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Comparison of cone pressuremeter data with results from other in-situ and laboratory tests

Comparaison des données du pressiomètre à cône avec des résultats de laboratoire et d'essais in-situ

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ABSTRACT: The Cone Pressuremeter tool allows determination of soil parameters using both piezo-cone penetration test data and pressuremeter test results. Various comparisons have been made of soil parameters determined from CPMTs and soil parameters determined from other in-situ tests and laboratory tests. The comparisons show that fundamental soil properties, such as shear modulus, undrained shear strength and relative density as well as Menard Pressuremeter type parameters can be reliably determined.

RESUME: Le pressiomètre à cône permet le détermination des paramètres du sol en utilisant les résultats de la pénétration du cône et ceux du pressiomètre. Après comparaison avec les résultats des essais in situ et des essais de laboratoire, il s'est avéré que les propriétés fondamentales d'un sol(module de cisaillement, résistance dans l'état non drainé, densité relative, et paramètres du pressiomètre de Ménard) peuvent être déterminées de façon fiable.

1 INTRODUCTION

A Cone Pressuremeter (CPM), sometimes referred to as a Full Displacement Pressuremeter, consists of a pressuremeter mounted behind an electrical piezo-cone penetrometer. This tool allows determination of soil parameters using both piezo-cone penetration test data and pressuremeter test results. Results with the first version of this tool, developed in the mid-eighties, proved that the fundamental soil properties, shear modulus, undrained shear strength and relative density, can reliably be determined. Recent results with this first type version of the CPM have been published by Powell and Shields (1995). The second, improved, version of this tool also provides Menard Pressuremeter type parameters due to the pressuremeter being recessed relative to the cone. A description of the equipment and test procedures can be found in Zuidberg and Post (1995).

In total some 500 tests have been performed world-wide with the latter Cone Pressuremeter. This paper describes experience obtained at four large soil investigation projects in The Netherlands. In total approximately 85 Cone Pressuremeter Tests (CPMT) were performed in sands, clays and peats. The CPT is always included in the CPM test. Other in-situ tests included Menard Pressuremeter Tests (MPMT), Seismic Piezocone Penetration Tests (SPCPT), Marchetti Dilatometer Tests (MDMT) and Vane Shear Tests (VST). In addition deformation and/or strength laboratory tests were performed on undisturbed soil samples.

This paper gives various comparisons of soil parameters determined from CPMTs and soil parameters determined from other in-situ tests and laboratory tests on sands and clays. Menard type parameters from the MPM are compared with those obtained with the CPM.

Due to the commercial nature of the projects of which the data are presented herein, the comparison of the CPM data with other tests has never been dominant in the project design. Unfortunately this has led to a limited amount of available data, both for comparison with other in-situ devices and for comparison with laboratory tests. The selected sites, for which the comparisons were made, showed a large horizontal and vertical variation in soil type and consolidation history, as is common in the Netherlands. These circumstances are not ideal for data comparison, but are nevertheless representative for the geotechnical design practice.

2 TEST RESULTS

Factual data of CPMTs are presented as curves of inflation pressure versus volume. Volume (in ml) represents the volume added to the membrane initial volume and is measured at the ground surface. Pressure represents the net membrane inflation pressure, measured at probe level. Net pressure means that the membrane resistance was subtracted from the pressure measured inside the membrane. CPM testing and interpretation is divided into two categories:

1. Routine testing and interpretation includes determination of the following basic parameters:
   - Limit pressure (ψ_l)
   - Shear modulus (G_{UR}) in three unload-reload loops, with a constant volumetric strain amplitude
   - Menard modulus (E_{Menard})
   - Undrained shear strength (c_u) in clays
2. Advanced parameter determination may include:
   - Relative density (D_R), horizontal effective stress (σ_{h0}') and friction angle (φ) in sands
   - "Mass" shear modulus (G), as defined in Houlsby and Withers (1988), and horizontal stress (σ_{h0}) in clays
   - Shear modulus (G_{UR}) in multiple unload-reload loops, with variable volumetric strain amplitude to assess the influence of strain amplitude
   - Determination of G_{UR} as a function of stress level

