Numerical analysis of a cyclic pressuremeter test

R. Bahar
Université des Sciences et de la Technologie Houari Boumediene, LGEA-LEEGO, Algeria

O. Belhassani
Université Mouloud Mammeri de Tizi-Ouzou, Laboratoire de Géomatériaux, Environnement et Aménagement, Algeria

SUMMARY:
The paper presents a numerical modelling of a cyclic pressuremeter test using FLAC software. A monotonic pressuremeter test is modelled in the first step. In the second step a cyclic pressuremeter test is modeled taking into account the Strain Hardening/Softening model (SS). A sensitivity study is carried out in order to understand the influence of the model parameters on the numerical response of cyclic pressuremeter path. A comparison between experimental and numerical results shows that the cyclic pressuremeter test allows gaining valuable information on the cyclic behaviour of the soil.

Keywords: Soil, pressuremeter, cyclic, behaviour, numerical

1. INTRODUCTION

It is generally accepted that in situ tests offer one of the best means of determining the engineering soil properties. A pressuremeter test is one of the most promising procedures among in situ tests because of its defined boundary conditions (Baguelin et al., 1978; Briaud, 1992), its potential ability to measure the initial in situ horizontal stress. It has also an advantage to provide in the case of a monotonic expansion, a stress strain relationship of soil, which is very rich of information, essential quantities for design and analysis. The design of foundations based on a pressuremeter test results can using pressuremeter rules that require soil parameters such as the limit pressure and the deformation modulus, or indirectly to determinate soil intrinsic parameters. These parameters are affected by a soil remoulding or a disturbance which occurs during installation.

From pressuremeter testing observations, it appears that the modulus derived from an unload-reload cycle is representative of the in situ initial tangent modulus. Several studies have shown that the unloading portion of pressuremeter tests appears to be insensitive to disturbance caused by installation. It would, therefore, appear useful to incorporate the unloading portion of pressuremeter tests into any interpretation technique. For these reasons, the analysis of the unloading phase of the pressuremeter test has received attention by many researchers (Jefferies, 1988; Ferreira et al., 1992). They proposed analyses taking into account the unloading phase of a pressuremeter test. Other researchers have developed a cyclic pressuremeter test, it is found to be effective, because its insensitivity to disturbances in cavity wall, and applicability to wide range of strain (Yutaka et al., 1995). The cyclic test should also allow gaining valuable information on the cyclic behaviour of the soil, which is very important to examine the stability of structures during earthquakes or wave loading.

This paper presents a numerical analysis of a cyclic pressuremeter test. This study constitutes a first step in the development of methods aimed at evaluating parameters characterizing the cyclic behaviour of soils, based on an analysis of the results of a cyclic pressuremeter test. The analysis is performed using the FLAC program taking into account the Strain Hardening/Softening model (SS model). A sensitivity study is carried out in order to understand the influence of the SS model parameters on the numerical response of a cyclic pressuremeter path.

2. PRESSUREMETER TESTS

Cyclic pressuremeter tests were carried out at Cran site, in France (Fay t al., 1990; Soegiri, 1991). The site consists of normally consolidated, very plastic silty clay. The identification properties of the clay are given in Table 2.1. A typical monotonic self boring pressuremeter test results performed at this site are shown in Figure 2.1. Figure 2.2 shows an example of self boring pressuremeter test for 50 cycles with amplitude of 20 kPa corresponding to a volume variation of 5 to 6 cm^3. The enlarged diagram (see Fig. 2.3) shows the increase in deformation due to the cyclic loading between the second and the 50th cycles. It is clear there is appreciable successive movement from cycle to cycle.

Table 2.1. Results of laboratory tests at Cran site (Soegiri, 1991).

Depth (m)	γ_d (kN/m^3)	E (Mpa)	c_u (kPa)	c' (kPa)	φ' (°)	C_c
1.0 – 2.2	11.0	13	45	-	-	0.45
2.2 – 4.0	6.6	29	15	0.0	30	1.64
4.0 – 8.0	9.3	18	40	-	-	0.70
8.0 – 17.0	9.1	17	39	0.0	34	0.85

