Interpretation of a pressuremeter test in cohesive soils

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ABSTRACT: The proposed paper compares various methods used for assessing the undrained shear strength of cohesive soils from a pressuremeter test. The Ménard pressuremeter tests carried out on clays in different regions of Algeria are analysed by four methods, the empirical methods suggested by Ménard (1957) and Amar and Jezequel (1972), the method called "President" which is a numerical program taking into account non-viscous and viscous models for soil, and the method developed by Bahar and Olivari in order to determine the undrained shear strength. The last one uses the generalised Prager model associated to the Von Mises criterion. Correlations established between limit pressure and undrained cohesion.

1 INTRODUCTION

Insitu tests such as Cone Penetration Test (CPT), Menard Pressuremeter Test (MPT) and Standard Penetration Test (SPT) have been used extensively to measure in situ soil properties and for the design foundations in Algeria. These tests are an useful and economical way for obtaining reliable in situ properties of soils. The pressuremeter test provides the measurement of in situ stress-strain response of soils. From this test, the design foundations can be performed using pressuremeter rules that require a limit pressure and a pressuremeter modulus. They are derived from the pressuremeter curve or deduced from existing correlations with undrained cohesion and internal angle friction (Ménard, 1957; Amar *et al.*, 1972). In particular, these parameters are used to evaluate the bearing capacity of soil foundations and the expected settlements. But they can also help to identify usual soil parameters required by simple constitutive models for soils in numerical calculations.

For saturated clays with low permeability, several empirical, analytical or numerical methods based on pressuremeter tests have been proposed to evaluate the undrained shear strength and the stress-strain behaviour (Ménard, 1957; Amar *et al.*, 1972; Baguelin *et al.*, 1972; Palmer, 1972; Gibson *et al.*, 1961; Prévost *et al.*, 1975; Ferreira et al., 1992; Monnet *et al.*, 1994). These approaches differ from each other in the assumptions made in soil condition and stress-strain behaviour. However, these methods made the same basic assumptions of plane strain radial expansion and undrained condition for analysing the problem. Numerical solutions are used if a more precise solution of the pressuremeter test involving complex constitutive model for soils is required (Boubanga, 1990; Bahar, 1992; Zentar *et al.,* 2001, Monnet, 2007). The proposed paper compares various methods used for assessing the undrained cohesion of soils from a pressuremeter test. The Ménard pressuremeter tests carried out on clays in different regions of Algeria are analysed by the empirical methods suggested by Ménard (1957) and Amar & Jezequel (1972), the

numerical one method called "Pressident" which is a numerical program taking into account the Duncan and Chang model (Cambou and Bahar, 1993; Bahar et al., 1995) and the approach proposed by Bahar and Olivari in order to determine the undrained shear strength (Bahar et al., 1999; Bahar et al., 2012). The last one uses the generalised Prager model associated to the Von Mises criterion. The two last approaches have successfully been used to define the soil parameters using non-viscous and viscous models for soil (Cambou *et al.*, 1993; Bahar *et al.*, 1995; Bahar, 1998; Bahar *et al.,* 2005; Bahar et al, 2012).

2   INTERPRETATION OF A PRESSUMETER CURVE TESTS

2.1   *Limit pressure and pressuremeter modulus*

The limit pressure P_L is defined at the pressure reached when the initial volume of the cavity has been doubled. The pressuremeter modulus E_M was determined from the slope of the linear portion of the corrected pressure versus corrected volume. E_p is given by the equation :

$$E_p = 2(1+\nu)(V_o + V_m)\frac{\Delta p}{\Delta V} \qquad (1)$$

where ν is Poisson's ratio; assumed 0.5 for undrained tests, Δp and Δv are the differences in pressure and volume, respectively, between two points taken along the straight line portion of the curve, V_m is the average volume of the cavity measured at midpoint of straight line an V_o is the initial volume of the probe.

2.2   *Undrained cohesion*

Several empirical, analytical or numerical methods based on pressuremeter tests have been proposed to evaluate the undrained shear strength and the stress-strain behaviour. Bahar & Olivari and "Pressident" methods have been used to determine the undrained cohesion of some clay sites in Algeria. The results obtained are compared to those derived by the empirical methods proposed by Menard (1957) and Amar *et al.* (1971). The two empirical methods are established by correlation between the limit pressure obtained from pressuremeter tests and the undrained shear strength obtained from field vane and triaxial tests for soft cohesive soils.

