Pressiometric and Non-Pressiometric Tools on a Mediterranean Deltaic Deposit

Essais pressiométriques et non pressiométriques dans un delta méditerranéen

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ABSTRACT : The paper describes results of an experimental program in a test site located in Mediterranean deltaic environment of fluviomarine interbedded silt, clay and sand deposits. The results of a number of in situ characterisation tests are presented including pressiometric, (flexible dilatometer and cone pressuremeter) as well as non pressiometric tools (CPTU, SDMT). Emphasis is made on the more clayey levels, where results from the in situ tests might be compared with those obtained in laboratory tests on high-quality samples extracted from the same location by means of a Sherbrooke sampler. A comparative analysis is given of the stiffness and undrained shear strength of the materials for the different tests performed.

RÉSUMÉ : Le document décrit les résultats d'un programme expérimental dans un site d'essai situé dans un environnement deltaïque méditerranéen avec dépôts intercalées de limon, argile et sable. Les résultats d'un certain nombre de tests de caractérisation in situ sont présentés, y compris deux outils de types pressiomètrique : dilatomètre flexible et pressio-pénétromètre ainsi que des outils non pressiométriques (SDMT). L'accent est mis sur les niveaux plus argileux, où les résultats des essais in situ peuvent être comparés à ceux obtenus dans les essais de laboratoire sur des échantillons de haute qualité extraits d'un même emplacement à l'aide d'un échantillonneur Sherbrooke. Une analyse comparative, de la rigidité et la résistance au cisaillement non drainée des matériaux, pour les différents essais effectués, est donnée.

KEYWORDS : Deltaic deposit, pressuremeter, stiffness, undrained shear strength
MOTS CLES : dépôts deltaïques, pressiomètres, raideur, résistance au cisaillement non drainée.

1 INTRODUCTION.

The cone pressuremeter (CPM) in essence is an apparatus that combines a CPT or CPTu tip and a pressuremeter unit and it is installed by pushing in the ground. The inclusion of a CPT tip is what distinguishes it from simpler push-in pressuremeters, like the PENCEL. The CPM first appeared some 30 years ago (Withers et al., 1986); similar apparatuses were later presented by Zuidberg & Post (1995), Ghionna et al. (1995), Failzmeger (2005), amongst others. The apparatus was initially developed (Withers et al., 1986) with the explicit aim of obtaining an easily deployable presiometric tool for offshore applications that would allow fundamental interpretation of test results –as opposed both to direct correlation with foundation performance and to the more empirical approach that was associated with DMT.

Judged against those initial aims, the CPM has not been a success. Despite initial interest, a very limited offshore use has been reported (Lunne, 2010). No clear reason is given for this, but perhaps it might be due to a somewhat unreliable deployment operation. The apparatus remains relatively delicate and membrane protection an issue that is only partly solved by usual Chinese lanterns. Indeed, damage or even destruction of the Chinese lantern (Anderson et al. 2005) has been reported when penetrating granular soils; another concern is the clogging potential of that same lantern.

Moreover, the interpretation of CPM test results turned out to be of a more empirical nature than initially expected. In sands calibration chamber correlations are the mainstay of parameter inference from CPM results (Schnaid, 1990; Ghionna et al., 1995). In clays theoretical interpretations of the test results are a more common starting point. Houlsby & Withers (1989) developed a cavity expansion analysis of the unloading section of the test from which undrained shear strength, shear modulus and initial horizontal stress could be obtained. However, due to the simplicity of the underlying material model (elastic-perfectly plastic with a Tresca yield envelope), the stiffness and strength values thus obtained usually require further interpretation to be applied in design. As for the initial horizontal stress values thus obtained, they require empirical corrections (Powell, 2008).

It is therefore unsurprising that a certain turn towards a more pragmatic use and interpretation of CPM results is discernible in recent literature (e.g. Powell et al. 2005; Peuchen & Everaars, 2008). The core advantage of a CPM, when compared with other pressuremeter tools, remains its faster deployment which is particularly economic in cases where a CPT is also required. When compared with a DMT that deployment advantage is much reduced, and the choice should have other basis.