The above soil parameters are determined by the following CPM interpretation methods:

- Various definitions of pressuremeter limit pressure exist. In accordance with common French practice the CPM limit pressure is defined as the pressure at 700 ml. inflation. This coincides approximately with a mid-height radius increase of 50% or a volume increase of 100%. It is noted that the determination of the CPM limit pressure does not require any extrapolation, since the applied (maximum) inflation is also 700 ml.
- Shear modulus is determined in the conventional manner from pressuremeter unload-reload loops (see e.g. Houlsby and Schnaid, 1994). The Menard modulus (E_{Menard}) is determined from the shear modulus in the initial semi-elastic part of the inflation curve. Both moduli are corrected for system compliance.
- Undrained shear strength for clays is determined from the unloading curve, following the Houlsby and Withers (1988) method. According to this method the slope of the unloading curve, plotted on a double logarithmic scale, is directly related

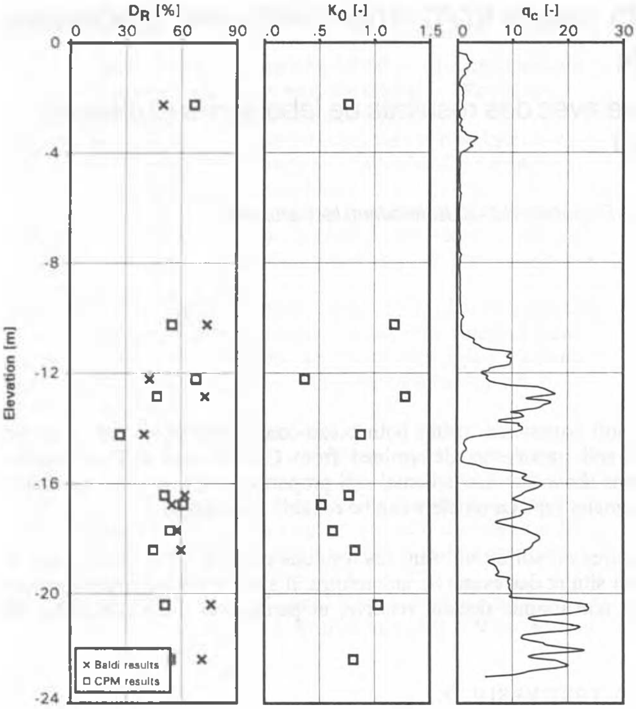

Figure 1. Example CPT profile, interpreted relative density (D_R) from CPMT and from CPT (Ref. Baldi et al., 1986), and coefficient of horizontal earth pressure at rest (K_0)

to the undrained shear strength (c_u). The Houlsby and Withers (1988) analytical model for clays allows determination of horizontal stress and shear modulus. However no satisfactory results have been obtained to date. Powell and Shields (1995) describe some success using this method with the previous version of the CPM.

- For determining horizontal stress (σ_{h0}') and relative density (D_R) in sands the empirical methods described by Schnaid and Houlsby (1992) can be applied. In this method horizontal stress and relative density are empirically correlated with cone resistance and limit pressure, based on calibration chamber tests. It is noted that a representative cone resistance, q_c, is difficult to assess in highly variable soil profiles. An example of thus determined D_R values and coefficients of horizontal earth pressure at rest, K_0, is given in Figure 1 (where σ_{h0}' was converted to K_0)
- The large stress increase during the CPM test is usually not representative for the stress increase that will be caused by a future structure. The measured G_{UR} can be converted to a G_{UR} which is representative for the in-situ stress level, or for any other future stress level, following the Houlsby and Schnaid (1994) method, as will be described in Section 3.2.