  – The method of Menard (1957) is an empirical relationship often used in the analysis of Menard pressuremeter data. It is given by:

$$c_u = \frac{p_l - p_o}{5.5} \qquad (2)$$

 – The method of Amar *and Jézéquel* (1972) is an empirical relationship given by:

$$c_u = \frac{p_l - p_o}{10} + 25 \,(\text{kPa}) \qquad (3)$$

  p_l, p_o, and c_u are the limit pressure, the in situ total horizontal stress and the undrained shear strength respectively.

  – Pressident (Pressuremeter Identification) is a numerical program developed at the Ecole Centrale de Lyon, France (Boubanga, 1990; Bahar, 1992), to analyse 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. It has successfully been used to define the soil parameters using non-viscous and viscous models for soil (Cambou *et al.*, 1993; Bahar *et al.*, 1995; Bahar, 1998; Bahar *et al.,* 2005). Figure 1 shows an identification example using this "Pressident" with the non linear elastic Duncan model.
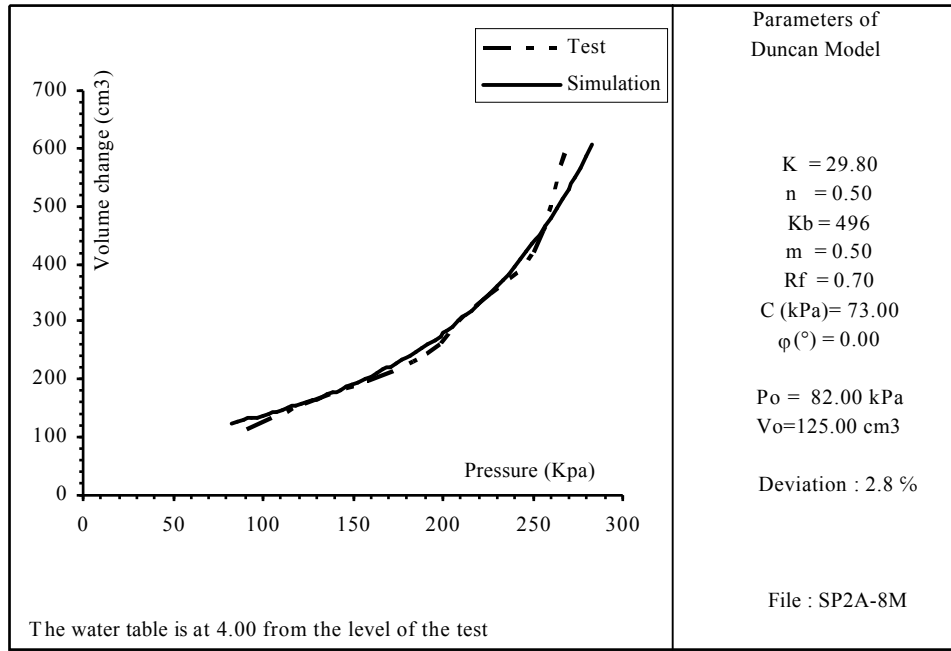
Figure 1. An example of the Duncan model constants identification.

– The method developed by Bahar and Olivari uses the generalised Prager model associated to the Von Mises criterion. Using an analytical representation of the total stress-strain curve obtained during an undrained triaxial test (Bahar *et al.*, 2012), given by equation (3), the model, a polygonal line that can be considered as a discretisation of the experimental curve, takes into account only three parameters which are the elastic shear modulus G, a shape parameter characterising the curvature of the test curve, A, and the undrained cohesion c_u.

$$\varepsilon_d^p = -A\left(Ln(1-R) + (1-2R)\frac{R}{1-R} \right) \tag{4a}$$

$$R = \frac{\sigma_1 - \sigma_3}{(\sigma_1 - \sigma_3)_f} \tag{4b}$$

σ_1 and σ_3 are the principal total stresses, $(\sigma_1 - \sigma_3)_f$ is the asymptotic value for the difference between the major and the minor principal stresses that is related closely to the strength of the soil, and *A* is a positive parameter defining the curvature of the curve.

Therefore, the following expressions are deduced:

$$dp(r) = r_o \Delta u_o \left[\left(\frac{1}{r^2 C(r)} \right)_r^{r_e} + 2\int_r^{r_e} \frac{dr}{r^3 C(r)} \right] \tag{5}$$

$$\Delta u_o = \frac{\Delta p_o}{\dfrac{r_o}{r_e^2 C(r)} + 2r_o \displaystyle\int_r^{r_e} \frac{dr}{r^3 C(r)}} \tag{6}$$

Δp_o and Δu_o are the pressures applied to the cavity wall and displacement at cavity wall respectively.

