Numerical analysis for an interpretation of the pressuremeter test in granular soil

Jacques Monnet

Joseph Fourier University
L3S-R
Domaine Univeristaire, BP n°53, 38041, Grenoble, Cedex 9, France
jmonnet@ujf-grenoble.fr

Abtract :

The recent elasto-plastic pressuremeter theory of Monnet and Khlif (1994) for the granular soil has been used in several civil engineering constructions. The finite element method allows nowadays to check the validity of this theory. In the first part, we briefly present the interpretation of the pressuremeter test in granular soil and the theoretical expression of the limit pressure. In the second part, we present the analysis of the theoretical limit pressure compared with the result of the Mohr-Coulomb non-standard model used by the Plaxis finite element program. As the theory shows that the limit pressure depends on four parameters, we apply a variation of one of these parameters, the others remaining unchanged, and we study the resulting variation of the limit pressure. The theoretical evolution of the limit pressure as a function of each parameter shows a fine agreement with the numerical results.)

Résumé :

La théorie élasto-plastique de Monnet et Khlif (1994) pour l'interprétation de l'essai pressiométrique dans un sol granulaire, a été utilisée dans plusieurs ouvrages des génie civil. La méthode des éléments finis permet maintenant de vérifier la validité de cette théorie. Dans la première partie, nous présentons rapidement la théorie et les expressions théoriques de la pression limite. Dans la seconde partie, nous présentons la comparaison entre la pression limite déterminée de façon théorique et les résultats obtenus avec le modèle de Mohr-Coulomb non-standard utilisé dans le programme Plaxis. Comme la théorie montre que la pression limite dépend de quatre paramètres, nous appliquons une variation de l'un de ces paramètres en maintenant les autres constants et nous étudions l'évolution des différentes pressions limites. L'évolution de la pression limite théorique en fonctions de chaque paramètre, montre une bonne concordance avec les résultats numériques

Key-words :

Pressuremeter, friction angle, finite element method

1 Introduction

The pressuremeter is a well-known apparatus (Ménard, 1956), which is widely used nowadays in foundation engineering (Ménard, 1975, Gambin, 1979; Amar et al., 1991; Clarke B.G., 1996). Its use, however, often relies on a set of empirical rules (DTU 13.12, 1988; French Standard NF P 94-110, 2000; French Standard P 94-250-1, 1996).

A pressuremeter test may be considered as an in situ shearing test because the instrument measures soil deformability and shear resistance of the soil and the test is performed in situ, in any soil, without sampling. This avoids problems of grain size distribution, change in consolidation or remoulding, often encountered in samples used for laboratory testing.

2 Hypothesis

Following Baguelin et al. (1978), we assume a drained test with an elastic behaviour at low level of shear with two elastic parameters, the Young modulus E and the Poisson ratio ν and a non standard elasto-plasticity with a dilantancy angle (eq. 1) which is :

[1] $\Psi = \Phi' - \Phi_\mu$ [2] $0.8\Psi = \Phi' - \Phi_c$

The relation between dilatancy and friction angle was also investigated by Bolton (1986), who proposed relation [2], close to the previous one, as the angle Φ_{cv} is larger than the interparticle angle Φ_μ (Rowe, 1962; Rowe 1969; Frydman et al., 1973). The use of fixed angles of dilatation and friction is a simplification and it would be preferable to consider these angles as function of density and pressure. This would, however, result in even more complex mathematics and it is not compatible with the aim of finding simple mechanical characteristics.