2 CASE DESCRIPTION

2.1 *Testing campaign*

The tests here discussed include

(a) 2 CPM in which the CPT profile reached 21 and 17 m and 15 pressuremeter tests were performed at regular intervals

(b) 2 boreholes, 14 m deep, where samples were taken at regular intervals for identification purposes and cyclic pressuremeter tests were performed using a flexible dilatometer at 5.2 m depth

(c) Laboratory triaxial and oedometer tests on specimens retrieved from Sherbrooke samples taken at 5.4 m and 13.5 depth

(d) 2 SDMT (20 and 8.8 m depth) performed and interpreted following the recommended procedures (TC16, 2001)

2.2 *Pressuremeters*

The CPM employed in the tests is an in-house development of Igeotest, in which a third-party cone tip of standard size (3.57 cm base diameter) is mounted in front of single-cell pressuremeter of 3.2 cm external diameter. The cell has a slenderness of 10 and the distance between cone tip and cell center is 46.8 cm. The pressure cell is volume controlled and is protected by a Chinese lantern. The external control unit allows several loading programmes to be implemented; for the tests described here a loading program following the standard monotonic Ménard procedure (AFNOR 2000) was implemented. The resulting average cavity strain rate during the tests was afterwards evaluated as 2-4 % min^{-1}.

The flexible dilatometer employed is also an in-house development by Igeotest, called PRD. Is a single cell, compressed gas apparatus of 560 mm length and 82 mm outer diameter. Radial deformation is measured at mid-cell section by three LVDT. The apparatus is fully controlled trough a dedicated PLC, that may be interfaced with a PC for manual operation. The two tests described here included three unload reload cycles, and loading at a strain rate of 1-2% min^{-1}.

2.3 *Testing site*

The test site is located in the vicinity of Castelló d'Empúries in the Alt Empordà. Castelló lies in the flat central section of the Costa Brava, located between the Paleozoic Pyrineic relief and the Mesozoic Montgri massif. This is an alluvial plain mostly formed by deposits of the rivers Fluvià and Muga which originate a typical Mediterranean deltaic ambient (Diaz & Ercilla, 1993; Figure 1). Holocene deposits reach here a thickness of about 20-30 m in the area, alternating sand-dominated deposits (e.g. dunes) and silt-clay deposits (coastal marsh).

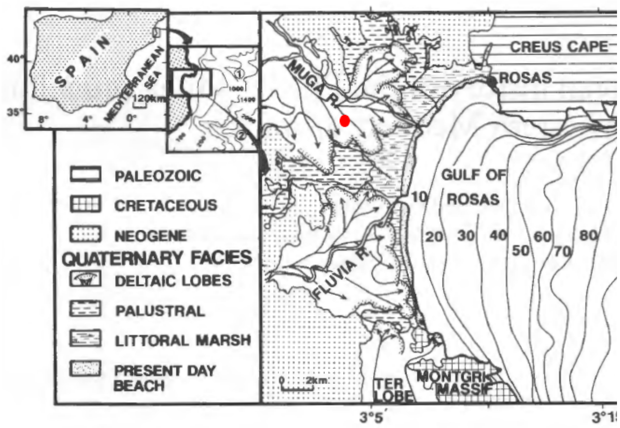

Figure 1 Test site location (dot); geological map (Diaz & Ercilla, 1993)

The test site is flat and lies at about 10 m above the local datum, having a roughly rectangular shape of 30 by 50 m. The water table oscillates significantly; at the time of testing for the tests reported here was located at 3.6 m depth; other records show it at up to 1.6 m depth. Grain size distribution analysis from samples recovered in a continuous borehole established a sequence of fine and granular soils that is characteristic of these deposits.

Fine grained levels dominate at 2-6 m and again at 12-14 m depth. These levels are classified as CL (USCS) and characterized by w_{LL} 30-50, IP 5-25 and w 28-30. The Yield Stress Ratio observed on CRS oedometers on specimens taken from the Sherbrooke samples is 1.2-1.3.