Figure 2 shows an identification example performed using Bahar and Olivari analysis.
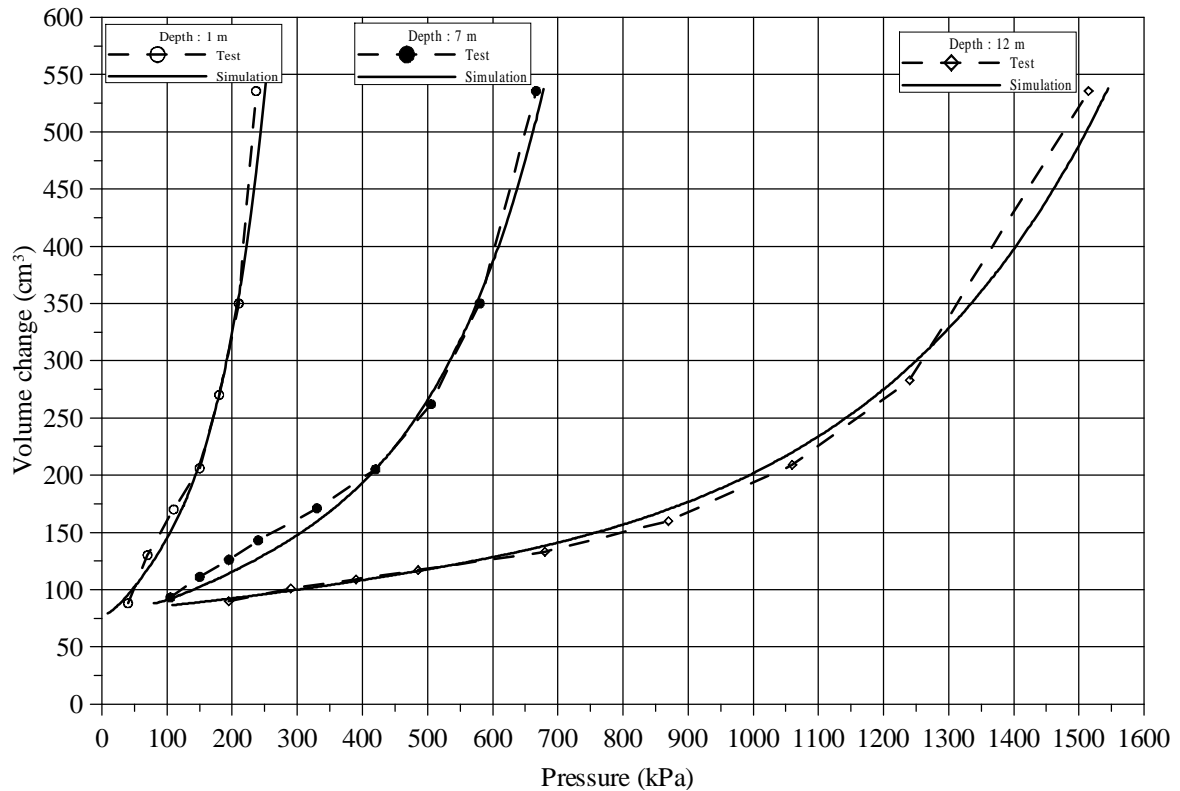
3

Figure 2. An example of the model constants identification using Bahar and Olivari analysis.

3   SITE INVESTIGATIONS

There are a number of sites where the in situ tests, particularly a pressuremeter tests, and laboratory tests are available. The most sites analysed in this paper are located at the center and the east of Algeria. The site investigations included boring, sampling, Cone penetrometer tests (CPT), Menard pressuremeter tests (MPT) and laboratory tests. The sites are:

  - Bordj-Menail site : Bordj Menail city is located about 60 km east of Algiers. The site was an area about 100 by 60 m. The soil consists of clay deposit described as stiff. A summary of the soil properties is shown in table 1. The ground water table was about 2.6 m depth from ground surface during testing. The nature water content w_n varied between 17 and 24%. The plasticity index varied between 24 and 30%. Figure 3 shows some results of static cone penetration and pressuremeter tests performed on the site. A wide scattering is obtained, most probably depending upon local variations in soils properties in the horizontal direction.

Table 1. Soil properties.