The Mohr-Coulomb relation gives the failure of the soil:

[3] $F(\sigma) = (\sigma'_1 - \sigma'_3) - \sin\Phi' . (\sigma'_1 + \sigma'_3)$

The non-associated flow rule is:

[4] $d\varepsilon^p = \xi . dH(\sigma') / d\sigma'$

with the unknown scalar ξ and the plastic potential:

[5] $H(\sigma') = (\sigma'_1 - \sigma'_3) - \sin\Psi . (\sigma'_1 + \sigma'_3)$

Three different areas of soil are considered from the borehole wall to the infinite radius (Fig. 3)

Plasticity appears between the radial stress σ'_r and the circumferential stress σ'_θ in the horizontal plane (Fig.1). This first plastic area extends between radius a (borehole wall) and radius b (external radius of the first plastic area). As shown by Wood and Wroth (1977), plasticity may also appear in the vertical plane between the vertical stress σ'_z and the circumferential stress σ'_θ (Fig.1) in an area between the radii b and c (external radius of both plastic areas).

An elastic area extends beyond radius c

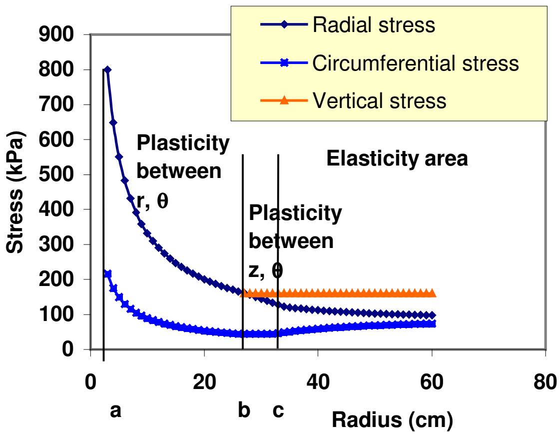

FIG. 1 The three areas around the pressuremeter probe

3 Theoretical elasto-plastic equilibrium around pressuremeter

The global elasto-plastic equilibrium was found with two plastic areas (Monnet and Khlif, 1994). The continuity of stress between the three different areas allows the evaluation of two internal constants of the model C_1 and δ. We can obtain the limit pressure p_l for a volume of the probe which is double the initial one. The borehole strain at the borehole is then equal to $\sqrt{2}-1$:

[6] $$p'_l = \gamma.z.\sqrt[\delta]{\frac{\left[(1+n).\left(\sqrt{2}-1\right)-C_1\right]2.G}{\left[(1-K_0).(1+n).\gamma'.z-2.G.C_1\right]}}\ ;$$

with $$C_1 = \frac{n.\left(\frac{u_a}{a}\right).(1+n).\left(\frac{\gamma.z}{p}\right)^{\delta} + (1+n).(N-K_0).\frac{\gamma.z}{2.G}}{1+n.\left(\frac{\gamma.z}{p}\right)^{\delta}}$$

[7] $\delta = (1+n)/(1-N)$; $n = (1-\sin\Psi)/(1+\sin\Psi)$; $N= (1+\sin\Phi)/(1-\sin\Phi)$

This relation is quite different from the Amar et al. (1991) relation, which is based on Ménard experimental correlations:

[8] $$p'_l = 250\left[2^{\left(\frac{\phi-24}{4}\right)}\right] + K_0.\gamma'z$$

The Ménard relation was derived from pressuremeter tests. Theoretical considerations show that the main shearing takes place between the radial stress σ'_r and the circumferential stress σ'_θ, which lie in the horizontal plane. For a granular soil, the plasticity condition shows that the level of shearing is proportional to the level of stress applied on the shearing surface. For the pressuremeter test, the vertical stress is normal to the horizontal surface, so σ'_z can be considered to be the stress along which shearing takes place. As the limit pressure is linked to a particular value of the shearing stress, it must be also proportional to the vertical stress, which is obtained from eq. [6]. The Ménard eq. [8] seems to fit these considerations only for a mean depth close to 12m. For a test close to the surface, it seems to underestimate the friction angle, and for very deep test it seems to overestimate the friction angle. Futhermore, the Ménard relation does not take into account the nature of the soil, and the variation of the interparticle angle of friction. It overestimates friction angle for loams, which have lower interparticle angle of friction than sands and gravels.

