Stiffness of clayey silts of the Venetian quaternary basin from laboratory tests

Déformabilité des limons argileux du bassin quaternaire vénitien à partir d'essais de laboratoire

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ABSTRACT: The cohesive soils of the Venetian quaternary basin, mainly composed of silty-clays and clayey-silts, show a great non-homogeneity. This is due to the very complex past geological history which has brought about strong variations in soil particle-composition and in the overconsolidation ratio with the change in depth. The soil stiffness is influenced by this non-homogeneity, thus showing appreciable variations even in samples of a few centimeters in length. In order to characterize the stiffness of the cohesive soils an extensive in-situ and laboratory experimental investigation has recently been undertaken. Some preliminary results obtained at the University of Padova using a new triaxial stress/strain path apparatus equipped with a local strain measuring system are presented and discussed in this paper.

RESUME: Les sols cohésifs constituants le basement quaternaire de la Lagune de Venise sont généralement composés par des argiles silteuses et des silts argileux très hétérogènes. Cela est du à la complexe histoire géologique qui a déterminé des variations considérables avec la profondeur de la composition granulométrique et du degré de surconsolidation. L'hétérogèneité de ces sols cohésifs influence leur déformabilité laquelle peut varier considérablement meme dans les échantillons de dimensions réduites. Afin de détérminer le déformabilité des sols cohésifs venetien on a commencé une recherche géotechnique in-situ et en laboratoire. Dans cet article les Auteurs examinent quelques résultats obtenus jusqu' aujourd'hui chez l'Université de Padoue par l'employ d'un nouveau systeme triaxial avec le mesurage interne des déformations.

1 INTRODUCTION

It is probably acknowledged world-wide that the city of Venice shows a precarious equilibrium and that the margin of safety is being eroded annually at an ever-increasing rate. The rate of deterioration is being accelerated by the increasing frequency of the flooding of the old city, by the increase in pollution of both the lagoon and the atmosphere, and by the reduction in the freeboard of the city as a result of the eustatic rise in sea level coupled with a subsidence of the lagoon area (Ricceri e Butterfield, 1974).

In the early eighties, the Italian Government decided to finance a large project regarding the design of special mobile barriers located at the three mouths of the lagoon which should be able to protect the old city and the entire lagoon against flooding.

The design of the barrier foundations requires the knowledge of the geotechnical parameters of the upper quaternary basin. For this purpose, a preliminary geotechnical investigation was carried out at Porto di Malamocco by making deep boreholes together with piezocone, dilatometer, selfboring pressuremeter, screw plate and cross/down hole testing (Ministero dei lavori pubblici - Magistrato alle acque, 1994). In addition, in order to obtain high quality, undisturbed specimens, a new large diameter (220 mm) sampler was also used.

The geotechnical laboratories of the University of Padova and ISMES of Bergamo have collaborated with Magistrato alle Acque and Consorzio Venezia Nuova. Therefore, some geotechnical tests have been carried out at the University of Padova.

In particular, some very accurate undrained triaxial compression and extension tests were performed on 70 mm diameter and 140 mm height specimens, trimmed from the large undisturbed samples. These tests were carried out using a new automated stress/strain path triaxial system, recently designed and set up at the University of Padova. In addition, since it was estimated that the amplitude of working stress under the barriers deforms the soil, thus inducing small strain levels, the triaxial cell was modified to measure internal strains on soil specimens.

The analysis and interpretation of test results for the determination of soil stiffness is presented in this paper, with particular attention placed on the influence of non-homogeneity on the overall behaviour of the soil.

2 BRIEF GEOLOGICAL HISTORY OF VENETIAN SOILS

The quaternary deposits of the Venice Lagoon, reaching a depth of approximately 900-950 m, have been formed throughout the Pleistocene. They are composed of a complex system of interbedded sands, silts and silty clay sediments. Their accumulation took place in different phases, during which marine regression and transgression alternated and the rivers transported fluvial materials coming from the nearby Alps. In the twelfth century, when the first would-be citizens of Venice settled on the islands, the rivers Brenta, Sile, Piave and others discharged waters and sediments into the Venetian lagoon. In order to prevent this, the rivers were diverted into extensive canals around the lagoon periphery. After the eighteenth century, no further hydraulic works were carried out and, consequently, the lagoon was not subjected to any significant alteration.