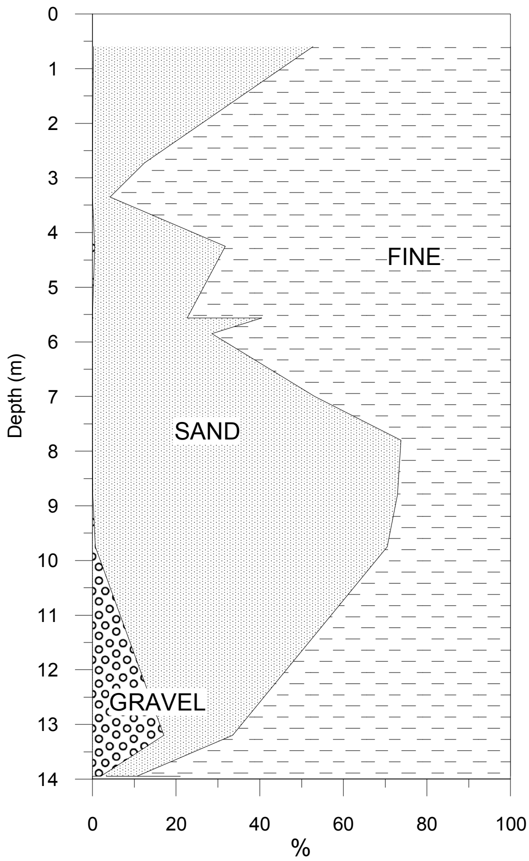

Figure 2 Grain size distribution with depth

3 RESULTS

3.1 *Instrument performance*

The configuration of the CPM employed in the tests has a smaller diameter in the pressuremeter unit than in the cone. The cone tip acts then as a friction reducer for the pressuremeter unit. This kind of arrangement should in principle lead to a more compliant initial response to probe expansion, more akin to a pre-bored installation. Indeed a reduction on lift-off stress has sometimes been recorded (O'Neill, 1985) but other results are more inconclusive (Anderson et al. 2005).

In the CPM tests performed, some curves showed the high initial stiffness that is typically associated with pushed installation, but others showed the typical shape of pre-bored instruments (test CPT1-CPM1 in Figure 3). Test location for both curve types is indicated on top of the corresponding cone tip resistance curves in Figure 4. Uncorrected q_c are shown because pore pressure readings were lost due to transducer malfunctioning. It is clear, however, that, with one exception, typical push-in curves appear in the clay levels and pre-bored shapes appear either within the granular levels or in their close vicinity. This suggests that the backflow of soil behind the tip enlargement is more effective when undrained penetration is taking place.

A lift-off stress could be estimated on most of the "typical" CPM loading curves, but there was no possibility of reading lift-off pressures in the "atypical" curves. The total horizontal stress thus deduced is compared with the value that follows from the K0 estimate of the DMT (Figure 5).

