Evaluation of soil parameters from pressuremeter tests : application to predict bored pile behaviour

Évaluation des paramètres du sol à partir des essais pressiométriques: application à la prédiction du comportement des pieux forés

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ABSTRACT: This paper presents and discusses an approach based on the results of pressuremeter tests proposed to identify the soil parameters. The identification approach is a numerical method developed to analyze pressuremeter tests using a very simple axisymmetric plane finite element method independent of the used constitutive model for soil. This program allows identifying the model parameters, taken into account the whole pressuremeter curve. The interpreted soil parameters had reasonable values when compared to other in situ and laboratory test results. Numerical calculations taking into account the rheological parameters derived from pressuremeter tests are performed in order to predict the behavior of a single bored pile subjected to an axial vertical loads. The predictions are compared to the measured data. The results show the applicability of the proposed approach.

RÉSUMÉ: Cet article présente et discute une approche d'identification des paramètres de comportement des sols basée sur les résultats des essais pressiométriques. La méthode utilise un programme numérique développé pour analyser ce type d'essais en utilisant la méthode des éléments dans le cas des hypothèses de déformation plane et d'axisymétrie, indépendamment du modèle constitutif du sol. Ce programme permet d'identifier les paramètres du modèle, en tenant compte de l'ensemble de la courbe pressiométrique. L'évaluation des paramètres du comportement des sols obtenus sont raisonnables comparativement à d'autres résultats issus d'essais in situ et de laboratoire. Des calculs numériques, prenant en compte les paramètres rhéologiques issus de cette approche, sont réalisés pour prédire le comportement de pieux forés isolés soumis à des charges verticales axiales. Les prédictions sont comparées aux mesures in situ. Les résultats montrent l'applicabilité de l'approche proposée.

KEYWORDS: pressuremeter, identification, behavior, settlement, bored pile.

1 INTRODUCTION

The pressuremeter test can be performed in all kinds of grounds, from soft soils to soft rocks. It is a particularly good tool to analyze axial bearing capacity, pile settlement and behaviour under lateral loading (Briaud 1995). In the Algerian geological context this has turned out to be a great advantage. The test is used by practising geotechnical engineers to design foundations in Algeria. Direct correlations between the measured parameters and the design parameters are used for estimating the bearing capacity and settlement of piles, and for their behaviour under lateral loading (Ménard 1957; MELT 1993).

Another trend of interpretation of these tests consists of identifying the usual soil parameters required by simple constitutive models for soils in numerical calculations. This paper deals with the estimation of bearing capacity and settlement of bored piles using the results of the pressuremeter tests. The interpretation of pressuremeter test results is performed by the numerical method called "Pressident" which is a numerical program taking into account the non linear elastic model (Cambou & Bahar 1993; Bahar et al. 1995; Bahar et al. 2012). Then, numerical calculations taking into account the rheological parameters derived from pressuremeter tests are performed in order to predict the behaviour of a single bored pile subjected to a static axial load. The predictions are compared to the measured data and the empirical methods.

2 INTERPRETATION OF THE PRESSUREMETER TESTS

PRESSIDENT (Pressuremeter Identification) computer program is developed at the Ecole Centrale de Lyon, France (Boubanga, 1990; Bahar 1992). The determination of the parameters of the non-viscous and viscous constitutive model from the pressuremeter test consists in solving the inverse problem to find a set of parameters which minimize the difference between the experimental data, the pressuremeter curve defined as the applied pressure versus the cavity wall deformation, and the simulated curve (Cambou & Bahar 1993; Bahar et al., 1995). Only the non-linear elastic Duncan model, described in several papers, is presented in this study (Duncan & Chang, 1970). The hyperbolic stress-strain relationship is developed for incremental analyzes of soil deformations where nonlinear behavior is modeled by a series of linear increments. It takes into account a tangent modulus E_t and a bulk modulus B_t in the following form:

$$E_t = \left[1 - \frac{R_f(1-\sin\varphi)(\sigma_1-\sigma_3)}{2.c.\cos\varphi+2\sigma_3\sin\varphi}\right]^2 K_e Pa\left(\frac{\sigma_3}{Pa}\right)^n \qquad (1)$$

$$B_t = K_b Pa\left(\frac{\sigma_3}{Pa}\right)^m \qquad (2)$$

k_e , k_b, n, m, R_f, c, φ are the model parameters.

