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Application of cyclic pressuremeter tests to evaluate soil liquefaction

Application des essais cycliques au pressiomètre pour évaluer la liquéfaction des sols

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ABSTRACT: This paper presents an application of cyclic expansion tests carried out with the pressuremeter at various experimentation sites in France. These cyclic tests were performed using the pre-bored Ménard pressuremeter and the Cambridge self-boring pressuremeter. Two sites were particularly studied consisting of normally consolidated sandy and silty soils. These unique pressuremeter tests, interpreted in terms of deformation (volume change or radial strain) and number of cycles, made it possible to draw relationships as a function of the cyclic shear ratio. New procedures and technologies were also developped to improve the quality of these tests. The interpretation was compared to a database which allowed the results to be used to develop charts for liquefaction prediction. This article presents a summary of the analysis and application of these tests.

RÉSUMÉ:
Cette communication présente une application des essais d'expansion cycliques réalisés avec le pressiomètre sur différents sites expérimentaux. Ces tests cycliques ont été réalisés à l'aide du pressiomètre Menard préforé et du pressiomètre autoforeur. Deux sites ont été plus particulièrement étudiés composés de sols sableux et silteux à l'état normalement consolidé. Une interprétation en déformation volumique et radiale et en nombre de cycle permet de tracer des courbes en fonction du rapport de cisaillement cyclique. Cette interprétation est appliquée à une base de données riche et étendue. Les résultats de ces tests de haute qualité permet de proposer des abaques pour la prédiction de la liquéfaction. Cet article présente une synthèse de l'analyse des différents résultats dans ce cadre.

Keywords: clays, swelling pressure, laboratory testing, soil-structure interaction

1 INTRODUCTION

The Ménard pressuremeter test equipment used in this project allows operators to achieve monotonic expansion tests (EN ISO 22476-4 similar to ASTM D4719) and cyclic tests (NF P94-110-2) (ASTM, 2004 and AFNOR, 2000). These tests include an unload-reload cycle performed in steps, in the same conditions as the Ménard pressuremeter test described in the EN ISO 22476-4 standard.

The interest of achieving several cycles, i.e. unload-reload loops with the pressuremeter to obtain small strain modulus values, appeared very early (Ménard, 1960). However, a single cycle is insufficient to identify the evolution of soil characteristics under cyclic loading (Dupla and Canou, 2003). With a sufficient number of cycles it is possible to observe volume or pore pressure increase to identify failure representative of liquefaction. The present study, conducted as part of the national project ARSCOP (see the website for more information www.arscop.org) was an opportunity to perform multi-cycle tests with a probe inserted into a pre-drilled hole or by self-boring technique.

2 TEST PRINCIPLE

The principle of the expansion test is to measure changes in the volume injected during the application of pressure cycles. The cavity expansion cyclic tests can be performed with a pressuremeter probe inserted in the ground by self-boring or in a pre-bored hole.

2.1 Equipment

The equipment used in this project was developed by Jean Lutz SA (Figure 1).A pressure volume controller (CPV) (PREVO type), controls solenoid valves using a PC computer via a specific application program. Measuring the change in volume during probe expansion is done either by measuring the volume of water injected or by measuring the movement of a feeler probe.

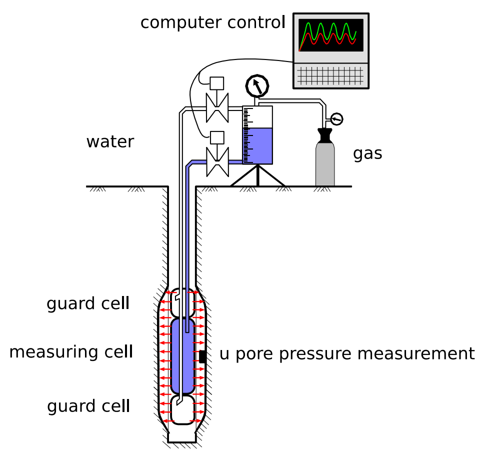

Figure 1. Schematic of the cyclic Ménard pressuremeter test

These operations are carried out automatically either directly on the CPV or by the software program. The cyclic control is performed on the basis of a test file modifyable with any type of signal, harmonic or multiple frequencies. The monitoring is done in real time on a datalogger.

