Predicting long-term settlements of coastal defences for the safeguard of the Venetian Lagoon

Évaluation des tassements de consolidation secondaire des structures côtières de protection pour la sauvegarde de la lagune de Venise

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ABSTRACT: Over the last decades, a number of engineering solutions, including both nearshore and offshore structures, have been designed in order to protect human activities of the whole Venetian coastal environment as well as the invaluable historical and artistic heritage of Venice (Italy) from sea storms, high tides and recurrent flooding. In recent years, in the context of the ambitious mobile barriers system project known as MOSE, the existing jetties were extended and new breakwaters were set up in front of the three inlets connecting the lagoon to the Adriatic Sea. In order to preserve integrity as well as effectiveness, a key issue in the design of such structures is represented by the estimate of both short-term and especially long-term settlements. Indeed, field observations as well as laboratory evidence have shown that time-dependent phenomena cannot be considered as negligible in the predominantly silty sediments forming the Venetian lagoon basin. This paper focuses on the prediction of the long-term response of Venetian coastal defences, using a one-dimensional settlement method in conjunction with a $C_{\alpha\varepsilon}$ profile determined by piezocone tests and based on a formulation recently calibrated on field data from a Test Site located in the Venetian lagoon area.

RÉSUMÉ : Au cours de ces dernières décades, plusieurs mesures de protection contre la marée haute et les fréquentes inondations ont été mises en œuvre afin de protéger la ville historique de Venise (Italie) ainsi que les activités des communautés qui se sont développées au long de la lagune vénitienne. Récemment, lors du projet MOSE, qui consiste en un système de barrières mobiles placées auprès des trois bras de mer reliant la lagune à la mer Adriatique, les jetées existantes ont été remodelées et prolongées et de nouvelles structures de protection ont été construites. L'évaluation des tassements dus à la consolidation primaire et surtout secondaire est essentielle pour que ces ouvrages soient efficaces et en bon état au long des années. En effet, des études en laboratoire ainsi que des observations en place ont mis en évidence la contribution élevée de la consolidation secondaire aux valeurs totales des tassements des sols limoneux du bassin de Venise. Dans cet article on présente un calcul de tassement de consolidation secondaire d'un brise-lame, à l'aide d'une méthode qui permet d'évaluer $C_{\alpha\varepsilon}$ à partir des essais de pénétration statique (CPTU). La corrélation utilisée a été récemment établie sur une base de données assemblée auprès de la station d'essai de Treporti, située dans la lagune de Venise.

KEYWORDS: piezocone tests (CPTU); silt; sand; secondary compression; coastal defences; Venetian lagoon.

1 INTRODUCTION

Over the last decades, a number of engineering solutions, including both nearshore and offshore structures, have been constructed in order to protect human activities of the whole Venetian coastal environment as well as the invaluable historical and artistic heritage of Venice (Italy) from sea storms, high tides and recurrent flooding.

First in the late 19th century, several long jetties were built at the three inlets (Lido, Malamocco, Chioggia) connecting the lagoon to the Adriatic Sea (Figure 1). More recently, in relation to the ambitious project known as MOSE, consisting on a mobile barriers system for the temporarily closure of the lagoon inlets, the existing jetties were extended, reinforced and finally reshaped, new breakwaters were built in front of the inlets and a small island was realized within the Lido inlet.

In order to preserve both integrity and effectiveness, a key issue in the design of such structures is represented by the estimate of both short-term and especially long-term settlements, being the unexpected or underestimated reduction in the structure height a probable cause of flooding. Indeed, field observations as well as laboratory evidence have shown that time-dependent phenomena cannot be considered as negligible in Venetian sediments, hence the proper evaluation of the relevant parameters is of crucial importance for settlement predictions.

This paper focuses on the prediction of the long-term response of Venetian coastal defence structures, using a one-dimensional settlement method in conjunction with a secondary compression coefficient $C_{\alpha\varepsilon}$ profile determined from piezocone test data.