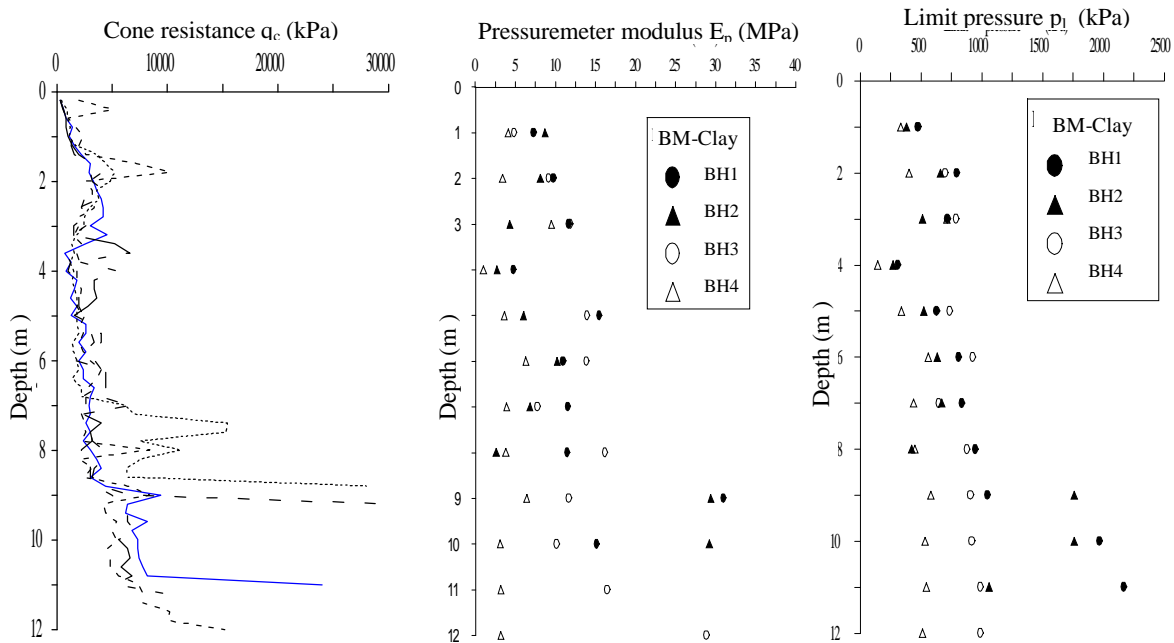| Borehole	BH1			BH2			
Depth (m)	1.4 - 1.8	3.7 - 4.0	5.4 - 5.7	2.0 - 2.5	4.0 - 4.7	6.6 - 7.0	10.0 - 10.5
γ_d (kN/m^3)	18.2	16.2	17.5	17.0	16.2	17.7	17.4
w_n (%)	17.2	21.3	19.4	20.2	23.9	18.7	20.1
S_r (%)	94	93	96	93	97	96	98
γ_h (kN/m^3)	21.2	20.3	20.9	20.5	20.1	21.0	20.9
w_L (%)	54	45.5	44	54.5	59	45.5	55.8
I_p %	28.2	24.3	22.8	28.2	29.6	24.4	29.5

Figure 3. In situ test results, Bordj-Menail site.

- Tissemsilt Site : Tissemsilt city is located about 220 km South east of Algiers. The soil consists of clay deposit, gravely marls overlying a marl stratum. The ground water table was about 2.00 m depth from ground surface during testing. The clay is saturated. The dry density varies between 15.4 and 17 kN/m^3. The water content w_n varies between 19% and 30%. The liquid limit and the plasticity index varie between 40 and 70%, and 17% and 30% respectively. The cohesion is ranging from 11 to 36 kPa. Consolidation testing indicates that the soils are unconsolidated to normally consolidated with a high compressibility index. A conventional limit pressure lower than 800 kPa characterizes the first six meters. The hard marl is characterising by a limit pressure ranging from 1200 et 3000 kPa.

- Boufarik Site : Boufarik city is located about 40 km south of Algiers. The soil consists of soft to very soft silty to sandy clays. The ground water table was about 4.00 m depth from ground surface during testing. The clay is saturated. The dry density varies between 14.5 and 17.1 kN/m^3. The water content w_n varies between 21% and 35%. The liquid limit and the plasticity index varie between 40 and 61%, and 17% and 30% respectively. The cohesion is ranging from 10 to 80 kPa. Consolidation testing indicates that the soils are unconsolidated to normally consolidated with a moderate to high compressibility index. The conventional limit pressure ranges between 200 and 800 kPa. The static cone resistance varies between 200 and 1500 kPa.

- Boumerdes site: Boumerdes city is located about 40 km east of Algiers. The soil consists of alluvium clays deposits. The ground water table was about 2.00 m depth from ground surface during testing. The clay is saturated. The dry density varies between 17 and 18 kN/m^3. The water content w_n is about 22%. The liquid limit and the plasticity index varie between 50 and 57%, and 25% and 30% respectively. The cohesion is ranging from 40 to 90 kPa. Consolidation testing indicates that the soils are unconsolidated to normally consolidated with a moderate compressibility index. Figure 4 shows some results of in situ tests.