2.2 Test Method

One specific type of tests was carried out; cyclic loading test between two pressure limits

p_M and p_m, the lower bound kept greater than the earth pressure at-rest p_o (Figure 2).

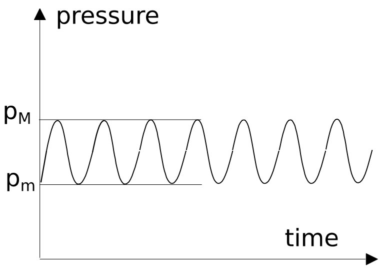

Figure 2. Cyclic portion of the pressuremeter test

The parameters used for the cyclic tests described above consisted in carrying out the test in pressure controlled mode and adapting the frequency to the type of soil in an attempt to remain undrained using a predefined stress level, a frequency varying from 0.01 to 0.05 Hz and a number of cycles equal to 50.

The initial pressure p_m used to start the cyclic portion of the test is defined as the horizontal stress not lower than the earth pressure at-rest (effective preferably) and the maximum pressure p_M fixed to obtain a specific stress ratio (Dupla and Canou, 2003). The pressure p_m was estimated from previous Ménard type expansion test results by the method proposed by Briaud (1992).

The Cyclic Stress Ratio (CSR), conventionnally defined as the ratio of the simple amplitude reported to twice the consolidation stress, σ'_c, is shown below:

$$CSR = \frac{\delta q}{2 \cdot \sigma'_c}$$

The rupture is generally defined as either the achievement of the liquefaction state ($\Delta u = \sigma'_{3c}$), or of an axial deformation of 5% in double amplitude reached in 20 cycles (Ishihara, 1993).

As presented on figure 3, tests are carried out at pressure amplitude, and the CSR evolution curves are plotted against the number of N cycles.

Figure 4 presents the results of a serie of tests performed under the Duchesse Anne dyke close to the Mont Saint Michel (France). The results show the increase of volume accumulation with pressure amplitude.

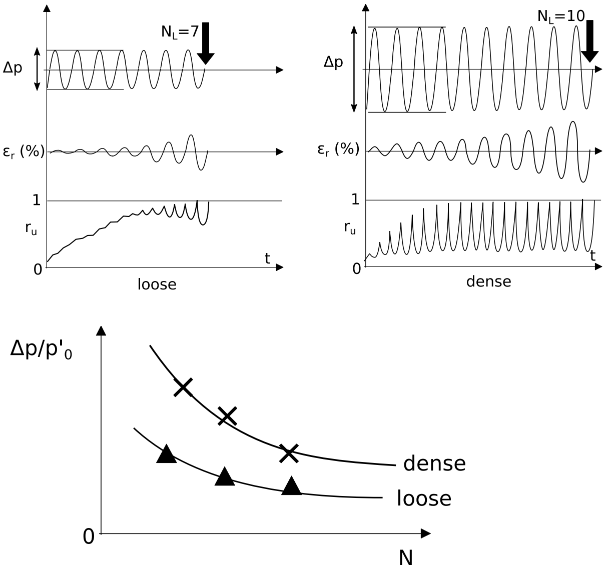

Figure 3 Cyclic behavior and CSR concept

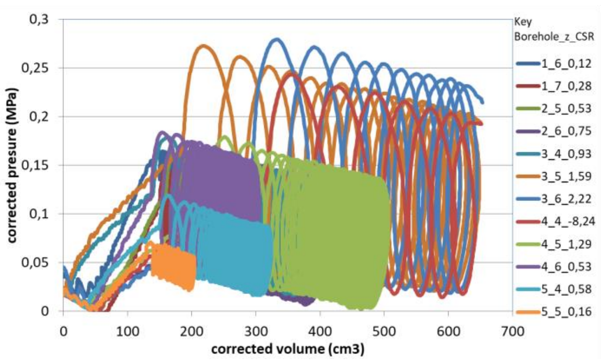

Figure 4 Cyclic tests performed using a probe with rubber and canvas cover (depths in meters)