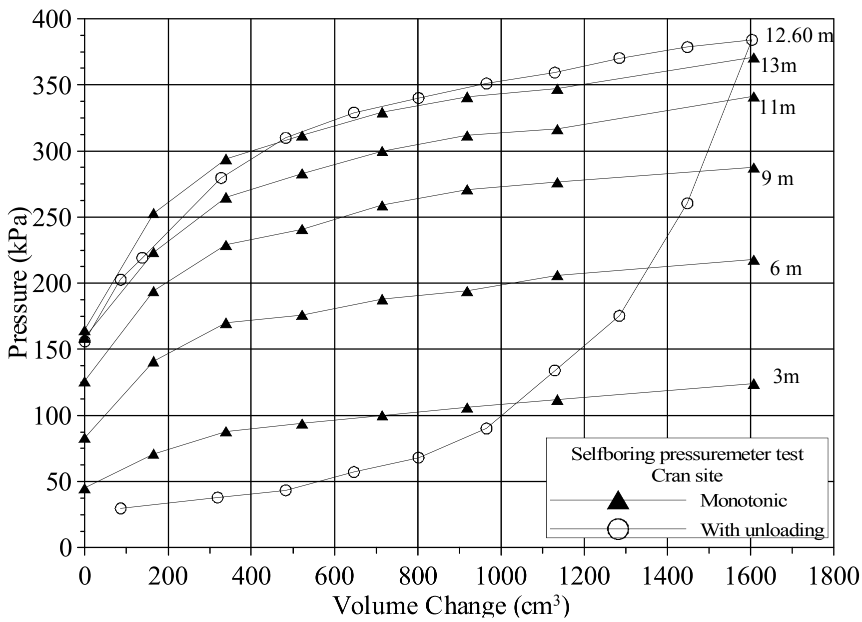


Figure 2.1. A typical monotonic and with unloading self boring pressuremeter test (Cambou et al., 1993).

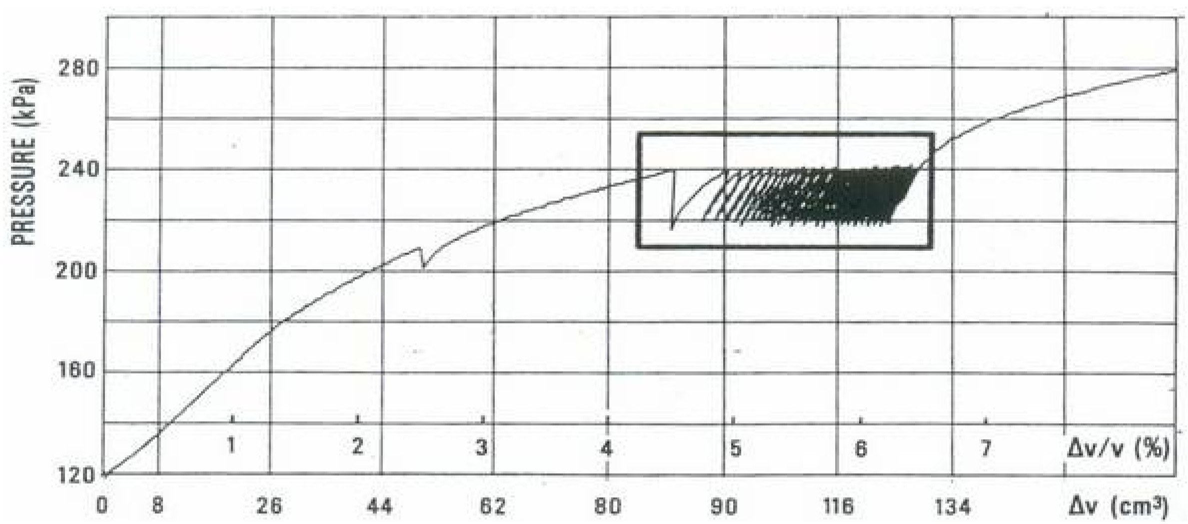


Figure 2.2. A cyclic pressuremeter test at Cran site, depth of 9.8 m (Fay et al., 1990).

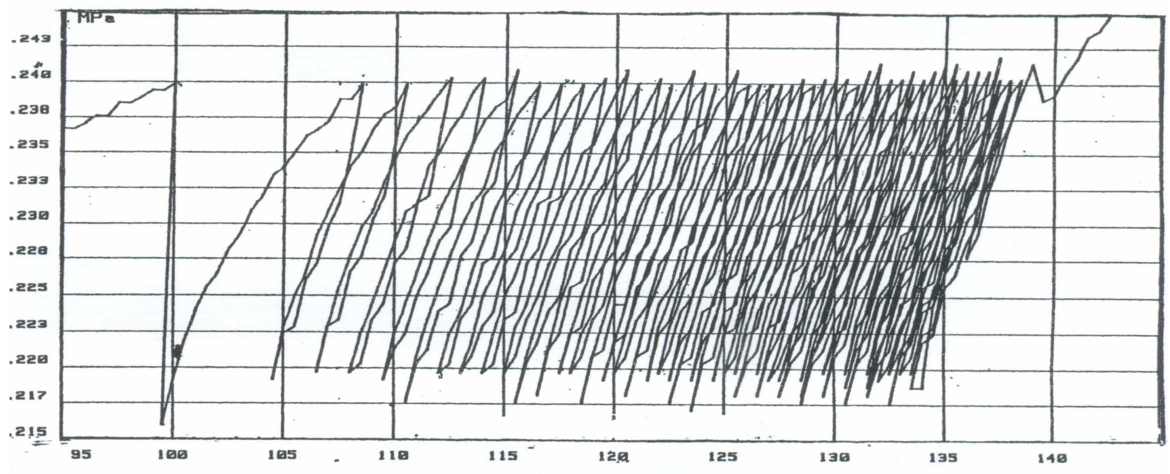


Figure 2.3. Enlarged cyclic pressuremeter test (Fay et al., 1990).