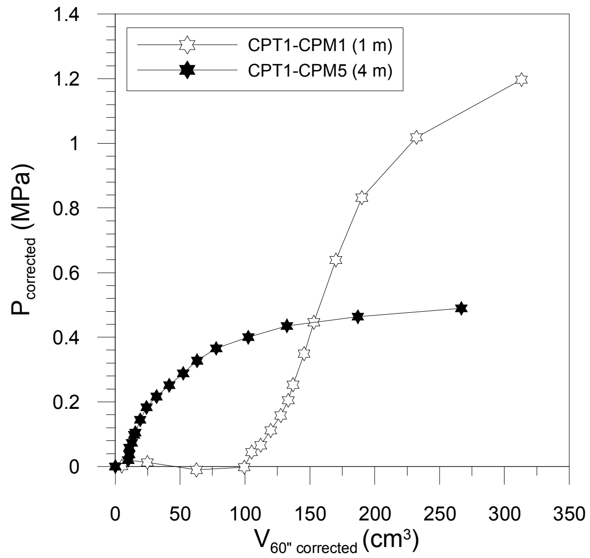

Figure 3 Example of raw expansion curves from CPM tests

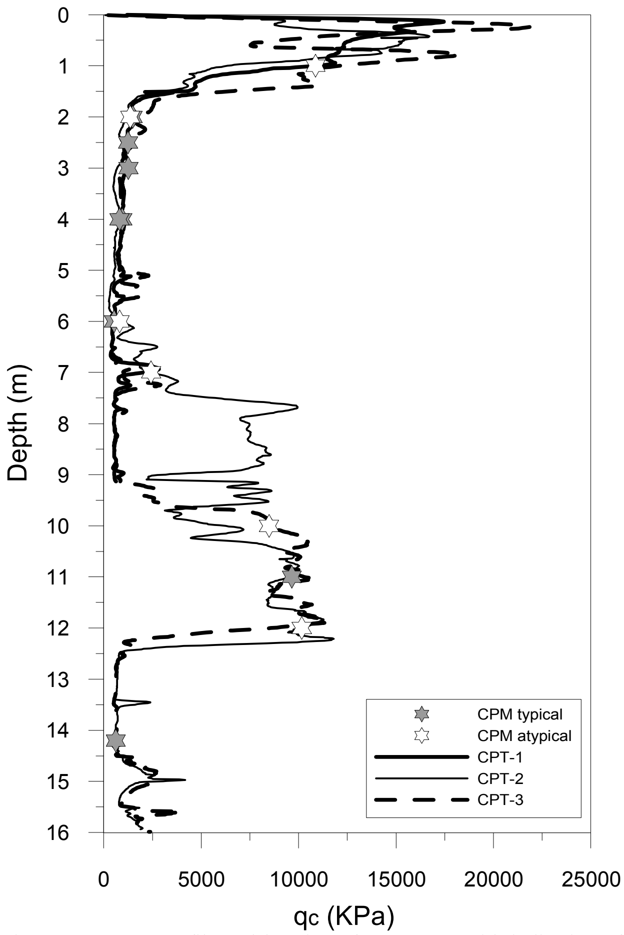

Figure 4 CPT qc profile and location of CPM tests with indication of curve shape

3.2 *Undrained shear strength*

Undrained strength values from triaxial CAUC (anisotropically consolidated undrained) tests, s_{uCAUC}, was available at two depths, one at the upper clay level and another at the lower one. Such values were employed to calibrate a local N_k cone factor,

$$N_k = \frac{(q_c - \sigma_{v0})}{s_{uCAUC}} \quad (1)$$

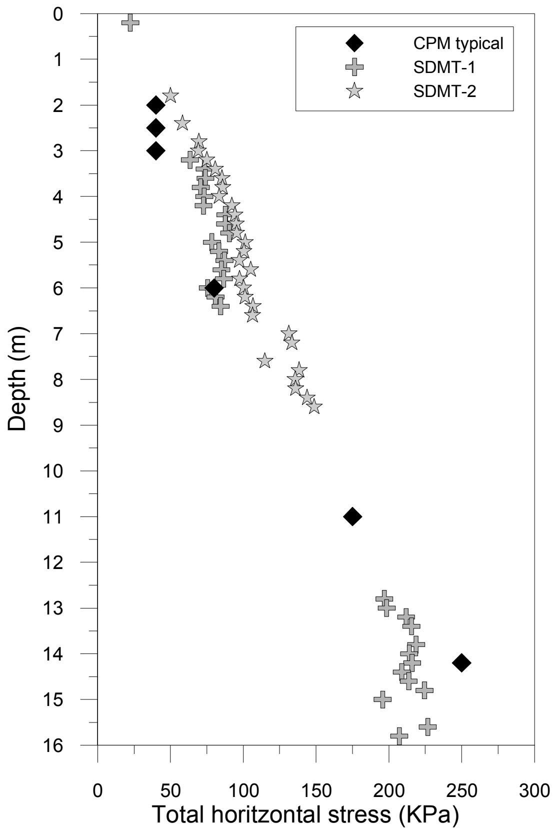

Figure 5 Horizontal stress estimates

The resulting cone factor (10 for the upper level and 5 for the lower level) was then applied to the different CPT q_c profiles to obtain estimates of undrained shear strength (Figure 6).

Undrained strength from the CPM, s_{uCPM} was obtained from the limit pressure and shear modulus deduced from the tests using the Marsland & Randolph (1977) iterative approach,

$$p_l - \sigma_{h0} = s_{uCPM}\left[1 + \ln\left(\frac{G}{s_{uCPM}}\right)\right] \quad (2)$$

In the formula the estimate of the total horizontal stress was, when available, that given by the CPM lift-off and, when that was missing, the one obtained from DMT. The results are shown in Figure 6, where also appear the estimates obtained following the same procedure from the pre-bored PRD and that from DMT. It appears that the CPM (and the DMT) estimates do match relatively well the profile based on the high quality triaxial CAUC results. A similar agreement between limit pressure based s_{uCPM} and high quality triaxial results had been observed by Powell & Shields (1995) at Bothkennar.

3.3 *Stiffness*

It has been repeatedly shown that stiffness deduced from unload-reload cycles on pressuremeters seems to be independent of installation method. However, it is also clear that cycling loads complicate and slow down the testing procedure.

