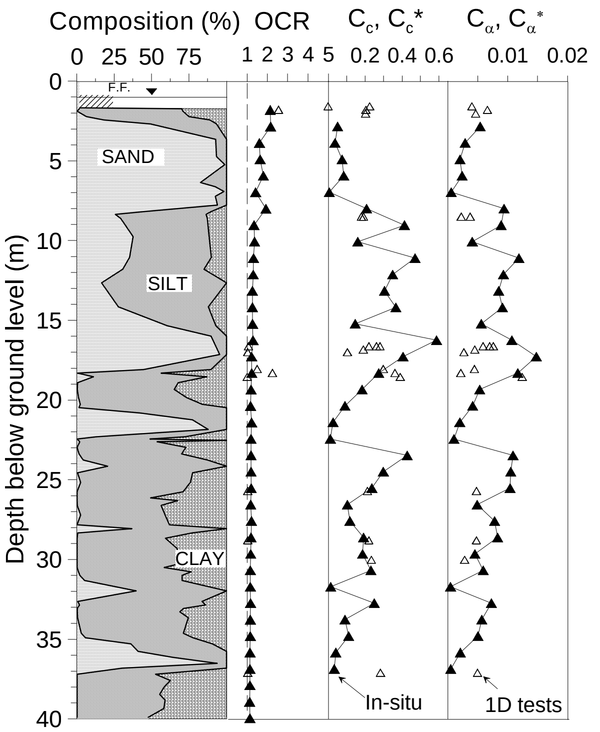

Figure 7. In-situ and laboratory values of primary and secondary compression coefficient.

TTS. Nevertheless, this difference can be probably attributed to the occurrence of a non-K_0 stress state under the bank centerline, inducing very small, but non-zero, horizontal deformations, thus increasing the secondary compression rate.

The Mesri approach has been also applied to both laboratory and in-situ results. To note that $C_\alpha*/C_c*$ represents the ratio between secondary and primary compression indexes estimated under non-K_0 in-situ stress states.

As found at MTS, upper values of C_α/C_c are due to SM-SP material (0.0291 at MTS and 0.0310 at TTS), intermediate to CL (0.0269 and 0.0281) and lower to ML (0.0236 and 0.0267). However no appreciable difference is noticed among the three different soil classes, confirming therefore the common geological and mineralogical features of all the Venice lagoon sediments.

$C_\alpha*/C_c*$ ratios are similar to those from the laboratory, but with upper values due to the deep formation E, composed prevalently of silty clay and clayey silt with some important peat lamination ($C_\alpha*/C_c*$= 0.0323) and lower values for the upper formation C composed of sandy silts ($C_\alpha*/C_c*$=0.0263). $C_\alpha*/C_c*$ ratio for sand layers of formation B shows values somewhat external to the typical range suggested by Mesri; it has, however, to be pointed out the relevant difficulty in the estimation of such ratio for sands is due to the limited range of induced deformation. It is interesting to notice that the difference in stress and deformation conditions from the laboratory (1-D) to the site (3-D) does not affect the ratio between secondary and primary compression.

5 CONCLUSIONS

From the laboratory and site investigation carried out so far it turned out that Venice lagoon soils are relatively free draining materials due to the predominance of the silt fraction chaotically combined with clay and/or sand.

It is therefore difficult to clearly distinguish between the primary and secondary compression response, the latter seeming to occur from the very beginning of the compression phase. Consequently, in these soils the prediction of settlement evolution with time is not straightforward, using the classical superposition method of primary and secondary compression contributions.

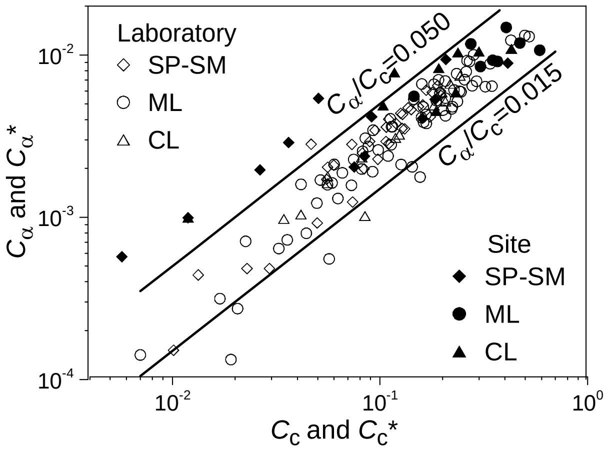

Figure 8. Site and laboratory primary and secondary compression coefficient.

The secondary compression coefficient, measured through several laboratory tests, is a function of the three typical classes of Venice lagoon soils, namely SM-SP, ML and CL and oscillates, very suddenly in the Venetian ground, as a consequence of relevant material heterogeneity. Any evaluation of scale effect is therefore extremely important in these soils.

The applicability of the Mesri's approach, linearly relating primary and secondary compression, has been also discussed by comparing the results of both laboratory and full scale tests. In addition, it has been shown that the ratio between secondary and primary compression indexes does not seem to be particularly dependent on the type of soil, as a consequence of the common geological and mineralogical features characterizing all the Venetian sediments.

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