3. NUMERICAL ANALYSIS

The problem of the expansion of a cylindrical cavity in an ideally plastic infinite medium has been treated by several authors (Gibson et al., 1961; Ladanyi, 1972, Boubanga, 1990; Bahar, 1992; Monnet 2007). This is of great interest in geotechnical engineering because the analysis has some important applications such as the interpretation of in situ soil tests and predicting the state of stress in the ground around piles. In this analysis, the expansion is assumed to occur under conditions of plane strain and axial symmetry in a medium. The expansion of a pressuremeter probe in an elastoplastic soil is considered. The axisymmetry imposes that the stress increments in the directions r, θ and z are principal (see Fig. 3.1). The boundary conditions can be specified either in displacements or in stresses.

– *Along the wall cavity* $r = r_o$:

$$\Delta u_r = \Delta u_o \quad \text{or} \quad \Delta\sigma_r = \Delta p_o \qquad (3.1)$$

– At an infinite distance $r = r_\infty$:

$$\Delta u_r = 0 \quad \text{and} \quad \Delta\sigma_r = 0 \qquad (3.2)$$

where r_o is the initial borehole radius and u_o is the radial displacement at the cavity wall.

There are two concentric annular zones around the probe (see Fig. 3.1). The first one is bounded by a circle of radius r_e in which the material is subject to elasto-plastic straining ($r_0 < r < r_e$). The second one is located beyond r_e in which the material behaves elastically ($r > r_e$). The pressuremeter loading is then governed by the following equilibrium equation:

$$\frac{\partial\sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \qquad (3.3)$$

σ_r and σ_θ are the radial stress and the circumferential stress respectively.

Analyses are performed using a FLAC program allowing various constitutive laws to be used to simulate soil behaviour. The Strain Hardening/Softening model (SS model) is considered. This model is based on FLAC Mohr-Coulomb model with non associated shear and associated tension flow rules (FLAC, 2008). The difference lies the possibility that the cohesion, friction, dilation and tensile strength may harden or soften after the onset plastic yield. In the Mohr Coulomb model, those properties are assumed to remain constant. In the SS model the cohesion, friction and dilation can define as piecewise linear functions of a hardening parameter measuring the plastic shear strain. The yield and potential functions, plastic flow rules and stress corrections are identical to those of the Mohr Coulomb model. In the softening/hardening model, the cohesion, friction, dilation and tensile strength are defined as a function of the plastic portion, e^p, of the total strain. Examples of these functions are shown in Figure 3.2, and may approximated as sets of linear segments (FLAC, 2008).

Soil behavior around the probe is analyzed using two different discretizations. In the first, cavity expansion is modeled as an axisymmetric problem for a soil thickness unit (see Fig. 3.3a). The second has a bidimensionnal mesh, in axisymmetric conditions, to take account the real dimension of the probe (see Fig. 3.3b). The maximum radius is 4 m and the height of the mesh is taken equal to the length of the probe for the first discretization. This boundary is sufficient to simulate the infinite distance in the radial direction (Bahar et al., 1995). For the pressuremeter test simulations in soft clays, a typical value of the ratio r_∞/r_o equal to 30 is sufficient to model the condition of infinite medium. However, for sands or stiff clays this ratio has to be higher as reported by Bahar (1992). The size of the mesh domain in both radial and vertical directions is set to be sufficiently large so that the outside boundaries would have little influence on the numerical results. The mesh is designed so that the density of elements was greatest in regions of possible high stresses. This allows for the greater accuracy of a fine mesh where it is needed. Figure 3.4 shows a comparison between the results obtained from the two discretizations. This figure shows that the two discretizations produce the same pressuremeter curve. Then, for the following works, the first discretization is considered.

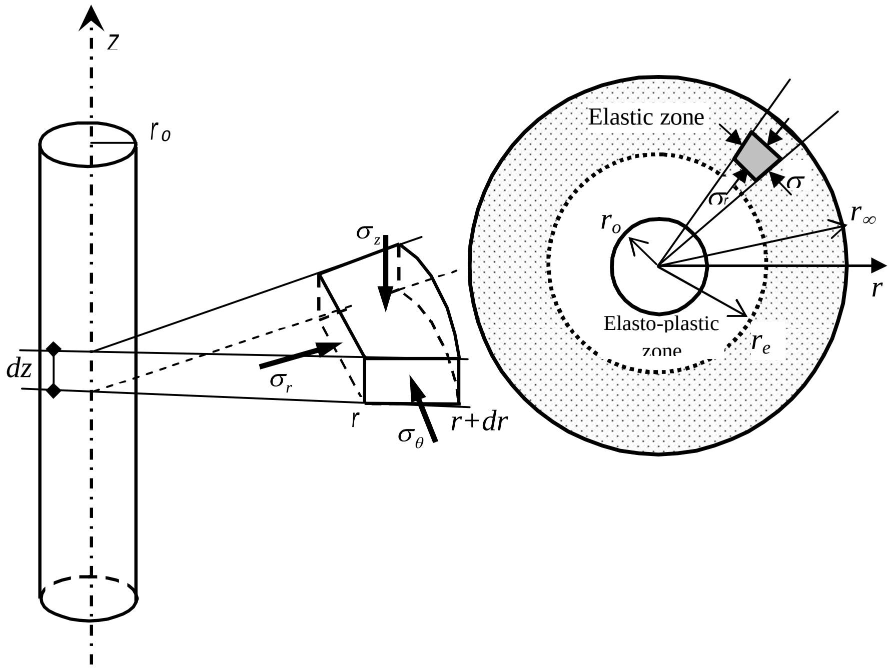


Figure 3.1. Equilibrium of a soil element around the pressuremeter probe.