The approach is based on a formulation recently calibrated on field data assembled during approximately 6 years at the Treporti Test Site (*TTS*, Venice), within an extensive research

Figure 1. Satellite view of the Venetian lagoon.

project aimed at thoroughly analysing the stress-strain-time response of the predominantly silty sediments forming the Venetian lagoon subsoil.

The estimated settlements are compared with vertical displacement measurements provided by a very accurate monitoring system, based on an advanced technique known as Persistent Scatterer Interferometry.

The verification of empirical relationships using experimental data obtained from a different site of the Venetian lagoon is likely to constitute an important contribution to the practice of geotechnical engineering in this area.

2 THE VENETIAN LAGOON SUBSOIL

Over the last decades, the shallow Pleistocene sediments underlying the Venetian lagoon have been thoroughly investigated. First in the 1970s, in relation to the regional land subsidence and then in the 1990s, following the extensive site investigation programme related to the MOSE project.

From the large amount of data assembled over approximately 40 years, it turned out that the Venetian subsoil conditions consist of a complex assortment of interbedded normally consolidated or slightly overconsolidated silts, medium-fine silty sands and silty clays.

Despite grain size heterogeneity, research has shown that these sediments have a common mineralogical composition and that their mechanical behavior is mostly controlled by intergranular friction. Furthermore, as a consequence of their predominantly silty nature and high heterogeneity, undisturbed soil sampling is rather difficult to achieve, hence geotechnical characterization must essentially rely on in situ testing.

More recently, a new extensive research programme was carried out at the Treporti Test Site (*TTS*), located in the mainland beside Lido Inlet, with the aim of having a better understanding on the mechanical response of these intermediate sediments (Simonini 2004).

The valuable experience gained from the overall analysis of the data collected at *TTS*, including a large number of piezocone tests (CPTU) and subsoil strain measurements beneath a full-scale test bank, showed significant limitations of the existing approaches for the characterization of the predominantly silty sediments of the Venetian lagoon, thus suggesting a critical review of empirical and theoretical formulations with regard to their applicability to such soils (Tonni and Gottardi 2011).

It was also observed that such intermediate soils are often characterized by permeability values within the range in which partial drainage phenomena are likely to occur during cone penetration (Tonni and Gottardi 2010) and that the identification of this effect is of fundamental importance for a proper interpretation of CPTU measurements.

Furthermore, field observations showed that in these soils the decay of excess pore pressures is in general rather rapid and thus secondary compression plays an important role in the whole deformation process. As a result, the proper evaluation of the relevant parameters is crucial in settlement predictions.

3 EVALUATING SECONDARY COMPRESSION FROM CPTU

Unlike clayey deposits, the estimate of secondary compression behaviour of sandy and silty deposits is not routinely taken into account in the classical settlement calculation, although there is experimental evidence that time-dependent behavior of granular soils is not negligible. At low confining stresses the deformations are caused to rearrangement over time due to sliding and rolling between sand particles, whilst at high confining pressures the deformations are associated to continuous fracturing and deformation of grains (Augustesen *et al.* 2004).

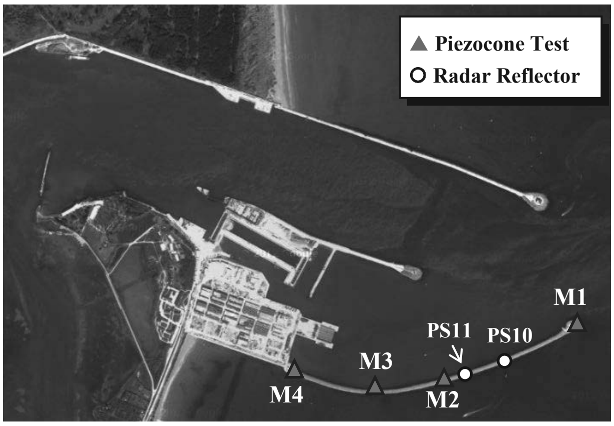

Figure 2. View of the Malamocco Inlet and location of the piezocone tests and radar reflectors (Persistent Scatterer, PS).