3 COMPARISON WITH OTHER IN-SITU MEASUREMENTS

The following subsections describe several comparisons of soil parameters determined using the CPM and other in-situ testing devices.

3.1 *Marchetti Dilatometer (MDMT)*

The (secant) Young's modulus at 50% of the peak deviatoric stress in a triaxial compression test, E_{50}, can be estimated from dilatometer tests and from pressuremeter tests. For the MPM and the CPM this parameter can be obtained from E_{Menard} according to:

$$E_{50} = \frac{E_{Menard}}{\alpha_0}$$

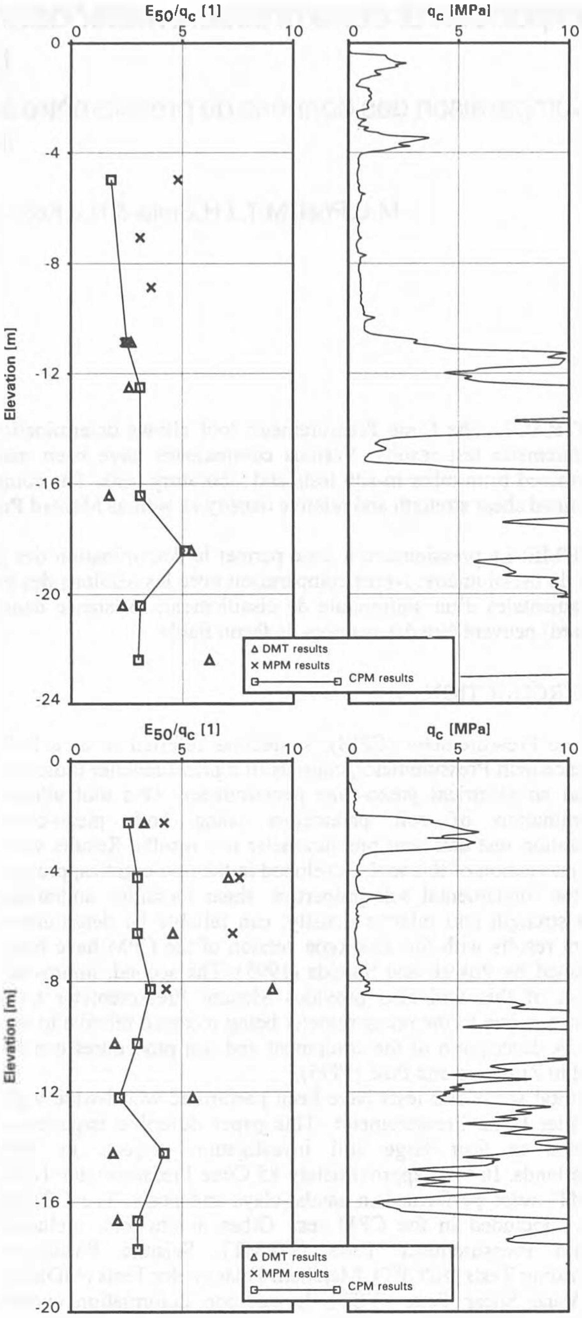

Figure 2. Example CPT profile and comparison of E_{50}/q_c from CPMT, from MDMT and from MPMT (two adjoining sites)

Where:

E_{Menard} = Menard modulus

α_0 = rheological coefficient, depending on soil type and overconsolidation

The E_{50}/q_c ratio from above in-situ tests was selected for comparison to reduce scatter caused by varying soil stratigraphy at two companion investigation locations. The E_{50}/q_c ratios from CPM tests, presented in Figure 2, range from about 2 to about 4, in both sand and clay. The E_{50}/q_c ratios based on the MPMT and the MDMT show a wider scatter, with values up to 8.