- Very soft to soft clay of Annaba site: The site is located in the east of Algeria, about 600 kms from Algiers. The soil stratigraphy encountered on site consists of muddy soft to very soft brownish clay. The thickness of the clay layer is about 25 to 30 m. The ground water table was about 5 m depth from the ground surface. The clay is saturated. The natural water content w_n varies between 18% and 60%. The plasticity index varies between 26% and 35%. The shear strength parameters derived from consolidated undrained triaxial tests with pore pressure measurement range from 10° to 21° for the friction angle and from 11 kPa to 36 kPa for cohesion. A conventional limit pressure ranging from 200 kPa to 800 kPa characterizes the clays. Consolidation testing indicates that the soils are unconsolidated with a high compressibility index, C_c ranging from 0.11 to 0.41.

5

- Stiff to very stiff clay of Bab Ezzouar: The site is located in Algiers (Algeria). The soil stratigraphy encountered on the site consists on stiff to very stiff clays, which overlies a layer of sandstone material. The thickness of the clay is about 15 to 18 m. The clay is saturated. The natural water content w_n varied between 7% and 21%. The plasticity index varied between 22% and 27%. The shear strength parameters derived from consolidated undrained triaxial tests with pore pressure measurement range from 7° to 21° for the friction angle and from 14 kPa to 126 kPa for the cohesion. A conventional limit pressure ranging from 500 kPa to 2600 kPa and pressuremeter moduli ranging from 4700 kPa to 44000 kPa characterizes the clay. Consolidation testing indicates that the soil is normally consolidated to slightly overconsolidated with medium compressibility, C_c ranging from 10% to 17%.
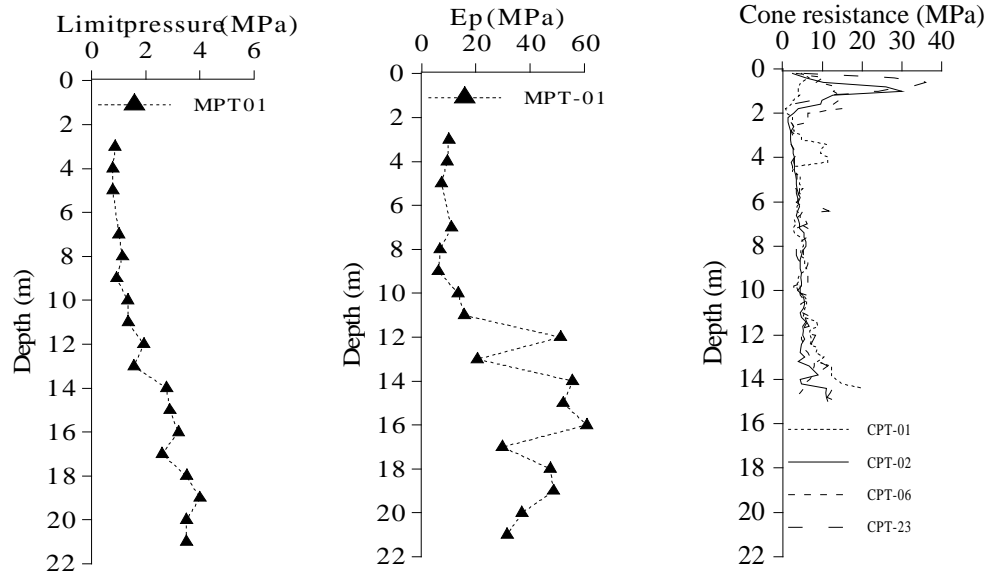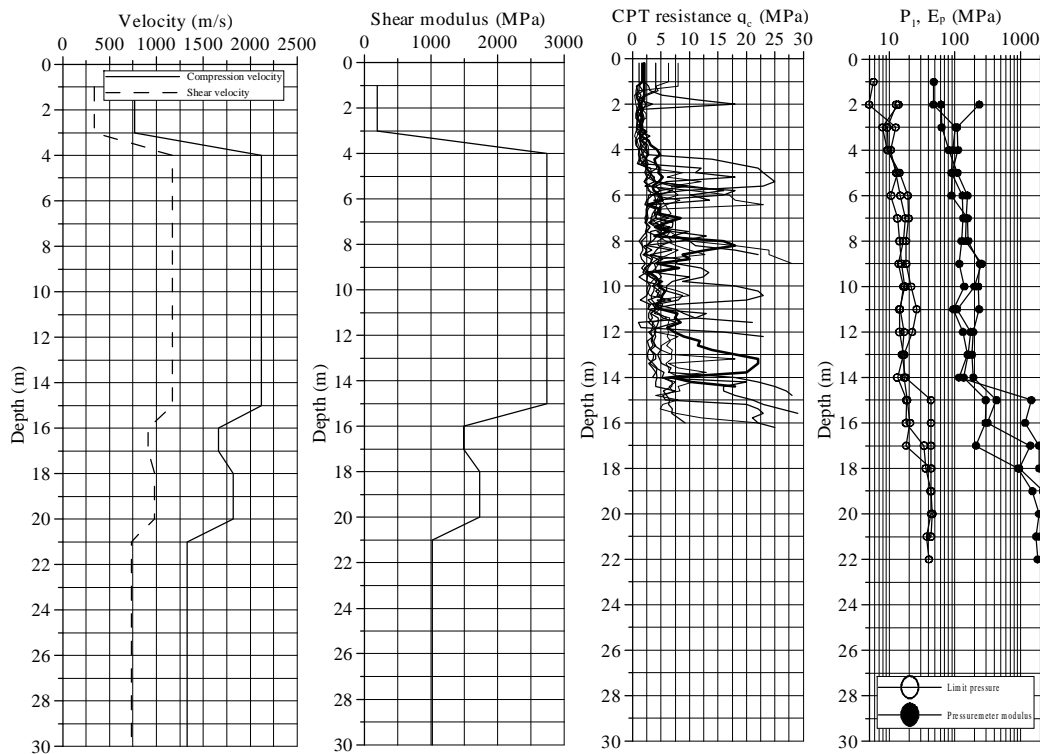