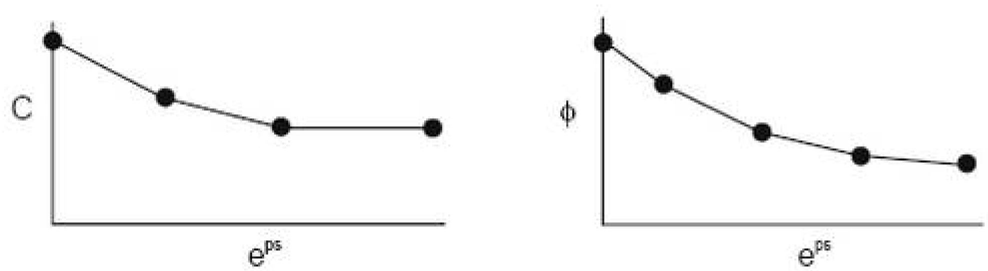
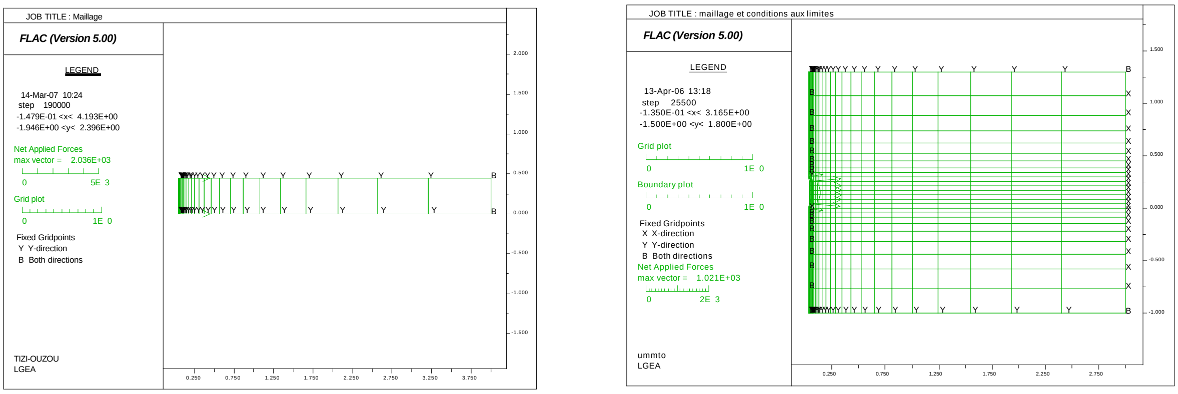


Figure 3.2. Variation of cohesion and friction with plastic strain (approximation by linear segments in FLAC).



a) b)

Figure 3.3. Model discretization: a) axisymmetric model of a soil thickness unit in vertical plane, b) bidimensionnal model with axisymmetric conditions in vertical plane.

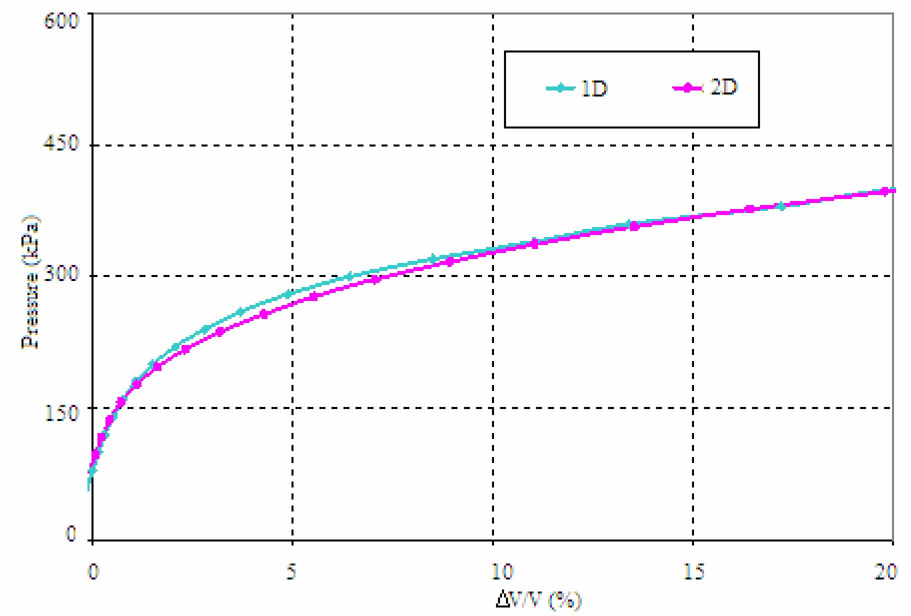


Figure 3.4. Comparison between an axisymmetric problem for a soil thickness unit and bidimensionnal mesh.