3.2 *Seismic Piezo-cone Penetrometer (SPCPT)*

The CPM shear moduli, determined from unload-reload loops (G_{UR}), can be compared with shear moduli determined from other

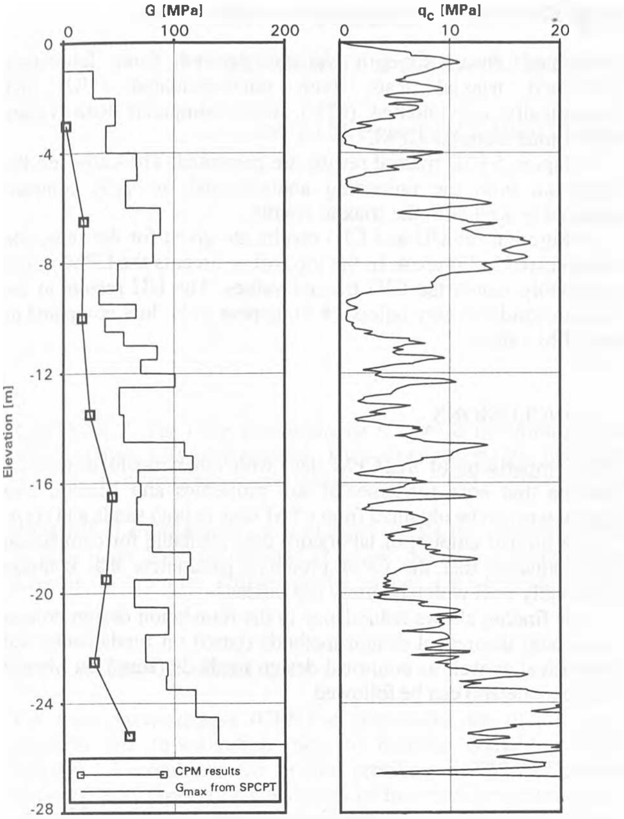

Figure 3. Example CPT profile and interpreted shear moduli (G) from SPCPT and CPMT unload-reload loops

tests. To enable a direct comparison, consideration must be given to the stress and strain levels at which the individual shear moduli were determined. The SPCPT produces shear wave velocity profiles, which can be converted to G_{max}, the shear modulus at very small strains. The SPCPT shear moduli are applicable for in-situ stress conditions. However the CPM unload-reload loops are performed at higher stress and strain levels, due to the CPM installation and subsequent inflation. To convert the shear moduli from CPM unload-reload loops to the values applicable for in-situ stress level, the following correlation was used:

$$\frac{G_{CPM}}{p_a} = K_G \cdot \left(\frac{p'}{p_a}\right)^n$$

Where:

G_{CPM} = shear modulus from CPM unload-reload loops converted to in-situ stress level

p' = average stress during the unload-reload loop, typically 0.50 times the CPM inflation pressure (Ref. Nutt, 1993)

p_a = atmosphere pressure

n = modulus exponent, typically 0.6 (Ref. Houlsby and Schnaid, 1994)

K_G = modulus number. This value has no influence on the extrapolation of shear modulus to other stress levels

Figure 3 shows a CPT profile, the interpreted G_{max}-profile from the SPCPT, and the interpreted corrected shear moduli from the CPM unload-reload loops (G_{CPM}), reduced to estimated average in-situ effective stress. The average G_{CPM} value from three unload-reload loops is plotted at each depth. The average ratio G_{CPM}/G_{max} is about 0.42 (range 0.21 to 0.64), which compares reasonably well with values reported by Houlsby and Schnaid (1994). The average ratio G_{CPM}/q_c is about 3.6 (range 2.0 to 5.5. This compares reasonably well with the ratio G_{SBPM}/q_c of 3.8 ± 0.85, reported by Jamiolkowski et al. (1985), for Selfboring Pressuremeter Tests in medium dense to dense sand.