Figure 4. In situ test results, Boumerdes site.

Figure 5. In situ test results, Bab-Ezzouar site.

6

4   RESULTS AND DISCUSSION

Some undrained cohesion profiles obtained using Bahar & Olivari method, "Pressident" method and empirical methods mentioned above are presented in Figures 6 and 7. It can be noted that the Bahar & Olivari method gives a values relatively similar to those deduced by "Pressident" method. These figures show also that, for limit pressure less than 300 kPa, the undrained cohesion values deduced from the two approaches are close to those obtained from the empirical methods. For limit pressure ranging between 300 kPa and 700 kPa the undrained cohesion values deduced from the two methods were on the average 170% higher than those deduced from the empirical methods. There are a lot of factors that can explain the observed difference in the values of c_u obtained by different methods. The two empirical methods are established by correlation between limit pressure obtained from pressuremeter tests and undrained shear strength obtained from field vane and triaxial tests for soft soils. Very often, pressuremeter undrained shear strength obtained using cavity expansion methods are significantly higher than the values obtained using other in situ or laboratory tests. High undrained shear strengths from pressuremeter tests have been frequently observed. The measured c_u will be affected by the in situ or laboratory method used and the stress path followed during the test (Wroth, 1984). Wroth (1984) showed that the undrained shear strength derived from pressuremeter tests should be larger than the strengths derived from field vane tests due to the nature of the different stress paths. As explained by other researchers (Baguelin *et al*, 1978) this difference is due to disturbance during prior boring testing and to the difference in the mode of failure during the test. It has also been recognized by many researchers that some drainage and creep can result in an overestimation of the undrained shear strength (Wroth, 1984).