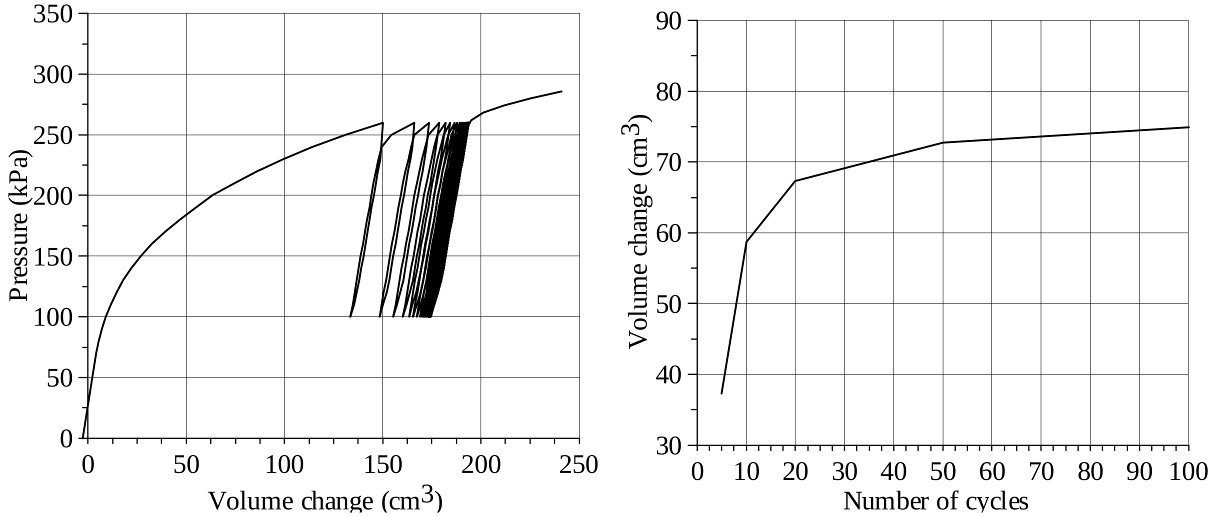
4. NUMERICAL ANALYSIS OF A CYCLIC PRESSUREMETER TEST

Figure 4.1a shows the results of pressuremeter test simulation with several cycles of unloading-reloading. The first observation from these results is that after a number of cycles, they tend to be closed on them, but they continue to move in the direction of increasing deformations. Figure 4.1b shows the volume variation with the number of cycles. Among the parameters which can be drawn from a cyclic test, the most significant are the tangent and secant cyclic deformation modulus, G_{PN}, G_{SN} given by their expression:

$$G_{PN} = \frac{P_a - P_0}{a_{M,N} - a_{m,N}} \tag{4.1}$$

$$G_{SN} = \frac{P_a - P_0}{a_{M,N}} \tag{4.2}$$

where P_0 and P are the initial and unloading pressure respectively, and $a_{M,N}$ and $a_{m,N}$ are the deformation corresponding to initial and unloading pressure respectively. Figure 4.2 shows the two calculated modulus with the number of cycles in case of clay and sand soil. These figures indicated that the modulus decrease until reaching a constant value. We have noted, from these results that the tangent and secant modulus reach the stability rather for the sand than for clay.



a) b)

Figure 4.1. Numerical simulation of a cyclic pressuremeter test: a) a cyclic pressuremeter curve, b) volume variation versus number of cycles.

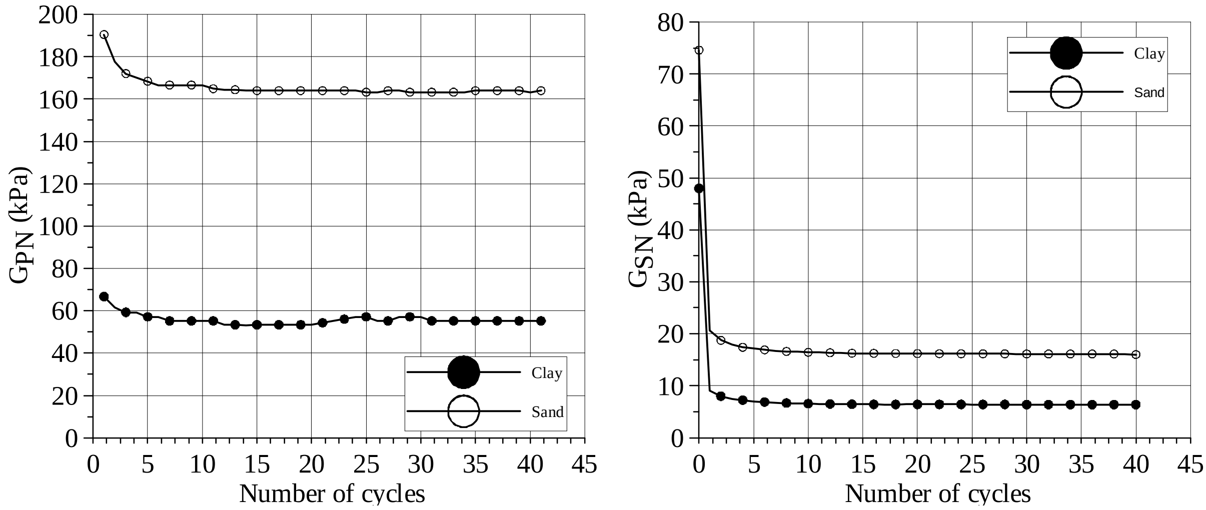


Figure 4.2. Variation of tangent and secant modulus.