The volumetric strain is derived from the volume measured during the pressuremeter expansion. The shape of the expanded membrane is essentially cylindrical where:

$$\varepsilon_V = \frac{\Delta V}{V_0} = \frac{V - V_0}{V_0}$$

V = measured cavity volume during the test

V_0= initial cavity volume

The volumetric strain, ε_V is converted into radial strain ε_r, and vice versa using elastic theory:

$$\varepsilon_V = (1 + \varepsilon_r)^2 - 1$$

Figure 5 shows the increase of this calculated radial strain with the amplitude of pressure.

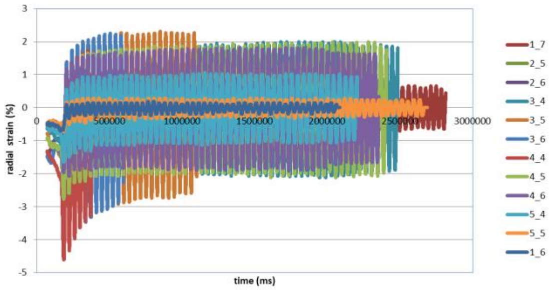

Figure 5 Radial strain as a function of pressure cycles (depth shown in meters)

Figure 6 presents the number of cycle to the conventional failure according to CSR.

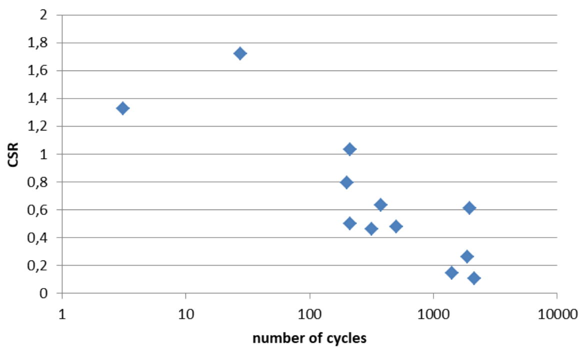

Figure 6 CSR evolution for a probe with a geotextile reinforced rubber cover

2.3 *Influence factor*

The use of a slotted tube is a common practice in France which protects the membrane against sharp particles. However it generates a higher inertia due to the resistance of the slotted tube necessiting a correction two time higher than the standard outer flexible cover.

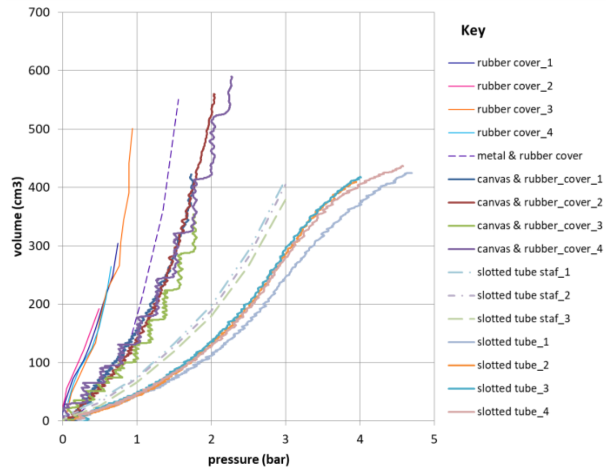

Figure 7 Correction curves for different membrane cover systems

Figure 8 shows the influence of these corrections on the cyclic pressure range applied on the soil.