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 500 tests were used in this study. Figure 8 shows the correlations obtained between net limit pressure and the undrained cohesion obtained from the two methods. 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 3.85 and 4.1 for Bahar & Olivari method and "Pressident" method respectively.
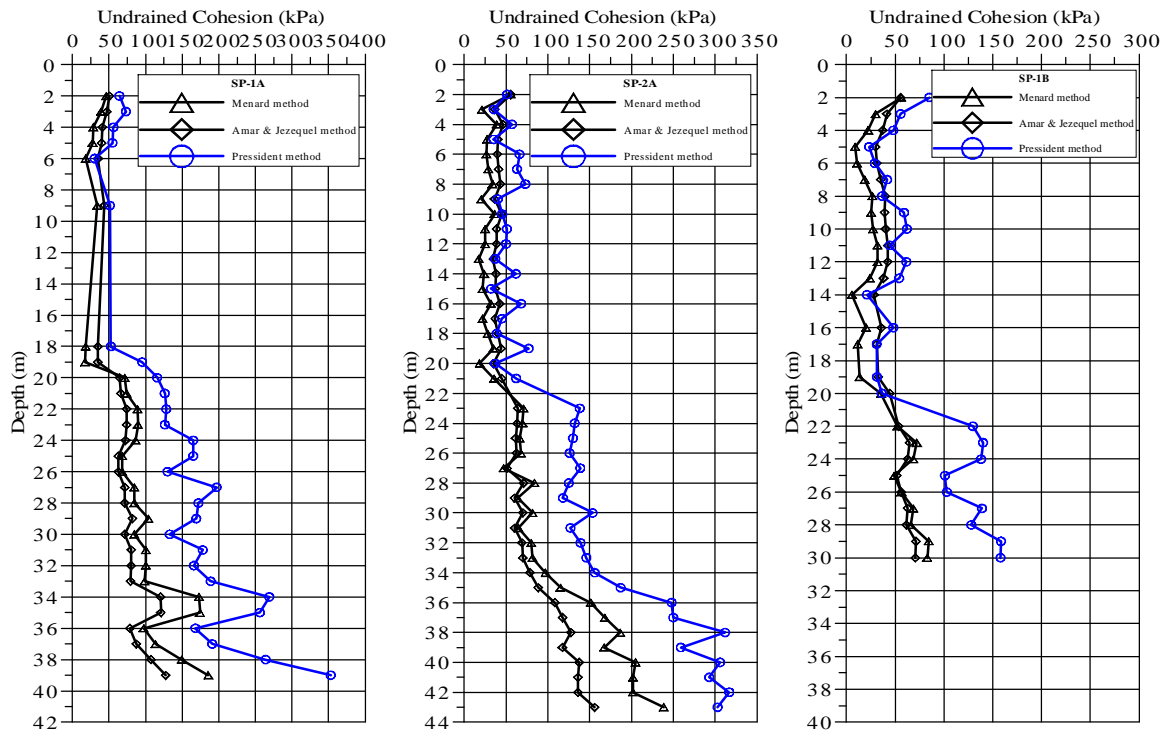