4.1. A sensitivity study

In order to understand the influence of the model parameters on the numerical response of a cyclic pressuremeter path, a sensitivity study is carried out using FLAC software taking into account the Strain Hardening/Softening model. This model involves five parameters: cohesion, friction, compressibility modulus, shear modulus and density. The influence of these parameters on the cyclic pressuremeter is analyzed by changing the value of one parameter by ±50% of its initial value. The reference parameters used in this sensitivity study are those identified from the experimental data obtained from a monotonic self boring pressuremeter test carried out on the clay of Cran site (France), at 10.0 m depth (shear modulus G=6.7 MPa, cohesion c=39 kPa and friction φ=9°). The results are presented in Figures 4.3, 4.4 and 4.5. It may be observed that all the three parameters influence the cyclic pressuremeter response, in particular the shape of the curves. It was noted that the increase of the cohesion c and the friction φ leads to more reversible deformations (increase of the volume of the cyclic deformations), which implies an influence on the secant modulus, whereas the tangent modulus is not affected. Concerning the shear modulus, It was noted that the volume of the cycles does not change with the variation of G, from where it does not have an influence on the cyclic deformations, on the other hand, an increase in the cycles slopes (unloading reloading loops) was observed, from where an influence on the cyclic modulus.

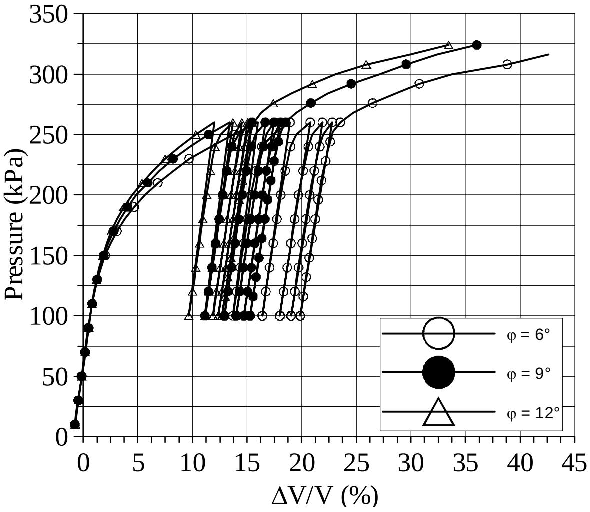


Figure 4.3. Influence of friction on the cyclic curve.

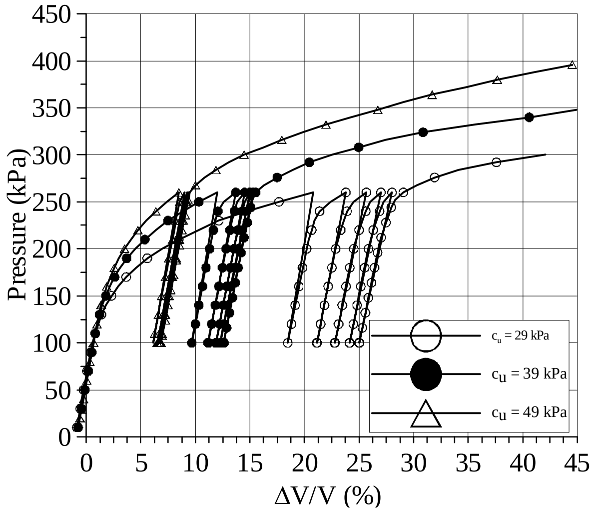


Figure 4.4. Influence of cohesion on the cyclic curve.

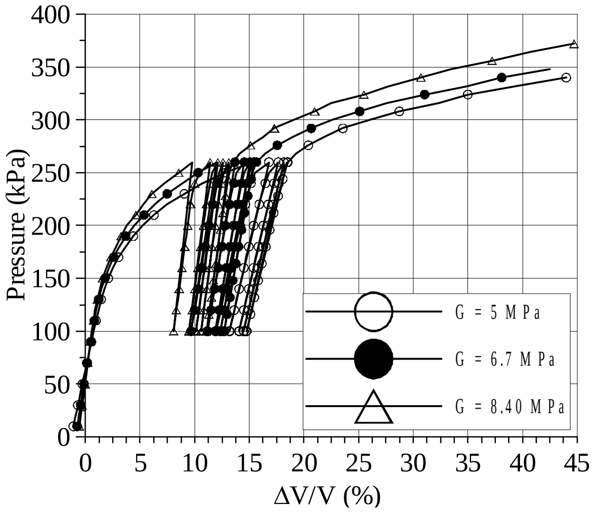


Figure 4.5. Influence of shear modulus on the cyclic curve.