In the case of one plastic area, the particular value of the borehole strain $\sqrt{2}-1$ leads to the value of the limit pressure:

[9] $$p'_l = \frac{2.K_0.\gamma.z}{(1+N)}.\sqrt[\delta]{\frac{\left[(1+n).(\sqrt{2}-1)-C_1\right]2.G.(1+N)}{K_0.\gamma.z.\left[(1-N).(1+n)-2.G.C_1.(1+N)\right]}}$$

with $$C_1 = \frac{K_0.\gamma.z + (1-N).(n-1)}{2.G.(1+N)}$$

4 Numerical analysis for the elasto-plastic theory

4.1 Method used to determine the characteristics of the soil

The measurement of the slope δ (Fig. 2) of the linear relationship between the logarithms of pressure and borehole strain at the borehole wall allows the determination of the angle of internal friction using eqs. [7]. This value is then put into eq. [6, 9] to find the theoretical pressuremeter curve. The conventional limit pressure can also be pbtained by a direct theoretical and FEM analysis for a precise expansion of the pressuremeter probe (which is double of the initial volume). We used the Plaxis program, with the non-standard elasto-plastic model of Mohr-Coulomb to compare theses numerical results with the theoretical ones.

The common set of parameters used is, E = 40MPa, $\nu = 0.42$, $\sigma_z = 250$kPa, $\Phi_\mu = 27.8$, $\Phi' = 30°$. We then apply a perturbation on one of these parameters, for example on the Young modulus so that the shear modulus varies, or on the Poisson ration so that K_0 varies, or on the vertical stress, or on the friction angle, or on the interparticle angle of friction, while keeping the others parameters constant (Table 1). For the study of K_0, it is necessary to change also the angle of friction so that two plastic areas appear.

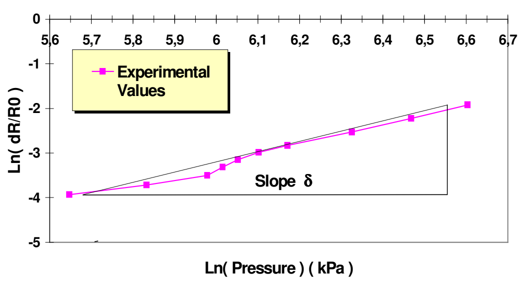

FIG 2: Linear transformation of the pressuremeter relationship for a test in a gravel site

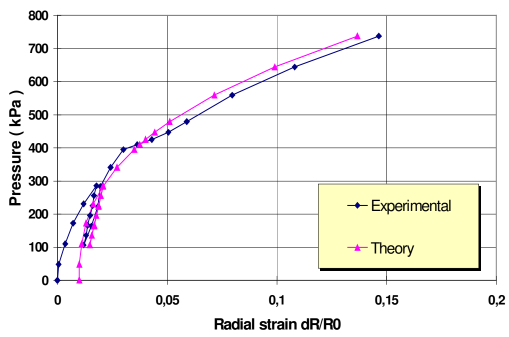

FIG. 3: Control of the stress strain parameters for a test in a gravel site

Parameter studied	E (MPa)	ν	G (MPa)	K_0	σ_z (kPa)	Φ_μ (degree)	Φ' (degree)
σ_z -1 zone	40	0.42	14.12	0.724	50-1000	27.8	30
σ_z -2 zones	40	0.30	7.26	0.429	50-1000	27.8	30
G –1 zone	10-100	0.42	3.52-35.21	0.724	250	27.8	30
G -2 zones	10-100	0.30	3.84-38.46	0.429	250	27.8	30
K_0 -1 zone	40	0.37-0.5	14.6-13.33	0.587-1.	250	27.8	45
K_0- 2 zones	40	0.2-0.36	16.7-14.71	0.25-0.56	250	27.8	45
Φ_μ -1 zone	40	0.42	14.09	0.724	250	10-30	30
Φ_μ 2 zones	40	0.30	15.38	0.429	250	10-30	30
Φ' - 1 zone	40	0.42	14.29	0.724	250	27.8	30-45
Φ - 2 zones	40	0.30	15.38	0.429	250	27.8	30-45