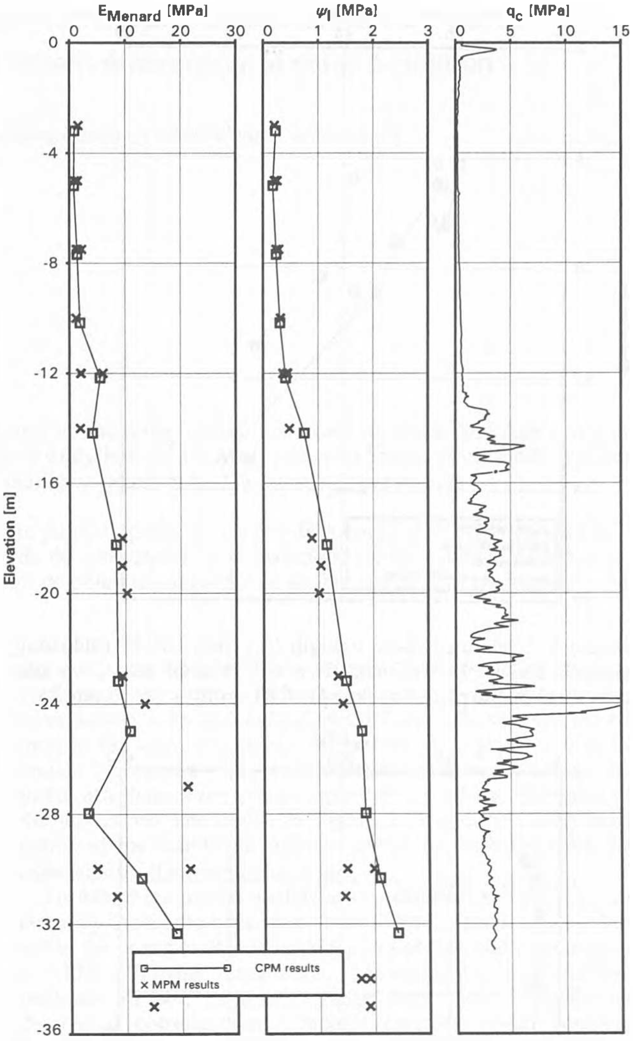

Figure 4. Example CPT profile and limit pressure (ψ_l) and Menard Modulus (E_{Menard}) from MPMT and CPMT

3.3 *Menard Pressuremeter (MPMT)*

The Menard parameters limit pressure and Menard modulus were derived from the CPM and from a predrilled MPM. Both sets of parameters from CPM tests compare well to those from MPM tests, as can be observed in the example presented in Figure 4.

Disturbance due to CPM installation apparently does not influence Menard parameters more than the installation of a MPM in a predrilled hole for this example. However, a poor agreement was obtained in the E_{50} stiffness values in clay for the test data presented in Figure 2. It is noted that the MPM tests presented in Figure 2 and in Figure 4 were performed by different companies.

3.4 *In-situ Vane Shear Test (VST)*

The VST is used to determine undrained shear strength (c_u) in clays. The VST based values are compared with other c_u estimates at two adjacent sites in Figure 5. Other data for the same sites are presented in Figure 2. The VST data however appear to be high in comparison to the CPM values and the triaxial values. Application of a correction factor, as suggested by Aas et al. (1986), reduces the VST c_u values. The correction factor ranges from about 1.0 to about 0.4, depending on plasticity index and overconsolidation ratio. For the VST c_u values presented in Figure 5 a correction factor of about 0.5 is applicable for the test at 5 m., reducing to about 0.7 for the test at 14 m. Thus reduced VST c_u values are similar to the CPM based c_u values.