4.2. Identification of soil parameters from a cyclic pressuremeter test

4.2.1. Monotonic pressuremeter test

The parameters defined in Table 1 are identified from laboratory tests performed at Cran site (Soegiri, 1991). These parameters are used to simulate the pressuremeter curve considering the Strain Hardening/Softening, Mohr Coulomb and Cam Clay models. Figure 4.6 shows a good agreement between simulations using different models and test results. This analysis allows to find the result already found by other authors (Cambou et al.,1993; Soegiri, 1991) where they have noted that the modeling of the pressuremeter test can be used to identify the soil intrinsic parameters.

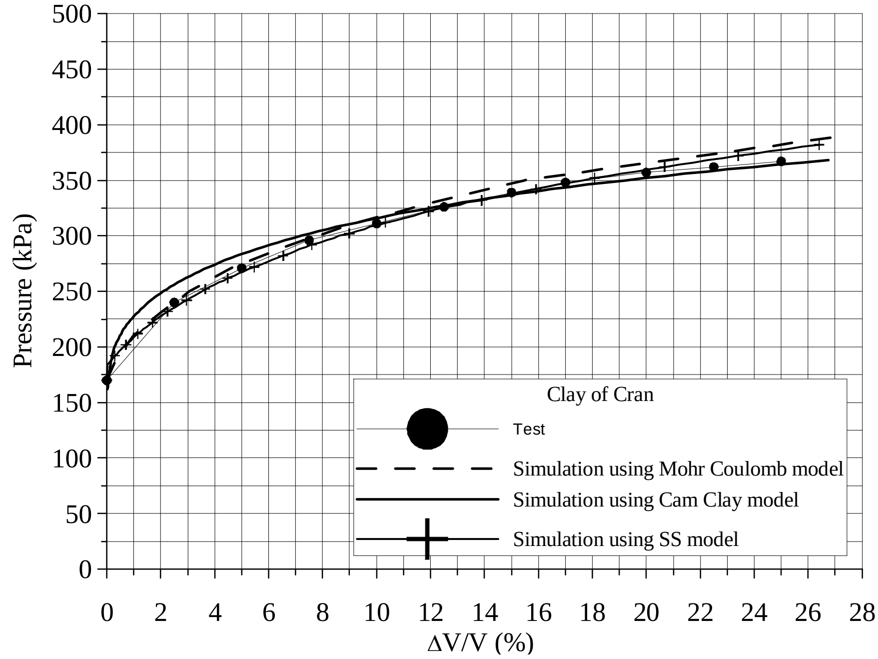


Figure 4.6. Pressuremeter curve responses using different models.

4.2.2. A cyclic pressuremeter test

Cyclic tests with the self boring pressuremeter are performed at the Cran clay, Brittany, France (see Fig. 2.2), carrying out fifty (50) cycles unloading-reloading between two bounds, 240 et 220 kPa. The test is carried out at 9.80 m depth. A simulation of this test is performed considering the parameters defined from a monotonic pressuremeter test in the similar conditions. The analysis of the influence of the cohesion and the friction on the shape of the cyclic curve made it possible to see how the volume of the cyclic deformations varies, and leads to simulate this test with varying the cohesion and the shear modulus. Figure 4.7 illustrates a simulation of a cyclic pressuremeter path. The best simulation compared to experimental curve is obtained by introducing the values of cohesion and shear modulus equal to 30 kPa and 12.7 MPa respectively. The shape of the two curves is similar in both loading and unloading-reloading part, and the volume of the cycle strains (reversible deformations volume) is almost close for the two curves. It is noted that the value of the cohesion given in the literature varies between 20 kPa and 49 kPa. The identified value of the cohesion agrees with those defined from other means. The promising results allow gaining valuable information on the cyclic behaviour of the soil, which is very important to examine the stability of structures during earthquakes or wave loading. The cyclic pressuremeter test can be used as a means and helpful for the identification of soil parameters.

4.2.3. Identification of the model parameters using the results of a pressuremeter test with unloading

The proposed approach is used to interpret the pressuremeter response of the Saint Herblain clay (Zentar, 1996). This clay was subjected to laboratory tests and in situ tests. Presssuremeter tests were carried out at different depth, with unload reload loop. Figure 4.8 shows a comparison between the pressuremeter test performed at 7 m depth and the numerical response curve with unloading part. The two curves are quite close. The horizontal and the limit pressure are 80 kPa and 205 kPa respectively. This test is carried out by loading at the beginning until reaching a value of pressure equal to 165kPa, and unloading reloading and an unloading at the end from a pressure of 204 kPa. For this simulation the undrained cohesion used is equal to 41kPa, it is obtained by using the Gibson-Anderson method (Gibson and Anderson, 1961). The shear modulus is determined from the unload reload portion of the experimental curve, it is found equal to 850 kPa. The undrained cohesion and shear modulus identified values are in the range determined by in situ and laboratory tests confirming the previous observations that the cyclic pressuremeter test allow gaining valuable information on the cyclic behaviour of the soil. The unloading part of the curve can be used in a very profitable way to confirm the elastic value for the modulus of soils.