3 COHESIVE SOIL BASIC PROPERTIES

Due to such a complex geological history, the sediments exhibit a great non-homogeneity with variation in particle-size distribution even in a sample of a few centimetres. Therefore, it was very difficult to schematize a soil profile within which the different formations (cohesive/granular) can be clearly distinguished.

Figure 1 depicts a tentative soil profile, up to 60 m below zero IGM level (≈ mean sea level), determined from a borehole log and compared with the results of a piezocone test (q_c = tip resistance; u_w= pore pressure) carried out on a nearby vertical. Eleven basic formations were selected on the basis of the in situ testing results.

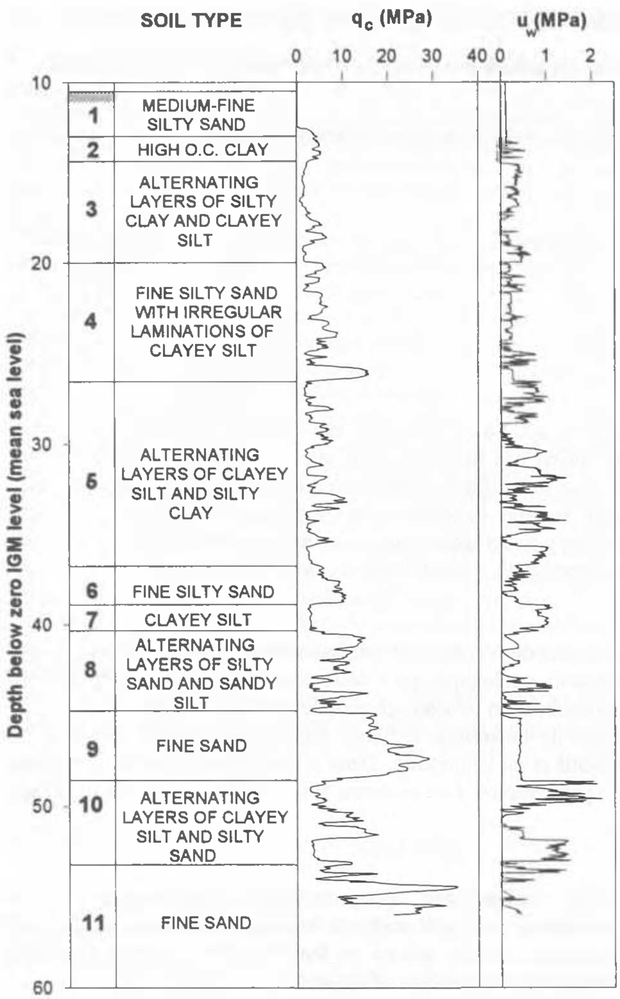

Figure 1. Soil profile at the Porto di Malamocco.

Figure 2 highlights the variation with depth of some soil characteristics determined on samples coming from standard and large diameter boreholes: particle size composition, bulk density (γ_{sat}), Atterberg limits (*LL*, *PL*) and natural water contents (w_o). It can be noted that the great majority of samples, other than sands, fall in the category of silt ($PI \leq 10\%$, $LL \leq 35\%$) and very silty clay ($10 \leq PI \leq 25\%$, $35 \leq LL \leq 50\%$). Observing the moisture content profile it is evident that the subsoil has a slightly decreasing water content with depth but always above the plastic limit.