To obtain a useful measure of stiffness from the CPM test we followed here a different approach. A secant modulus was obtained following the Menard procedure to select the elastic section of the loading curve. The cavity strain –deduced from the volumetric readings- at the middle of the secant modulus section was taken as representative of the CPM modulus. Cavity strain was then transformed into shear strain following a proposal by Jardine (1992). The secant modulus from the PRD cycles were similarly interpreted.

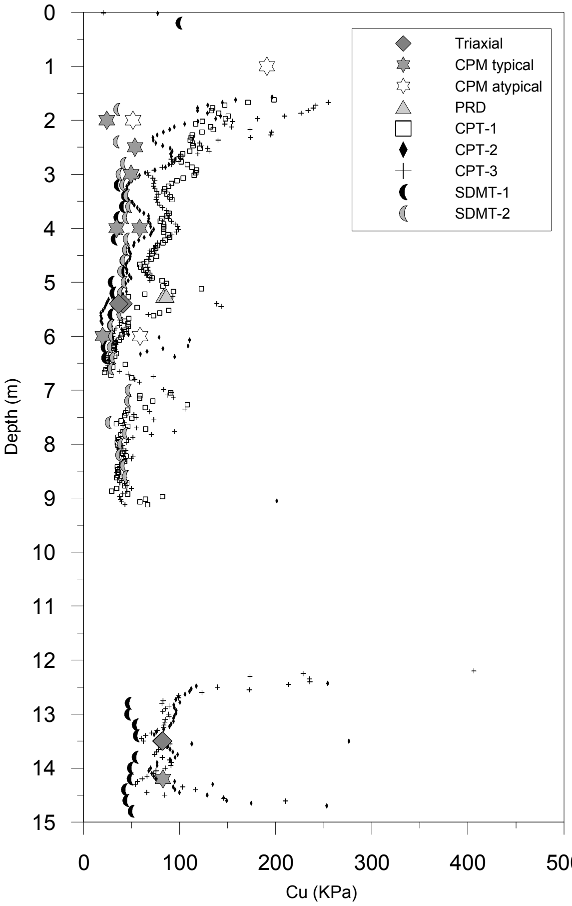

Figure 6 Undrained shear strength profiles

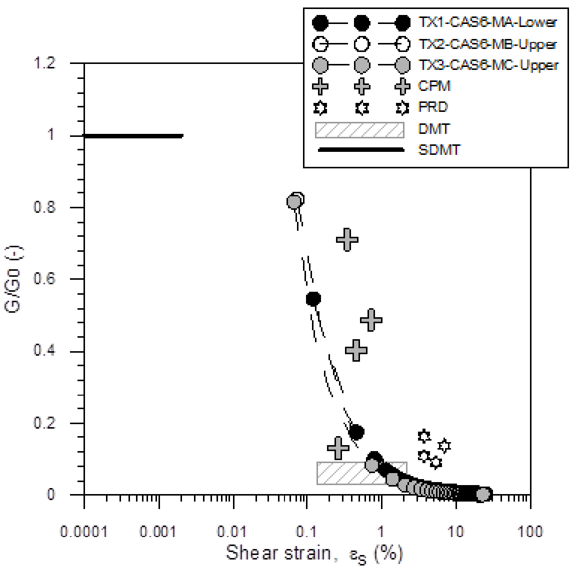

Figure 7 Modulus decay curves from the upper clay level (4-6 m depth). The G0 obtained from SDMT is 30 MPa

Normalised triaxial modulus decay curves obtained from the Sherbrooke samples of the upper clay level are presented in Figure 7. The normalising small strain stiffness was obtained from down-hole measures in SDMT. The normalised values corresponding to the CPM, PRD and DMT tests performed in the upper clay level at 4-6 m depth are also plotted. The strain range for the DMT is that suggested by Amoroso et al. (2012). The CPM modulus seems to cluster around the stiffness decay curve.

4 CONCLUSION

The CPM testing here exemplified used simplified procedures (standard Mènard-type loading) and equipment details (friction reducer). These simplifications did not seem detrimental for the quality of the test results in clay, where comparisons with other tests were favourable. In particular, the CPM deduced normalised modulus values followed closer the laboratory reference than those obtained from other in-situ tests.

5 ACKNOWLEDGEMENTS

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