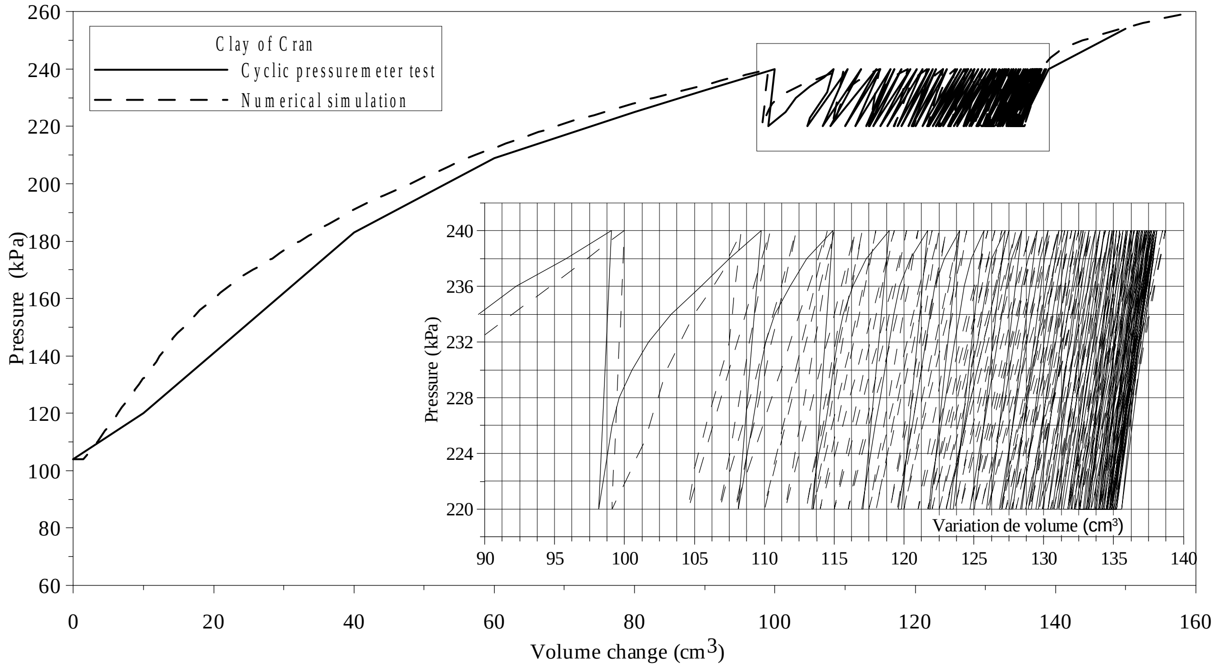


Figure 4.7. Identification of the soil parameters from the pressuremeter test.

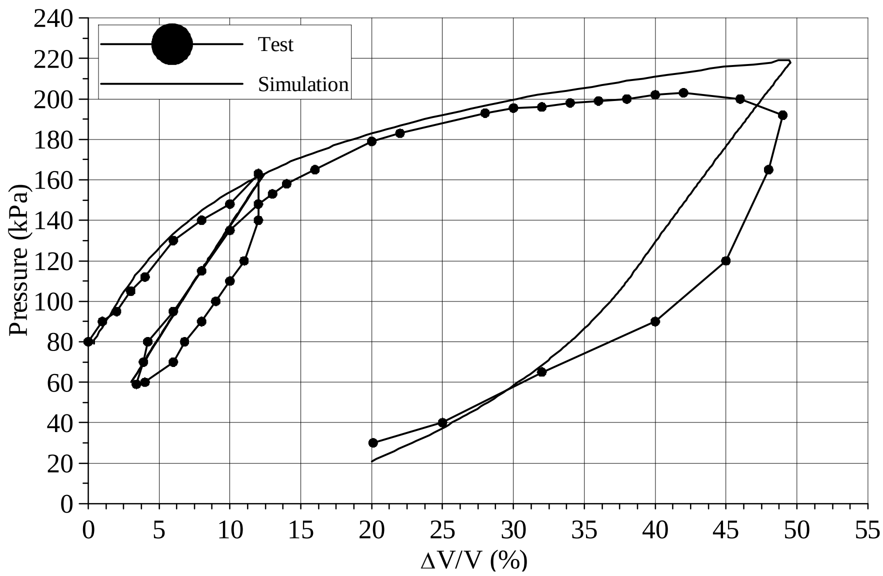


Figure 4.8. Identification of the soil parameters from the pressuremeter test with unloading-reloading cycle.

5. CONCLUSION

The reliability of the cyclic pressuremeter test using FLAC software is analysed taking into account the strain hardening/softening model. The sensitivity study shows that the increase of the cohesion and the friction of soils leads to appreciable successive movement from cycle to cycle, accumulation of cavity strain is observed for the increasing number of loops. This result implies an influence on the secant modulus, whereas the tangent modulus is not affected these two parameters. Cyclic loops of wide range of strain seem giving more reliable relationship of shear modulus and shear strain, than ordinary analysis. A comparison between experimental and numerical results shows a good agreement and the cyclic pressuremeter test allows gaining valuable information on the cyclic behaviour of the soil, which is very important to examine the stability of structures during earthquakes or wave loading. The result showed the reliability of the cyclic pressuremeter test.

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