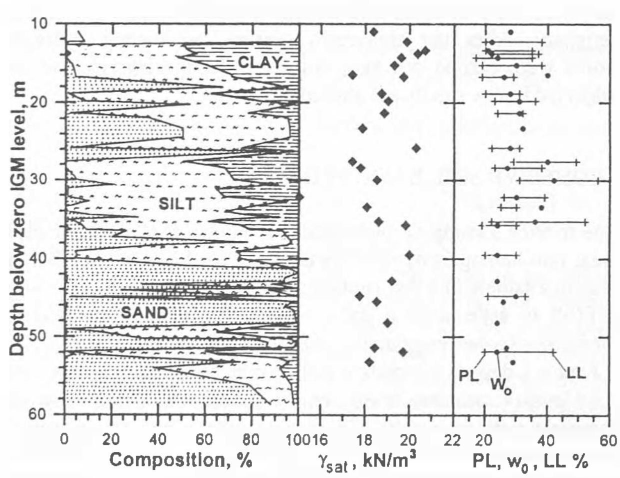

Figure 2. Trend of some soil properties with depth.

4 ESTIMATION OF IN-SITU STATE OF STRESS

The prediction of in situ stress state is usually a complicated problem and in the case of the Venetian soils it is even more so mainly because they have undergone a complex stress history of unloading and reloading which has been shown to be very difficult to reconstruct precisely.

The trend of effective overburden stress σ'_{vo} with depth, estimated using the values of bulk densities determined in the laboratory from the large-diameter borehole samples (called MSgM1), is reported in fig. 3a. The fig. 3a also shows the values of preconsolidation stress σ'_p determined from oedometric tests using Casagrande's method.

Calculated laboratory values of the overconsolidation ratio $OCR=\sigma'_p/\sigma'_{vo}$ are plotted in fig. 3b and compared with those estimated using the dilatometer test (DMT), carried out close to the MSgM1 borehole. An appreciable decrease in the *OCR* was clearly observed. The high *OCR* values (>10) in formation 2 are characteristic of the well-known *caranto*, an high o.c. clay on which most historical Venetian buildings are founded. The deeper formations are usually n.c. or slightly o.c., but there are some layers with $OCR \approx 2$: for these soils, as in the case of *caranto*, the overconsolidation is caused by superficial oxidation during glacial periods.

The in situ stress state was estimated by considering the values of the coefficient of pressure at rest K_o at various depths in the ground (fig. 3c). These were determined from the DMT and from the uniaxial reconsolidation stage in computer controlled CK_0D/U triaxial tests. The latter values have proved to be independent of depth and always lower than the DMT values, but this may probably be due to the effects of laboratory reconsolidation (Mayne and Kuhlhawy, 1982) and to the stress relief caused by sample disturbance which is important in silty soil. The effect of overconsolidation on horizontal stress can be clearly appreciated: K_0 decreases strongly with depth starting from values much higher than unity above 20 m and approaching 0.5 at great depths.

5 EXPERIMENTAL PROGRAM

In order to carry out the laboratory investigation on cohesive soil stiffness, several standard compression and extension triaxial tests, both drained and undrained, were carried out at the ISMES and the University of Padova laboratories.

Among these, some tests were performed on large specimens using a automated computed controlled stress/strain path triaxial system, recently designed and set up at the University of Padova

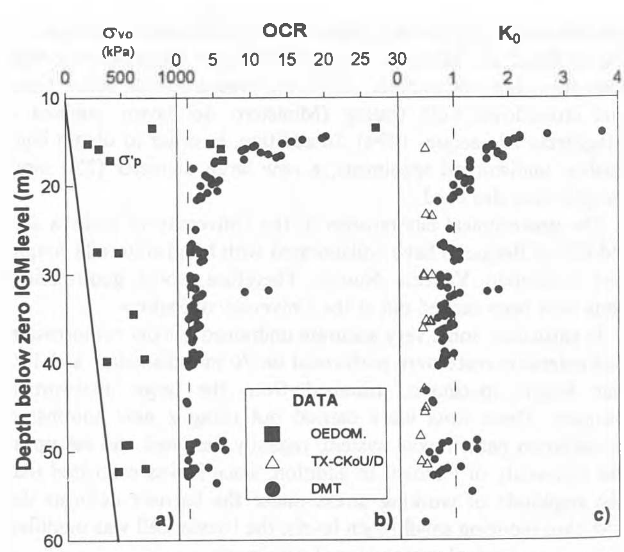

Figure 3a,b,c. Soil stress history at the Porto di Malamocco.