Using the PRESSIDENT approach, these parameters are identified as follows. For cohesive soils, the pressuremeter tests can be considered as undrained. In these cases, the internal friction angle can be considered equal to zero. Then, the optimization procedure only leads to the definition of the parameter k_e and the undrained cohesion c_u. For cohesionless soils, the pressuremeter tests can be considered as drained tests. Moreover, the cohesion of these materials is equal to zero. The procedure optimization procedure only leads to the definition of k_e end φ. For cohesive-frictional soils (general case), it will not be possible to determine c and φ if only one test is available, so it will be necessary to make an assumption for one of the two parameters c or φ. If two tests at two different depths can be analyzed it would be possible to define the three parameters: k_e, c and φ. For each depth it is possible to calculate the value of c and k_e corresponding to different given values of φ (20°, 25°,30°,...), so it is possible to determine several acceptable couples of values for c and φ. A representation of these acceptable values can be drawn for different tests realized at different depths. The values of c and φ which have to be taken into account are the values acceptable for all the tests: intersection point between the different curves corresponding to different depths. Figures 1 and 2 show an identification example using "Pressident" with the non linear elastic Duncan model.

The pressuremeter data, collected over the last twenty years on various research and consulting projects in the north of Algeria are used to explore the relationship between pressuremeter characteristics and undrained cohesion obtained the two methods described above. A total of 600 tests were used. Figure 3 shows the correlations obtained between net limit pressure and the undrained cohesion obtained from the method. This figure indicates that there is a constant ratio between net limit pressure and undrained cohesion. For the entire data base, the ratio p_l-p_o/c_u is approximatively equal to 5.17. The approach can help to identify usual soil parameters required by simple constitutive models for soils in numerical calculations, taken into account the whole pressuremeter curve.

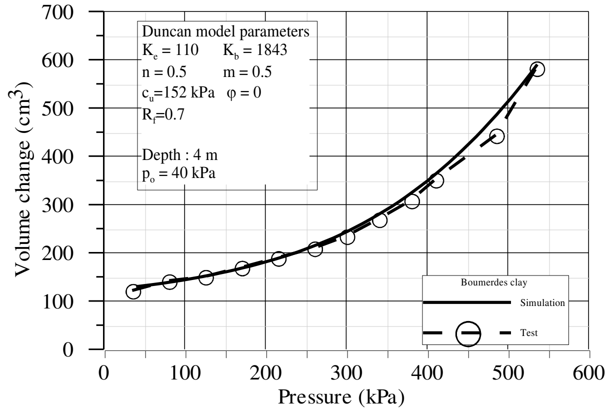

Figure 1. An example of identification for cohesive soil.

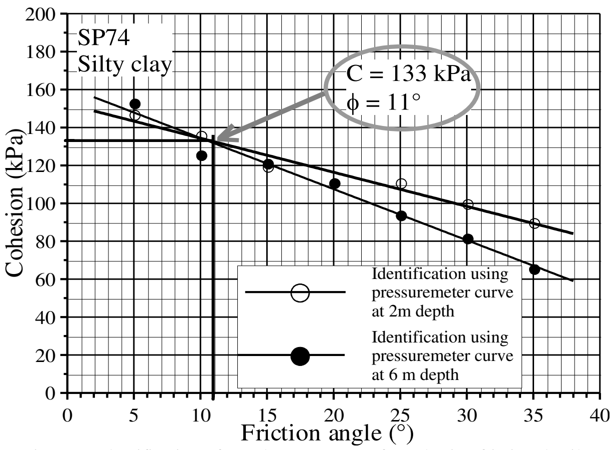

Figure 2. Identification of c and φ parameters for cohesive frictional soils.

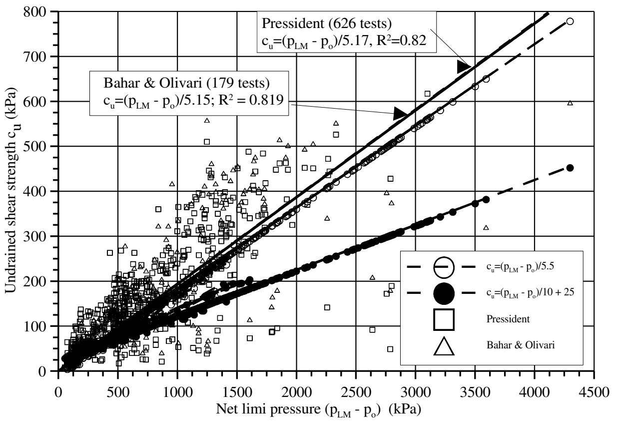

Figure 3. Undrained shear strength against net limit pressure obtained from different methods.