Figure 6. Undrained cohesion profiles obtained for Annaba site.
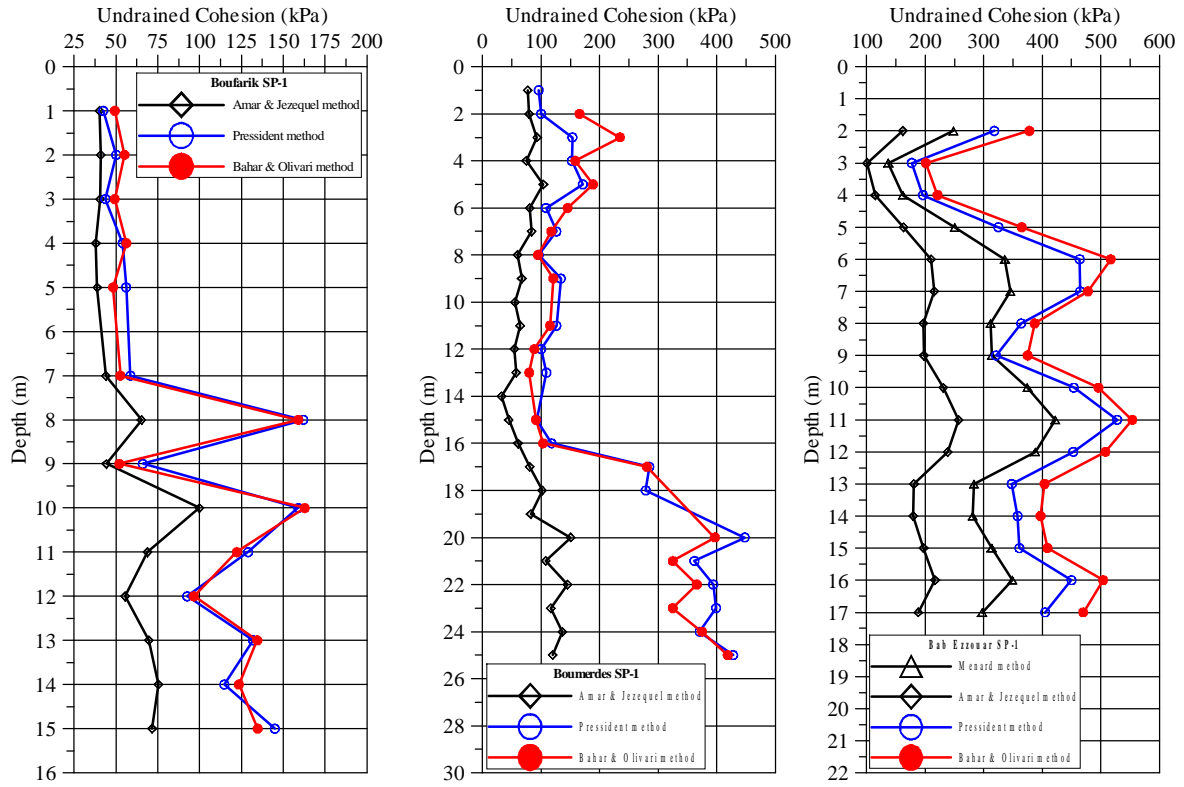
Figure 7. Undrained cohesion profiles obtained for Boufarik, Boumerdes and Bab Ezzouar sites.
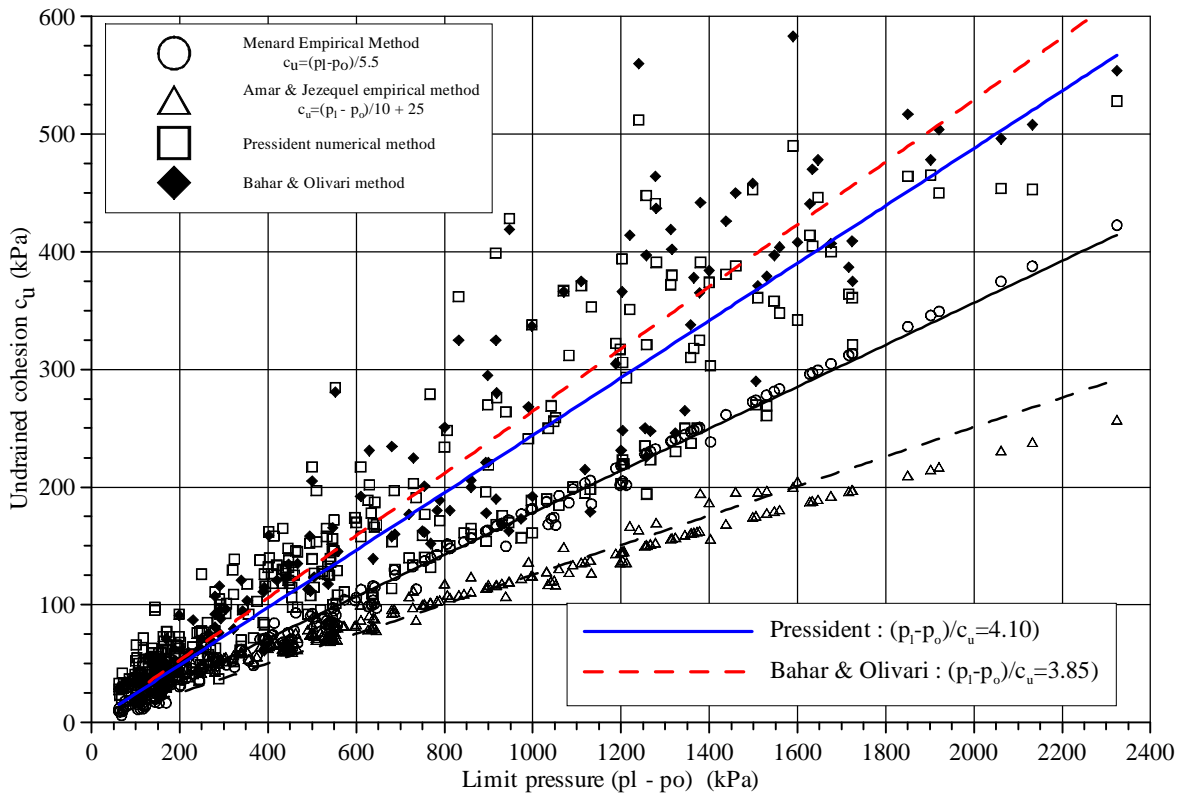

Figure 8. Correlation between undrained cohesion and net limit pressure.

5   CONCLUSION

The undrained shear strength of Algerian clay sites were determined by different interpretation methods. Bahar & Olivari method gives values relatively similar to those deduced by "Pressident" method. For limit pressure less than 300 kPa, the undrained cohesion values deduced from the two approaches are close to those obtained from the empirical methods. For limit pressure, ranging between 300 kPa and 700 kPa, the undrained cohesion values obtained were on the average 170% higher than those deduced from the empirical methods. A lot of factors, such as disturbance during prior boring testing, the difference in the mode of failure during the test, drainage and creep, can explain the observed difference. The analysis indicates that there is a constant ratio between net limit pressure and undrained cohesion. The comparison between the undrained cohesion determined with the two methods method and with other means illustrates their applicability. However, further researches are needed to verify these conclusions for various clay types with both field and laboratory test results.

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