(Cola, 1992). This system is equipped with a special triaxial cell, capable of measuring local deformations on soil samples, the latter having height equal to 140 mm and a diameter/height ratio of 0.5. To this purpose, 6 proximeter transducers with an accuracy of 5 μm and a resolution of 1 μm were installed: 4 of these were used to measure axial deformations whereas the other two recorded the horizontal ones (Lo Presti et al. 1994).

The CK_0U triaxial compression and extension tests were carried out on the cohesive soils coming from formations 3 and 4 and drawn up from a large-diameter borehole (called MSgM2), which was drilled on a vertical close to MSgM1. The specimens were consolidated under the estimated insitu vertical stress and driven to failure with a strain rate of 0.008%/min.

Table 1 summarizes the test characteristics performed up to now. Some others are presently in progress at the Padova Geotechnical Laboratory and their results will be presented in a future paper.

Table 1 Main characteristics of some performed tests.

Test	Depth (m)	*LL* (av.value)	*PI* (av. value)	σ'_{vc} (kPa)
MSgM2-VE4-C	14.75-14.93	36	18	121
MSgM2-VE4-E	14.75-14.93	36	18	121
MSgM2-VE8-C1	21.80-22.00	48	29	202
MSgM2-VE8-C2	21.80-22.00	48	28	202

C=compression, E=extension

To measure the variation of elastic properties of cohesive soil with the strain level during the application of deviatoric stress, several small unloading-reloading cycles were performed (Tatsuoka and Shibuya, 1992).

6 TRIAXIAL TEST RESULTS

Figure 4 shows typical stress paths (compression tests VE4-C and VE8-C2) for the Venetian silty formations. Note the very low pore pressure - characteristic of silty soils - developed during the shear stage. K_o coefficient during consolidation turned out in each case to be around 0.64, independent of the in-situ acting stress state. Although the tests reached a final axial deformation of only 4-5%, the critical state line was, nonetheless, determined: it is characterised by M_c=1.34 meaning that ϕ_{cv}=33°.

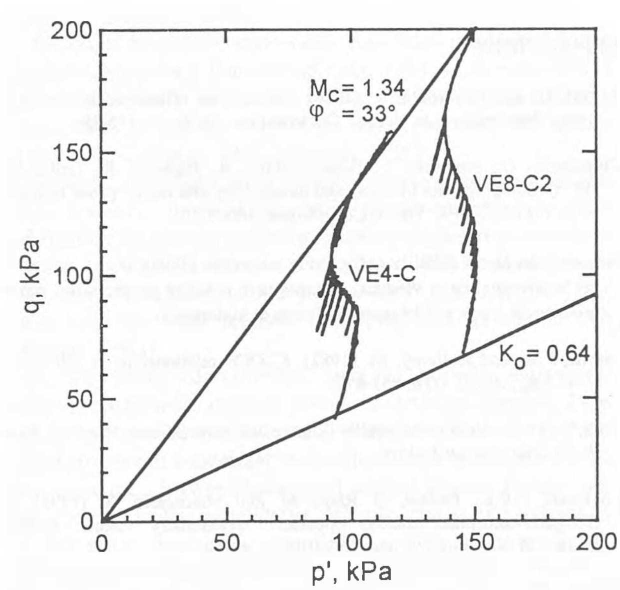

Figure 4. Typical stress-paths for triaxial CK_oU tests.