3 PREDICTION OF LOAD-SETTLEMENT OF A PILE

The axial response of static vertical bored piles is investigated using PLAXIS[3D] FOUNDATION (Brinkgreve & Swolfs 2007), which is based on finite element method. Linear elastic behavior is assumed for the pile and the Mohr-Coulomb criterion is considered for soils. The 3D mesh consists of 26176 tetrahedral elements with 10 nodes. PLAXIS imposes a set of standard fixities to the boundaries of the geometry model. The 3D finite element simulation was performed considering the geostatistical stresses characterizing the initial state, automatically generated. The initial stresses within the soil mass are established assuming that they are characterized by an earth pressure coefficient k_o condition, according to the consolidation state of the soil layers. The shear parameters for the cohesive and non cohesive soils used in the numerical calculations are deduced using the "Pressident" approach. The method of Frank and Zhao (Frank & Zhao 1982) was also used to find the mobilized vertical stress versus the tip displacement.

3.1 *El-Djazair Mosque site*

El-Djazair mosque site is situated in the central axis of the golf of Algiers, facing the Mediterranean Sea. The minaret is a very slender parallelepiped with a total height of 265 m above ground and a squared plane with the side of 26.5 m. The Geotechnical investigation survey for the Minaret site involved four pressuremeter boreholes down to 70 m depth, 3 boreholes to the same depth and one borehole to the 90 m depth for soil sampling and 28 SPT. The limit pressure and pressuremeter modulus profiles are shown in Figure 4.

The soil stratigraphy encountered on the minaret site consists of 10 m thick silty clay layer, underlain by silty sand extending to a depth approximately 40 m, underlain by sandy marl to the maximum explored depth. The marl consistency increases with depth. Groundwater was encountered at a depth of approximately 6.50 m. The soils are saturated. The measured natural water content varies between 10 and 35%. The plasticity index varies between 10 and 30%. The shear strength parameters derived from consolidated undrained triaxial tests with pore pressure measurement range from 11° to 26° for the friction angle and 18 to 212 kPa for the cohesion. Consolidation testing indicates that the soil is normally consolidated to overconsolidated with medium compressibility, C_c ranging from 10 to 14%.

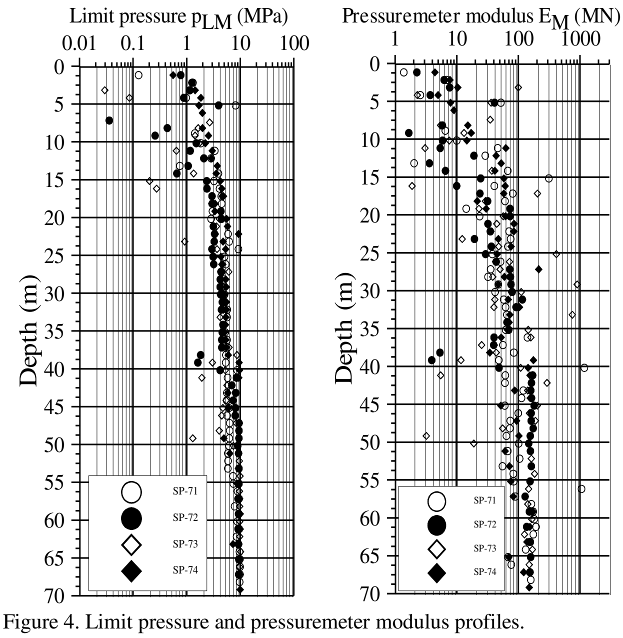

Figure 4. Limit pressure and pressuremeter modulus profiles.

For these soils, for each layer, using PRESSIDENT, it would be possible to define the three parameters, k_e, c and φ using two pressuremeter tests performed at two different depths. Figure 5 compares the simulations curves obtained using the average values and the experimental data for the silty clay layer.

Table 1 summarizes the average values of Duncan model parameters for each layer.

Two static vertical pile load tests, PV-01 and PV-02, are performed on non-working bored piles of 1000 mm diameters and 51.5 m lengths. For the bored pile construction, rotary drilling was employed for bored pile excavation under bentonite. The pile is instrumented by 27 extensometers over in entire length, defining a total of 9 measuring sections (3 extensometers by section at 120°) according to the project specifications. The piles are loaded up to 21.8 MN, 1.5 times the design working load (14.50 MN) of the foundation piles. The adopted loading cycle increments for the test piles are in according to the project specifications. Figure 6 shows the load-settlement curve for pile V1.

Numerical calculations were performed for the two static axial pile, 51.5 m deep and 1 m diameter, subject to maximum service load. Figure 9 shows the experimental load-settlement curves, the predicted by the Frank-Zhao method, the predicted by PLAXIS code taking into account PRESSIDENT approach and laboratory tests and the one predicted by Chin method. Frank and Zhao method and 3D calculation using parameters derived from laboratory tests give results quite close and provided ultimate resistance lower than those obtained by the PRESSIDENT approach and experimentally.