Table 1. Mechanical parameters used in the numerical analysis

4.2 Influence of the vertical stress

The theory takes into account the vertical stress as the intermediate stress between the radial and the circumferential stress. It shows that shearing takes place under a condition of stress close to the value of the vertical stress. For granular soil, the limit pressure is then a function of the vertical stress and when the vertical stress increases, the friction between the radial stress and the circumferential stress leads to an increase of the limit pressure. This variation is described by theoretical eqs. [6, 9] where the vertical stress is a multiplicative factor into the theoretical limit pressure. The finite element method (Figs. 4, 5) shows the same variation of the limit pressure. The difference between the theory and the Plaxis is close to 250kPa or 100kPa and stays constant during a variation of the vertical stress from 0 to 500kPa, which allows to validate the influence of the vertical stress on the limit pressure.

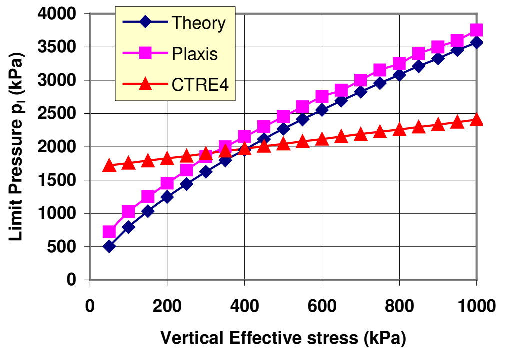

FIG. 4: Influence of the vertical stress on the limit pressure with a test with one plastic zone

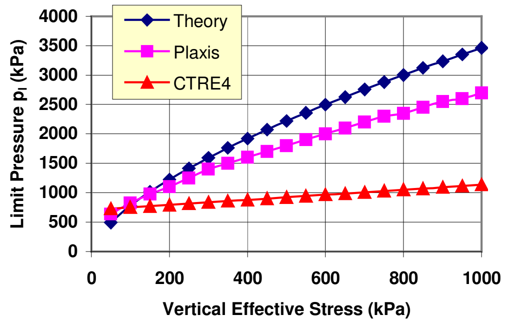

FIG. 5 : Influence of the vertical stress on the limit pressure with a test with two plastic zone

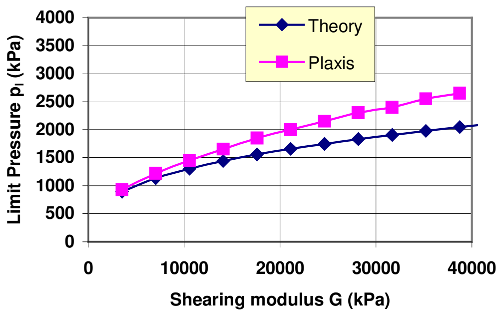

FIG. 6 : Influence of the shearing modulus on the limit pressure with a test with one plastic zone

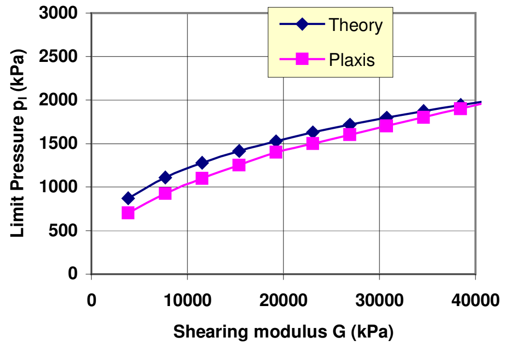

FIG. 7: Influence of the shearing modulus on the limit pressure with a test with two plastic zones

The Ménard correlative eq. [8] assumes that the net limit pressure (difference between the limit pressure and the horizontal at rest pressure) does not depend on the vertical stress and appears far from the numerical results (Fig. 4-5, curve CTRE4). The estimation of the limit pressure by this relation should be used only in the range of vertical stress between 100 to 200kPa, where the differences with numerical results remain in a small range.