Secondary consolidation is typically characterized by the slope of the straight line portion of the vertical strain (ε_z) – logarithm of time (log*t*) curve obtained from oedometer tests, giving the secondary compression index $C_{\alpha\varepsilon}$:

$$C_{\alpha\varepsilon} = \frac{\Delta\varepsilon_z}{\Delta \operatorname{Log} t} \tag{1}$$

In recent studies (Bersan *et al.* 2012, Tonni and Simonini 2012), empirical, site-specific correlations, obtained from calibration on the *TTS* field data, have been proposed in order to estimate the secondary compression coefficient from cone resistance q_t. The approach is based on the experimental evidence that, in Venetian soils, frictional response governs both cone resistance and secondary compression, hence empirical correlations between $C_{\alpha\varepsilon}$ and q_t are likely to be a useful alternative on the classical laboratory tests for the estimate of creep characteristics.

Log regression analyses performed on the available data provided the following more significant relationships, both expressed in terms of the dimensionless normalized cone resistance Q_{tn}:

$$C_{\alpha\varepsilon} = 0.03 \cdot (Q_{tn})^{-0.89} \tag{2}$$

$$C_{\alpha\varepsilon} = 0.077 \cdot (Q_{tn})^{-1.14} \cdot \left(1 + \frac{\Delta u}{\sigma'_{v0}}\right)^{-0.74} \tag{3}$$

Here, an iterative nonlinear stress normalization procedure (Robertson 2009), accounting for the stress level and the soil class effects, was applied to the corrected cone resistance q_t in order to determine Q_{tn}.

It is worth mentioning that, according to the analyses based on the *TTS* data, the regression including a dependence on the stress-normalized excess pore pressure ($\Delta u/\sigma'_{v0}$) apparently gave a slightly better fit in comparison with eq. (2). Indeed, such additional independent variable allows accounting in some way for the different pore pressure response of soils in relation to the partial drainage conditions around the advancing cone.

4 CASE STUDY APPLICATION

Accurate measurements of long-term displacements of the coastal structures built along the Venetian coastline, next to the three lagoon inlets, have provided an opportunity to evaluate the predictive capability of the relationships described by eqs. (2) and (3).

Indeed, movements of coastal defense structures have been monitored using an advanced technique known as persistent scatterer interferometry (PSI), based on satellite-borne remote sensors. As explained in Tosi *et al.* (2012), the method is based on the identification and exploitation of individual radar reflectors, or persistent scatterers (PS), that remain coherent over long time intervals so as to develop displacement-time series. A significant advantage of PSI is represented by the possibility of detecting displacements with very high spatial and temporal resolution. According to ENVISAT ASAR and TerraSAR-X satellite images acquired from April 2003 to December 2009 and from March 2008 to January 2009 respectively, displacements of Venetian coastal structures turned out to range from a few mm/year for breakwaters and jetties older than 10 years to a maximum of 50-70 mm/year in the case of new or recently reshaped structures. Details on the whole PSI monitoring performed from Lido to Chioggia inlets are provided in Tosi *et al.* (2012).

In this paper, we will focus our attention only on the long-term vertical displacements measured from March 2008 to January 2009 at the Malamocco inlet, with special reference to the 1280 m-long, curved breakwater built in recent years just outside the inlet. This structure has shown settlement rates that vary in the range 5÷25 mm/year, with the higher values observed close to the seaward edge of the breakwater.

In order to apply the method described in section 3 and determine reliable values of $C_{\alpha\varepsilon}$, profiles of four piezocone tests located along the breakwater (Figure 2) have been interpreted. As an example, Figure 3 shows the corrected cone resistance q_t and pore pressure u measurements from CPTU M2, taken to 60 m depth.