3.2 *Baraki stadium site*

The principal formations encountered on the Baraki stadium site are in general alternations of brownish to greenish clay and marl, containing passages of gray mud, blackened peat, followed in some places by deposits of fine to medium sand with gravel and pebbles (alluvial deposits) surmounting a yellowish marly substratum with light gray stains gravelly in some places

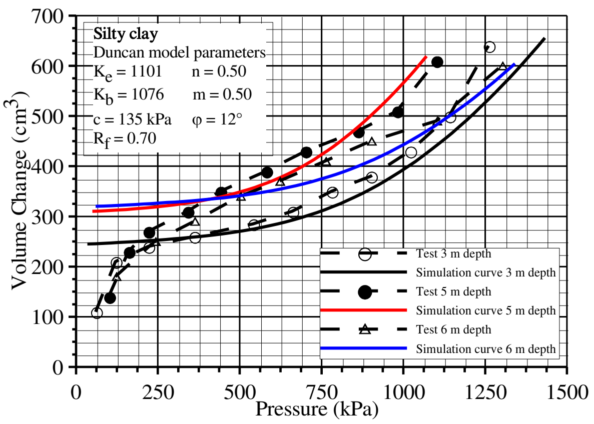

Figure 5. Simulation of pressuremeter curves by PRESSIDENT.

Table 1. Average values of identified model parameters.

	Depth	k_e	k_b	c	φ
Soil layers	(m)			(kPa)	(°)
Silty clay	0 - 10	1104	1076	135	12
Silty sand	10 - 40	2297	2252	165	27
Sandy marl	40 - 70	5317	5213	200	35

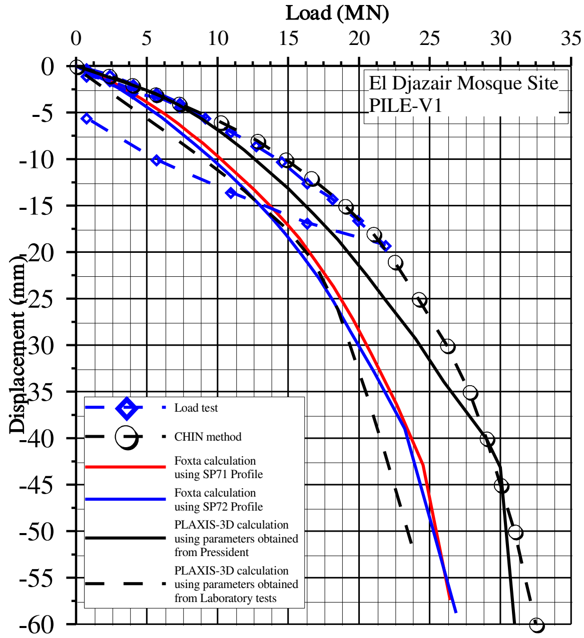

Figure 6. Measured and calculated load-settlement curves.

The formation of brownish to greenish marly clays is generally constituted by fine elements whose diameter is less than 80 µm is greater than 50%, which allows classifying these clays as fine soil. The natural water contents measured on tested samples are moderately high in places. They range from 29.3 to 29.4 %, with corresponding degrees of saturation ranging from 85.6 to 100%. Medium to high liquidity limits are noted, and are scattered in places and according to the soil levels tested. It generally approaches 50 %, with corresponding plasticity indices of between about 18.75% and more than 25%. According to the Casagrande diagram, the tested samples are in general plastic. The consistency index of the tested argillaceous marl samples is between 0.53 and 0.87. According to the results obtained from the oedometric tests, these clay materials are under consolidated and moderately compressible.

For the formation of brownish-to-greenish marly clays, the natural water content varies between 18% and 27.6%, with degrees of saturation ranging from 76 to 100%. The dry density varies between 15.3 kN/m^3 and 18.4 kN/m^3. The liquidity limit varies between 32.8% and 61.4% with corresponding plasticity indices of between about 16.4% and more than 25% up to 31.3% According to the Casagrande diagram, these tested samples are in general of medium to very high plasticity. The shear strength parameters derived from undrained consolidated shear tests range from 8° to 13° for the friction angle and from 33 kPa to 96 kPa for the cohesion. Consolidation testing indicates that the soils are overconsolidated with a low and moderate compressibility. The values of the triaxial compression resistance, R_c, test characterize very stiff to very hard materials, R_c ranging from 250 to 600 kPa. Figure 7 shows some results of pressuremeter tests performed on the site.