4.3 Influence of the shearing modulus

The limit pressure is the value of the pressure linked to a volume of the probe, which is twice the initial one. If the soil is stiffer, for a defined value of the pressure, the deformation of the soil should be smaller, and the deformation to twice the initial volume should be reached for a high value of the pressure. On the reverse side, for a soft soil, for a defined value of the pressure, the deformation of the soil should be larger, and the deformation to twice the initial volume should be reached for a low value of the pressure. This evolution is predicted by the theory, and we can see (Figs. 6, 7) that the shearing modulus has an increasing influence on the limit pressure. As the shearing modulus increases, the limit pressure increases. Furthermore, the theory can predict with a precision of 20% the limit pressure found by the Plaxis program.

The correlative relation [8] of Ménard assumes that there is no influence of the shearing modulus on the limit pressure and it is not drawn.

4.4 Influence of the friction angle

The angle of friction acts as a resistance factor of the deformation of the soil, and when the friction angle increases the limit pressure also increases. This is predicted by the theory where the limit pressure is a function (through the variable N) of the friction angle. This variation is reproduced by the finite element analysis made by Plaxis, and a precise fitting between the theory and the numerical result is obtained with an error smaller than 12% on the value of the limit pressure (Figs. 8, 9), which validates the theory for the variation of the friction angle.

If we consider the correlative relation of Menard, it can be seen that this gives an overestimation of the angle of friction below 35° and a poor estimation of the friction angle with a large under-estimation of above 35° for the two cases analysed (Figs. 8, 9, curves CTRE4)

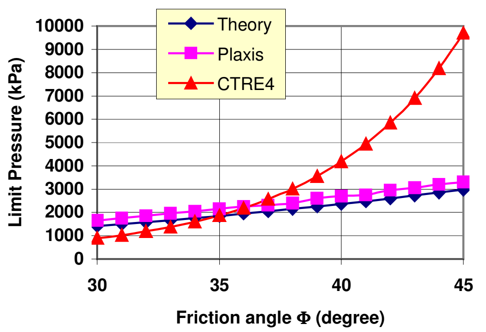

FIG. 8: Influence of the friction angle on the limit pressure with a test with one plastic zone

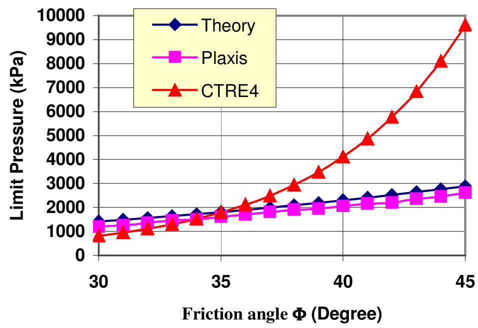

FIG. 9: Influence of the friction angle on the limit pressure with a test with two plastic zones

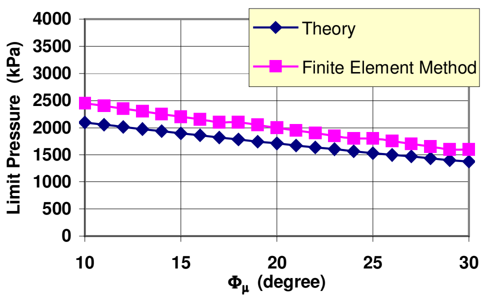

FIG. 10: Influence of the interparticle angle on the limit pressure with a test with one plastic zone

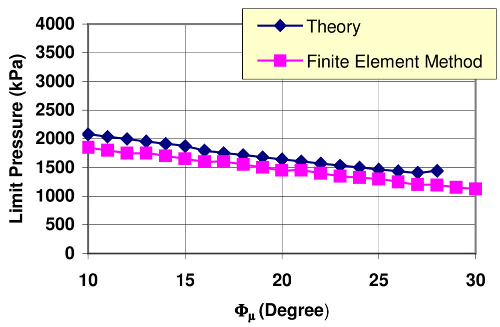

FIG. 11: Influence of the interparticle angle on the limit pressure with a test with two plastic zones