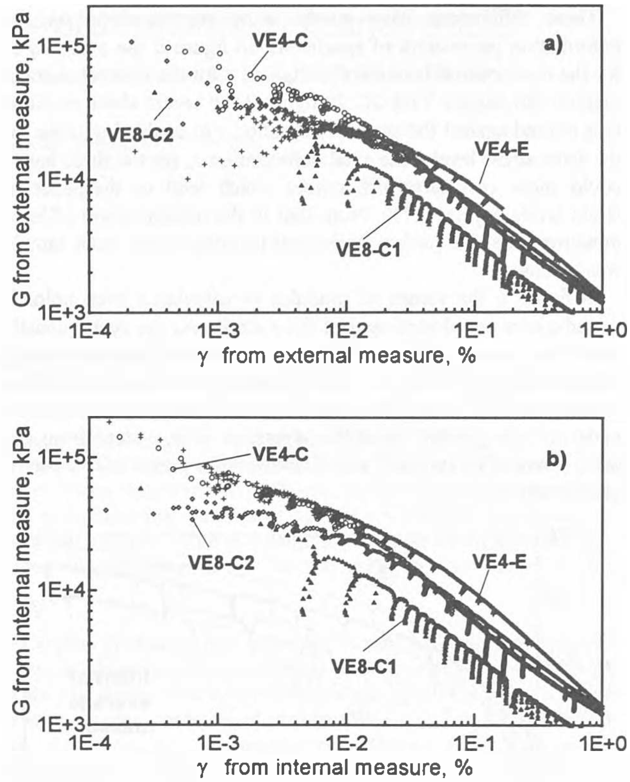

Figure 5a,b. Shear modulus G vs. external and local strain measurements.

The secant shear modulus $G = q/3\varepsilon_a$ was calculated using both external and internal measurements, on the stress-strain curve q-ε_a (q = deviatoric stress, ε_a = axial strain) determined from the triaxial tests. The trends of G are reported in figures 5a and 5b. The effects of local measurement can be appreciated especially for strain levels below 0.005%, where the local measuring system allows us to define the behaviour of soil even at 0.001% strain.

The high heterogeneity of Venetian soil suggested that the position of proximeters be modified in order to measure the distribution of axial deformations also within the specimen. To this purpose, the specimen VE8-C2 was divided into five parts, as shown in table 2, and the axial strains of the three central ones were considered. Note that the position of the four proximeters does not allow us to take into consideration here some possible bulging effects which are, therefore, omitted in the interpretation of test results. To avoid these effects prior to performing new tests, four additional proximeters are being presently installed in the triaxial cell.

Table 2 Composition of sample in the test VE8-C2.

Part	Thickness cm	w_o %	w_f %	γ kN/m³	LL %	IP %	IC
	2.02	36	29.5	21.4	37	12	0.08
4	1.52	36	32	20.5	39	13	0.23
3	4.99	35	30.5	19.2	37	10	0.20
	1.18	31.5	29	19.4	43	14	0.82
1	3.19	33	28	20.2	39	15	0.40

These differences have surely some repercussions on the deformation parameters of specimens. In figure 6 the curves q-ε_a for the three central layers are compared with the internal average measure for sample VE8-2C. In figure 7 the secant shear modulus G is plotted against the shear deformation γ in double log scale. At the same stress level q the axial deformation ε_a for the three layers could show very large differences which tend to disappear at strain levels beyond 0.1%. Note that in the interpretation of local measurements, the perfect horizontal layering within each sample was assumed.

In figure 8 the values of modulus G calculated from unload-reload cycles are plotted against the γ strain. As the cycles usually show a permanent deformation (their deformation amplitude being less then 0.01%), differences of an order of magnitude were found in some cases between the unload and the reload modulus: these variations are greater for stiffer layers, as it is evident from the comparison of G_u (unload) and G_r (reload) for part 3 with those of parts 2 and 4.