All the soundings detail a complex soil profile of alternating silty sands, silts and silty clay, as recognized from prior studies performed at different sites of the Venetian lagoon. The pore pressure profiles rarely follow up the hydrostatic level, at times fall below it, but more often describe a slight contractive response, with generally moderate values of Δu.

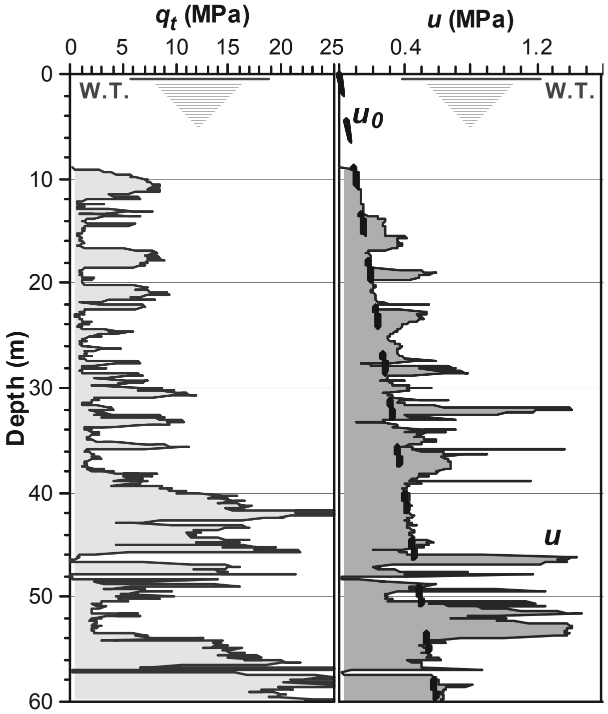

Figure 3. CPTU M2 log profiles.

Such stratigraphic complexity, typical of the whole Venetian lagoon subsoil, is confirmed by the well-known and newly revised piezocone-based classification framework proposed by Robertson (2009), aimed at identifying the *in situ* soil behavior type (SBT). Results from the application of the method to CPTU M2 data are shown in Figure 4. According to the SBT profile, the approach seems to predict a more pronounced clay-like behavior (zone 3) in comparison with the stratigraphic profiles obtained from nearby boreholes. Very thin layers of peat (zone 2) are at times detected, in particular from 22 to 48 m and from 51 to 53 m depth.

Results from the rather sophisticated classification approach developed by Schneider *et al.* (2008) are also plotted in Figure 4. This method, based on the normalized cone resistance ($Q = (q_t - \sigma_{v0})/\sigma'_{v0}$) and the stress normalized excess pore pressure ($\Delta u/\sigma'_{v0}$), was primarily derived to aid in separating whether cone penetration is drained, undrained or partially drained, hence the approach is recognized as superior to other classification charts when evaluating piezocone measurements in clayey silts, silts, sandy silts and transitional soils.

According to such classification framework, a large number of the CPTU M2 data fall in domains 1a and 3, this latter including a wide variety of mixed soil types.

Finally, Figure 5 provides the profile of the computed $C_{\alpha\varepsilon}$, as obtained from eqs. (2) and (3). Similar profiles have been obtained from the other available piezocone tests M1, M3 and M4. As evident from Figure 5, both formulations result in similar estimates of $C_{\alpha\varepsilon}$, although eq. (3) seems to provide lower values in the upper sandy layers.

In particular, the secondary compression coefficient in silts and silt mixtures (SBT zone 4) turns out to generally vary between 0.0015 ÷ 0.0035, rarely exceeding 0.004. Typical values of $C_{\alpha\varepsilon}$ in sand (SBT 6) fall in the interval 0.0005 ÷ 0.0008, whilst the range for sand mixtures (SBT 5) is somewhat higher (0.0007 ÷ 0.0018). Finally, $C_{\alpha\varepsilon}$ in clays-silty clays has been found to generally vary between 0.002 ÷ 0.006. It is worth observing that the computed values are in good agreement with the reference values of $C_{\alpha\varepsilon}$ derived from interpretation of long-term settlements observed at the Treporti Test Site.