For these cohesive soils, the pressuremeter tests can be considered as undrained. In these cases, the internal friction angle can be considered equal to zero. Then, the optimization procedure only leads to the definition of the parameter k_e and the undrained cohesion c_u. Table 2 summarizes the average values of Duncan model parameters for each layer. Figure 6 compares the simulations curves obtained using the average values and the experimental data for the silty clay layer.

A static vertical pile load test, SZ-12, is performed on non-working bored piles of 1200 mm diameters and 69.5 m lengths. For the bored pile construction, rotary drilling was employed for bored pile excavation under bentonite. The piles are loaded up to 21.8 MN, 2 times the design working load (10.90 MN) of the foundation piles. The adopted loading cycle increments for the test piles are in according to the project specifications. Figure 9 shows the experimental load-settlement curves, the predicted by the Frank-Zhao method, the predicted by PLAXIS code taking into account PRESSIDENT approach and the one predicted by Chin method. 3D calculation using parameters derived from laboratory tests give results quite close to the experimental test results.

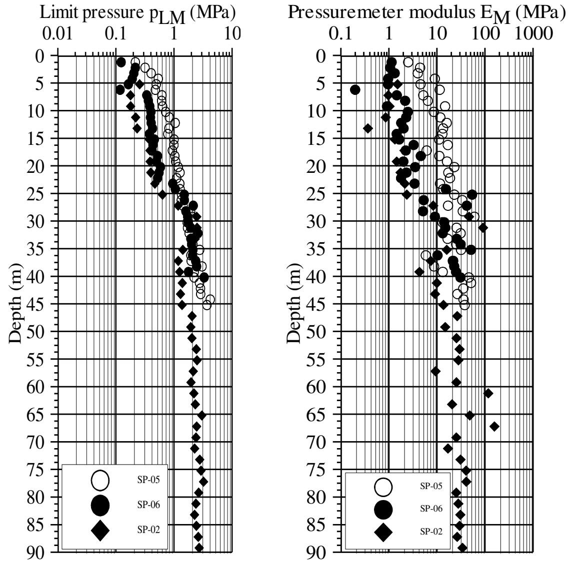

Figure 7. Limit pressure and pressuremeter modulus profiles.

Table 1. Average values of identified model parameters using PRESSIDENT approach.

	Depth	k_e	k_b	c_u
Soil layers	(m)			(kPa)
Greenish clay	0-23	58.5	974.5	47
Yellowish clay	23-33	293	4835	144
Compact clay	33-59	354	5905	219
Compact marl	59-90	702	11710	373

4 CONCLUSION

The usual soil parameters required by simple constitutive models for soils in numerical calculations are determined using PRESSIDENT method which is a numerical program developed to analyze pressuremeter tests. Numerical calculations taking into account these parameters are performed in order to predict the behaviour of a single bored pile subjected to a static axial load. For El-Djazair mosque site, the results show that the Frank and Zhao method and numerical calculations using laboratory tests give results quite close and provided ultimate resistance lower than those obtained by the PRESSIDENT approach and experimentally. For Baraki Stadium site, the obtained results using the PRESSIDENT method are in a fairly good agreement with the measured load-settlement curve on site. The numerical calculation results compared to in situ measurements show the applicability of the approach.

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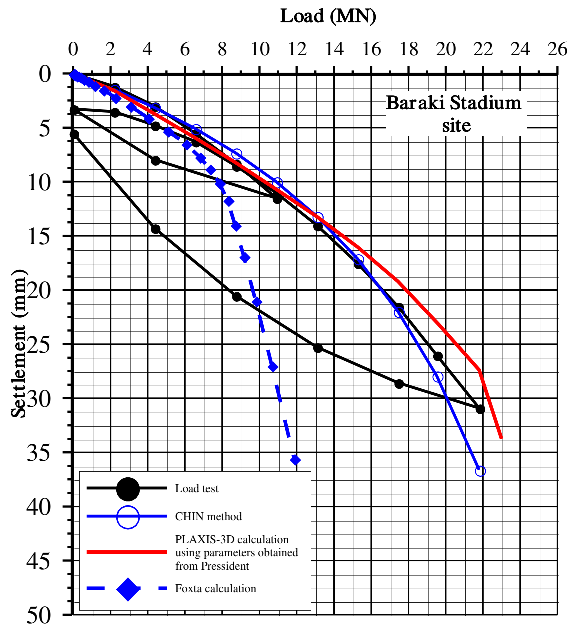

Figure 8. Comparison of measured and calculated load-settlement curves

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