4.5 Influence of the interparticle angle of friction

The interparticle angle of friction varies from 10° for clay to 30° for sand and gravel. The theory shows that it influences the dilatancy eq. [1]. It can be assumed that an increase of the dilatancy increases the limit pressure because the expansion of the soil increases the volume of the plastic area around the probe. This theoretical phenomenon is described by the theory (fig.10, 11), and when the dilatancy is high (equal to 20° for an interparticle angle of 10° related to a friction angle of 30°), the limit pressure is also high, while when the dilatancy is small (equal to 0° for an interparticle angle of 30° related to a friction angle of 30°) the limit pressure is also small. The difference between the theory and the finite element results stays in a small range and validates the influence of the interparticle angle of friction on the limit pressure. There is no influence of the interparticle angle of friction on the limit pressure in Ménard's equation, which is not drawn here.

4.6 Influence of the coefficient of at rest pressure K_0

The coefficient at rest pressure K_0 has a small influence on the limit pressure. A small increase ion this parameter should increase the horizontal at rest pressure and consequently the limit pressure. This evolution is predicted by the theory (Fig.12-13). The difference with the finite element calculation remains in a small range for a value of K_0 larger than 0.3, which is related to the more common case where Poisson's value is higher than 0.23.

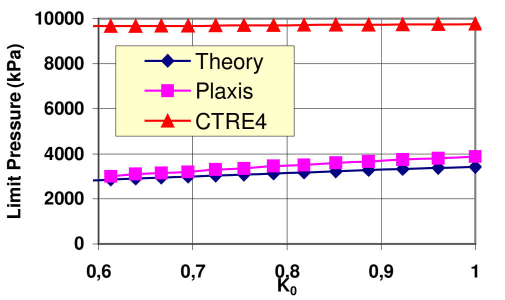

FIG. 12: Influence of the K_0 coefficient on the limit pressure with a test with one plastic zone

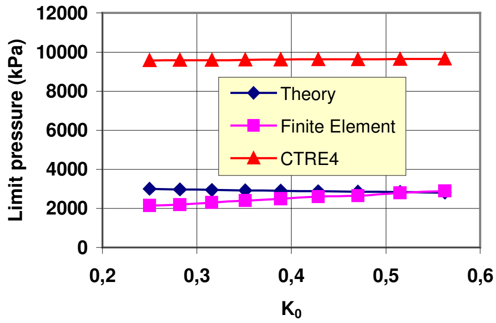

FIG. 13: Influence of the K_0 coefficient on the limit pressure with a test with two plastic zones

It can be seen that the relation proposed by Ménard gives a large difference with the theory. This is explained by the values used for the calculation, with an angle of friction of 45°, which is needed to have two different plastic zones.

6 Conclusion

We have presented a numerical analysis of the theory developed for the interpretation of the pressuremeter test, which takes into account the vertical and the horizontal non-standard elasto-plastic equilibrium around the pressuremeter probe. Plasticity may occur between the radial stress and the circumferential stress and between the vertical stress and the circumferential stress.

The theory shows that five mechanical parameters have an influence on the pressuremeter results in a granular soil (vertical stress, shearing modulus, friction angle, interparticle angle of friction, coefficient of at rest pressure) and that the conventional limit pressure is a function of these parameters. The numerical calculation of the pressuremeter test using the Plaxis code has been made with a variation of one of these variables, the others remaining unchanged. The numerical results show the same variation as the theory for each variable and a close agreement with the Plaxis results. This validates the effect of these parameters on the pressuremeter results, and shows the influence of the vertical stress, the shearing modulus, the friction angle and the dilatancy (through the interparticle angle of friction) on the conventional limit pressure. Furthermore it shows that plasticity may appear in the vertical plane between the vertical and circumferential stresses, which decreases the limit pressure.

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