Secondary compression of thin layers of peat, occasionally present throughout the stratigraphic profile, is described by rather high values of $C_{\alpha\varepsilon}$, such as 0.008 to 0.015. However, it is worth remarking that eqs. (2) and (3) have been not calibrated on such soil class, hence in this case the computed values of $C_{\alpha\varepsilon}$ cannot be applied without a great deal of uncertainty.

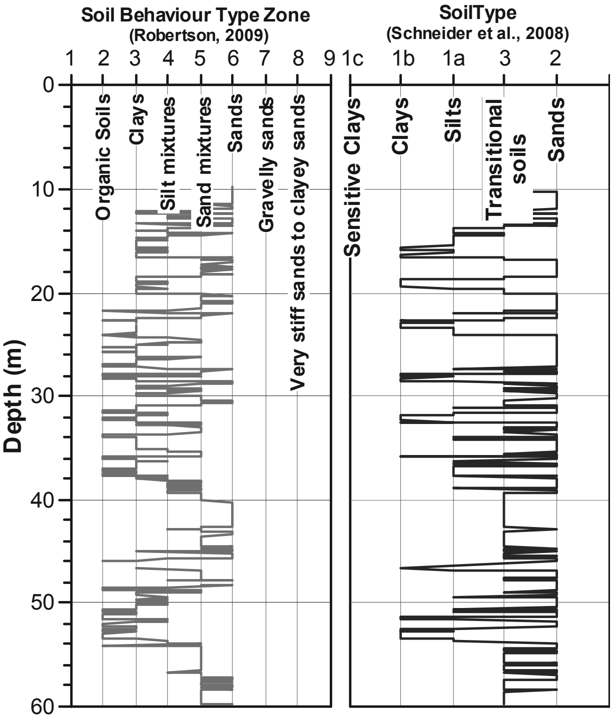

Figure 4. CPTU-based classification methods applied to test M2.

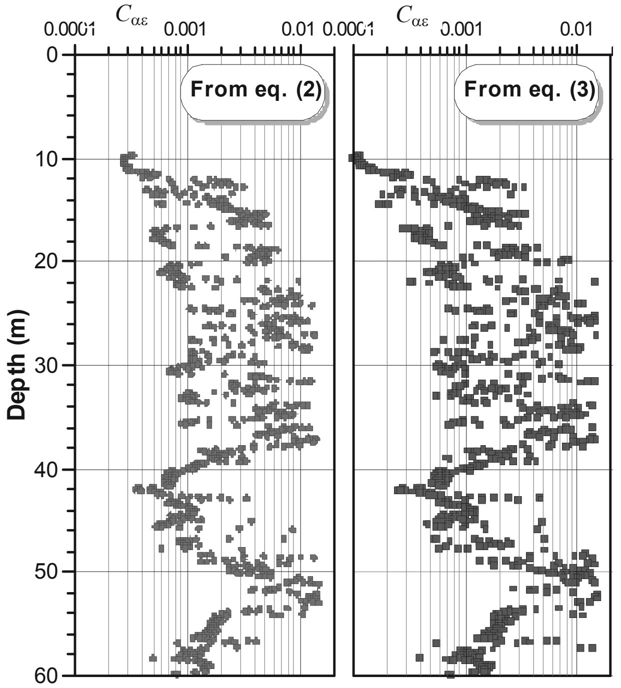

Figure 5. Profiles of the computed $C_{\alpha\varepsilon}$ from CPTU M2 data.