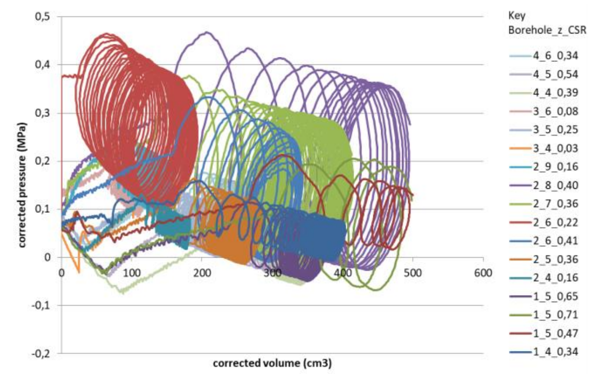

Figure 8 Cyclic tests performed using a probe with slotted tube

Due to this pressure loss generated during expansion, the amplitude of pressure decrease by a higher value.

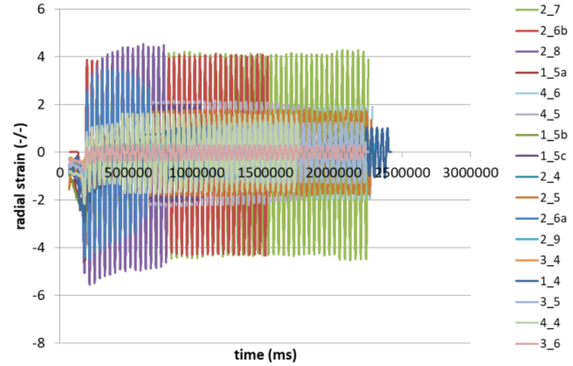

Figure 9 Radial strain for a probe with slotted tube

A comparable decrease of CSR is observed (figure 10)

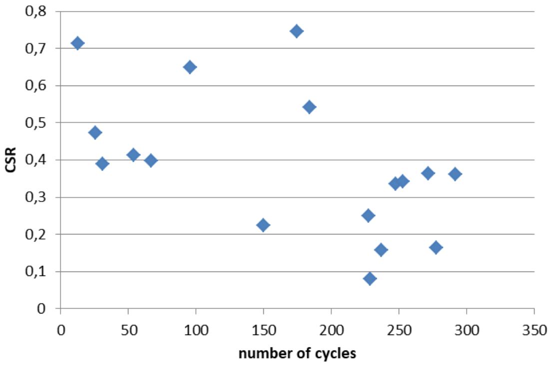

Figure 10 CSR evolution for a probe with slotted tube

2.4 *Membrane correction*

As presented previously the membrane correction is an important influence factor. The pressure loss correction accounts for the increase of resistance due to membrane expansion (CEN, 2004).

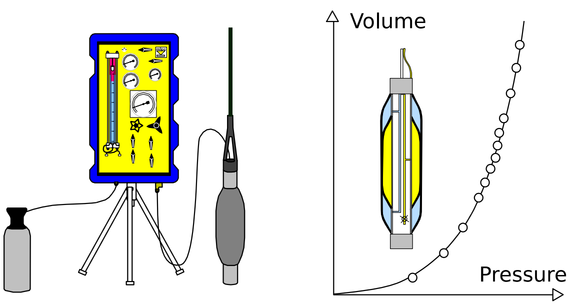

Figure 11 Membrane calibration

When cycling between two pressures due to volume increase, the pressures applied to the soil decrease. During the test, appropriate membrane inertia correction curves such as those shown on Figures 7 and 11 are applied automatically resulting in corrected curve similar to that of Figure 12.

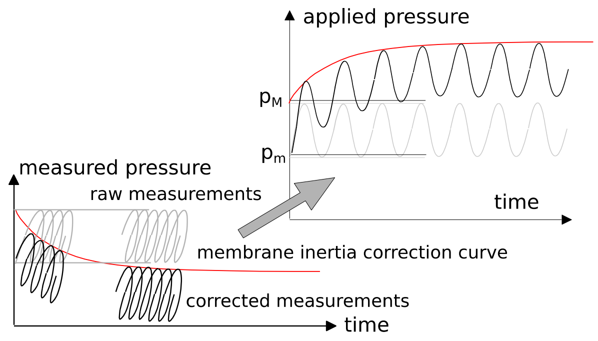

Figure 12 Loading pressuremeter test program to account for membrane stiffness

Figure 13 shows how this correction is used to maintain a constant pressure amplitude . The signal applied to the soil stays between two constant pressures.