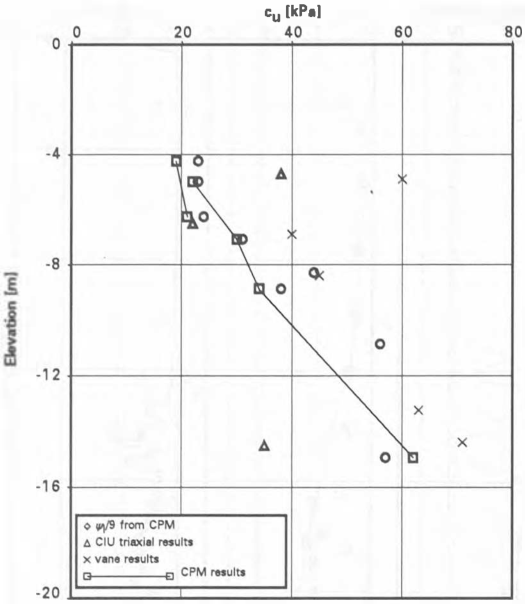

Figure 5. Undrained shear strength (c_u) from CPMT (unloading analysis and $\psi_l/9$), VST and from CIU triaxial tests (two sites combined in one plate, for example CPT profiles, see Figure 2)

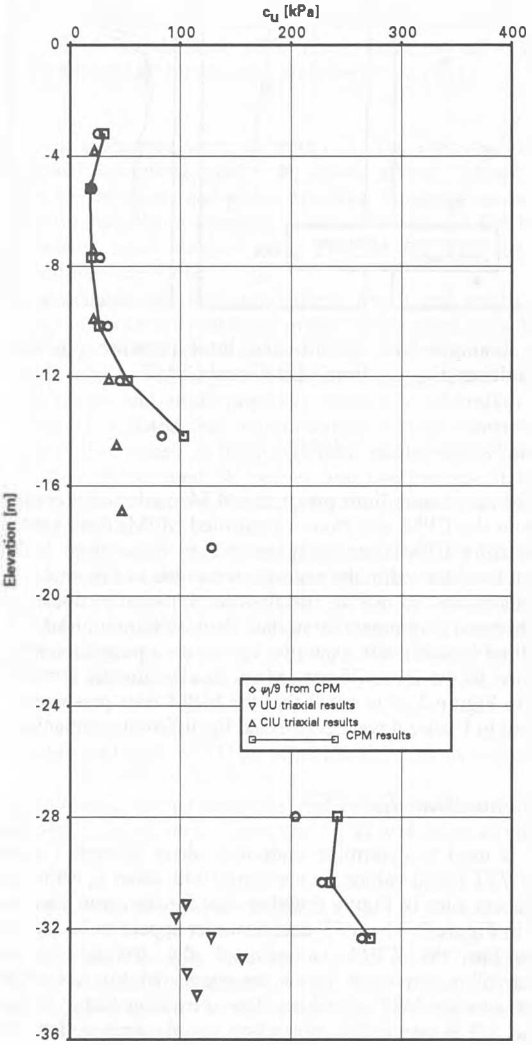

Figure 6. Undrained shear strength (c_u) from CPMT (unloading analysis and $\psi_l/9$) and from CIU and UU triaxial tests (for example CPT profile, see Figure 4)

4 COMPARISON WITH LABORATORY TESTS

Undrained shear strength values, derived from laboratory undrained triaxial tests, both unconsolidated (UU) and isotropically consolidated (CIU), were compared with values determined from the CPM.

In Figure 5 CIU triaxial results are presented. The CPM results, based on both the unloading analysis and on $\psi_l/9$, compare reasonably well with the triaxial results.

In Figure 6 the UU and CIU results are given for the same site as presented in Figure 4. In the top soft sediments the CPM values reasonably match the CIU triaxial values. The UU results in the overconsolidated clay below 28 m. appear to be low compared to the CPM values.

5 CONCLUSIONS

The comparisons of the CPM data with other in-situ test results indicate that both fundamental soil properties and Menard type parameters can be obtained from CPM tests in both sands and clays.

The limited amount of laboratory data available for comparison also indicates that the CPM produces parameters that compare reasonably well with laboratory test values.

This finding allows redundancy in the foundation design process since both theoretical design methods (based on fundamental soil properties) as well as empirical design methods (based on Menard type parameters) can be followed.

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