According to the so derived $C_{\alpha\varepsilon}$ values, a prediction of the secondary compression settlement S_{sec} occurred beneath the breakwater in the period March 2008–January 2009 has been carried out, using the well-known equation:

$$S_{\sec} = -\sum_{1}^{n} \left(C_{\alpha\varepsilon}\right)_i \cdot H_i \cdot \log_{10}\left(\frac{t}{t_{ref}}\right) \qquad (4)$$

where n is the number of H_i-thick homogeneous soil layers considered in the calculation, t_{ref} = March 2008 and t = January 2009. On the basis of previous experiences on Venetian sediment behaviour, the analysis has been performed to a depth of approximately 40 m from sea bottom.

Figures 6 and 7 show the results obtained from the application of the method to CPTU M1 and CPTU M2 data respectively, together with vertical displacements measured for the radar reflectors PS10 and PS11, located between the selected piezocone tests (Figure 2). The figures clearly show that eqs. (2) and (3) result in similar settlement prediction and that the calculated trend fits fairly well the PSI-derived settlements.

5 CONCLUSIONS

Accurate measurements of long-term settlements of a breakwater built along the Venetian coastline, outside the Malamocco inlet, have allowed evaluating the predictive capability of two slightly different empirical relationships between piezocone measurements and the secondary compression coefficient, recently calibrated on independent data from the Venetian lagoon.

The application of the method has provided long-term settlement predictions which agree fairly well with measured displacements, thus confirming the effectiveness of both available correlations.

Research is currently focusing on the verification of such correlations at different areas of the Venetian lagoon, using site investigations and settlement measurements available from other defence structures located at the Chioggia and Lido inlets. Indeed, the validation of the proposed solutions to independent cases is likely to provide a useful contribution to the practice of geotechnical engineering in the Venice lagoon area.

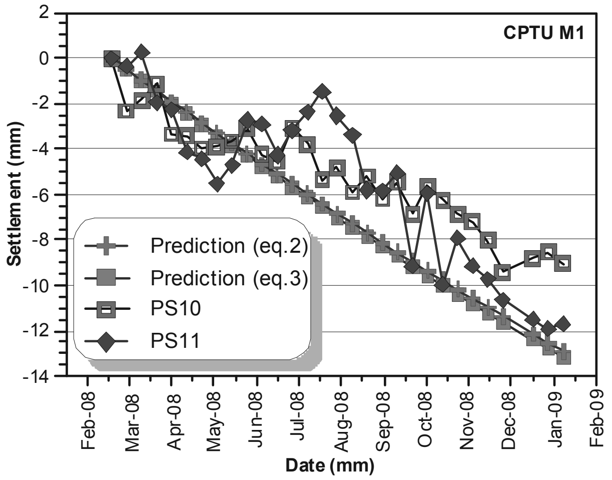

Figure 6. Settlement predictions using CPTU M1 data.

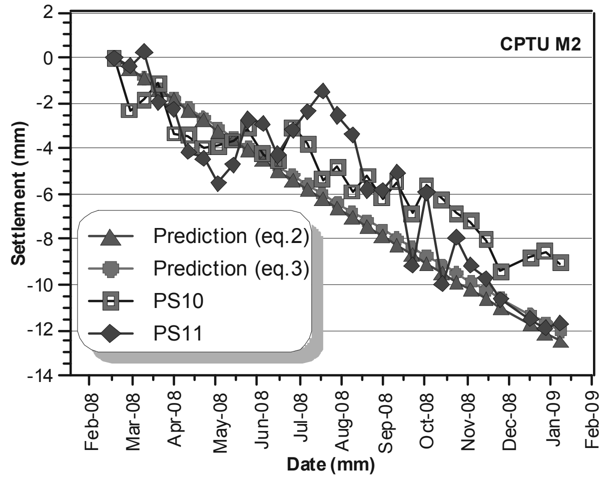

Figure 7. Settlement predictions using CPTU M2 data.

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