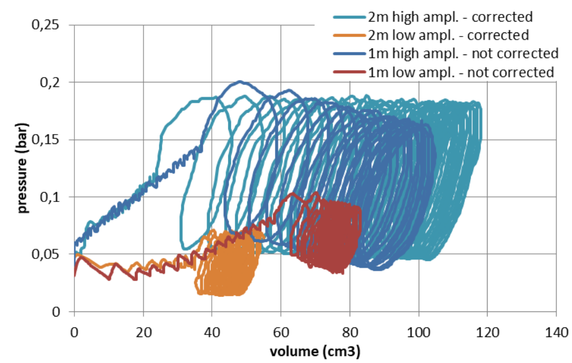

Figure 13 Comparison of test results with corrected loading program

3 PORE PRESSURE MEASUREMENT

When studied in laboratory, it is observed that soil liquefaction initiates when the value of the pore pressure has increased to equal the value of confining pressure, that is to say when the effective stress is zero.

Consequently, it is important to measure pore pressures during cyclic expansion in order to estimate the liquefaction potential of soils with fines.

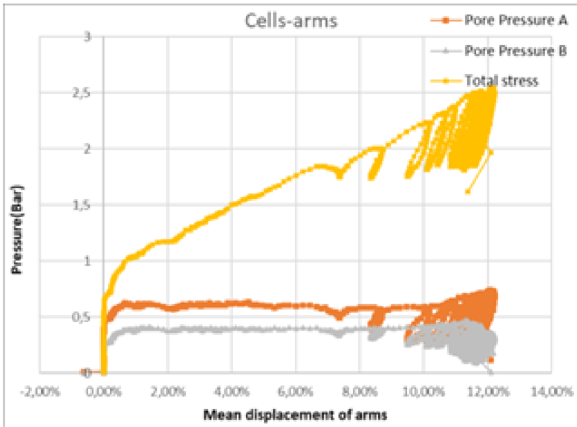

Figure 14 Measure of pore pressure in self-boring pressuremeter tests

Figure 14 shows the type of pore pressure measurement that can be obtained from a self-boring cyclic pressuremeter test in a marine clay in Newington, New-Hampshire USA. The probe was equipped with two pore pressure transducers fixed on the membrane. Figure 15 shows a newly developed simple and robust transducer that can be fixed on the standard pressuremeter probe directly on the membrane. The first prototype tests were done in Le Sillon dyke in the city of Saint Malo (France)

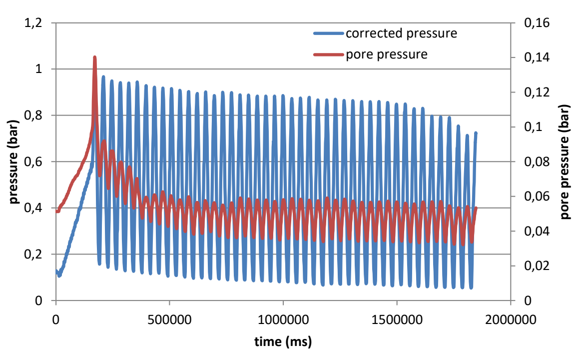

Figure 15 Measure of pore pressure in prebored pressuremeter tests

The permeable sand allows the pore pressure to dissipate rapidly. These first test results are promising and a serie of tests are planned on other sites previously investigated but with soils containing a significant amount of fines.

CONCLUSIONS

This paper has demonstrated the ability of prebored pressuremeter tests to apply a high number of cyclic loads. The membrane correction was determined to be a significant influence factor and a solution was proposed to account for the pressure loss during testing. The first tests have shown the ability to keep constant the pressures defining the cycles.

Once the pressures bracketing the pressure range applied to the soil are kept constant the addition of pore pressure measurements offer new potential insight on the influence of fine content on pore pressure development in soils in their initial state (Briaud, 2013).

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