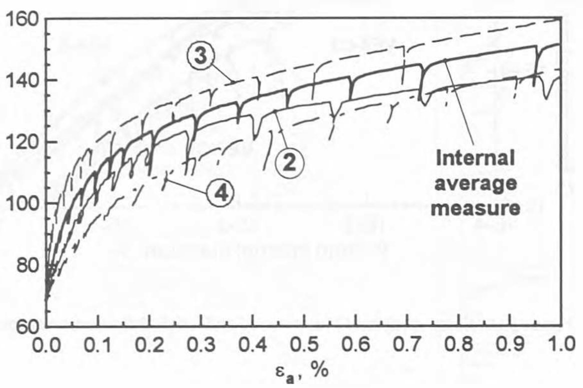

Figure 6. Deviatoric vs. axial strain in three parts of specimen VE8-C2.

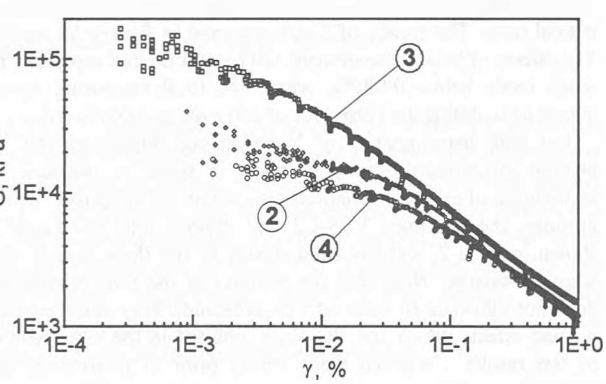

Figure 7. G modulus vs. shear strain in three parts of specimen VE8-C2.

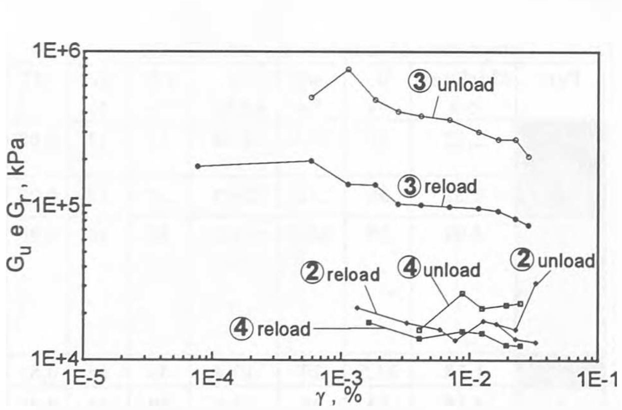

Figure 8. G values from unload-reload cycles vs. shear in three parts of specimen VE8-C2.

The comparison between the index properties of each layer (table 2) and the values of shear modulus may tentatively suggest that G (secant, during unoload and reload) are controlled to a greater extent by particle composition than by soil consistence: in fact, a higher silt component means higher values of G, as observed for part 2 of sample VE8- C2. Results of further tests are, of course, necessary to confirm these first experimental data.

7 CONCLUSIONS

In order to characterize the stiffness of the cohesive soils an extensive laboratory experimental investigation have been undertaken at the Geotechnical Laboratory of the University of Padova.

Some preliminary results obtained using a new triaxial stress-strain path device equipped with a local strain measuring system have been presented and discussed in this paper.

The undrained stress-strain behaviour of venetian cohesive soil is typical of silty soil and characterised by the development of low pore pressure during shear. In addition, this particular soil is very sensitive to sampling disturbance, as can be appreciated by observing the independence of depth of the K_o coefficient during laboratory reconsolidation.

The secant shear modulus was determined from the stress-strain curves of triaxial compression and extension tests using both external and internal measurement systems. The effect of local measurement has been appreciated especially for strain levels below 0.005%, where the local measuring system allowed us to define clearly the behaviour even at 0.001% strain.

To check the effect of soil non-homogeneity on soil stiffness, the position of internal measurement sensors was modified to measure axial deformations of the five parts within the specimen. The comparison between the index properties and the modulus of the different specimen parts suggested that the value of shear modulus is controlled more by soil composition and to a lesser extent by soil consistence: i.e. the higher values are for the soils within which the silt fraction is predominant.

However, this research is still in progress and the results of other tests deemed necessary to confirm the first experimental data, will be presented in a future paper.

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