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NUMERICAL ANALYSIS FOR AN INTERPRETATION OF THE PRESSUREMETER TEST IN COHESIVE SOIL

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Abstract: We present the theory used for the interpretation of the pressuremeter test in cohesive soil and its extension to the conventional limit pressure, which is defined as the pressure at the borehole wall for a volume increase ΔV equal to the initial volume of the borehole. This conventional limit pressure can be directly measured with the pressuremeter, whereas the determination of the theoretical limit pressure needs its extrapolation to an infinite expansion and cannot be directly measured. The validation of this theory is made by the finite element method with the results of the Tresca standard model of Plaxis, which is compared with the theoretical expression. Some conclusions are drawn on the validity of this new theory which allows the measurement and the control of shearing modulus and shear strength of the natural soil.

1. INTRODUCTION

The pressuremeter is a well-known apparatus (MÉNARD [5]). It is widely used nowadays for foundation engineering (AMAR et al. [1], CLARKE [2]) with mostly empirical rules. The commonly used methods for the interpretation of the pressuremeter measurement can be found in some states of the art (LADANYI [4], CLARKE [2]).

The elastoplasticity is the general frame of this study because it allows us to cover the total range from small reversible displacements to large irreversible displacements. The present approach may be considered as following the elastoplastic method (GIBSON and ANDERSON [3], SILVESTRI [7]) extended to the determination of the conventional limit pressure, which is influenced by the equilibrium in the vertical plane. The pressuremeter test is considered as an in situ shearing test, so that it measures soil deformability, shear resistance of the soil, and can be carried out in any soil, without sampling. The first part of the theoretical demonstration was previously published (MONNET and CHEMAA [6]) but the development to the conventional limit pressure was not shown then.

2. BEHAVIOUR OF COHESIVE SOIL AROUND THE PRESSUREMETER

2.1. HYPOTHESIS

We assume a test with an elastic behaviour at low level of stress. Numerical results with constitutive model (Cambou and Bahar, 1993) show that the test should be assumed as an undrained one with a permeability lower than 10^{-10} m/s. We assume a standard plasticity for a high level of shearing and positive stress in compression. The Tresca relation gives the failure of the soil between the maximum compression stress σ_1 and the minimum compression stress σ_3, with the associated flow rule and the scalar ξ

$$F(\sigma) = (\sigma_1 - \sigma_3) - 2.c_u, \quad d\varepsilon^p = \xi \,.\, \frac{dF(\sigma)}{d\sigma}\,. \tag{1}$$

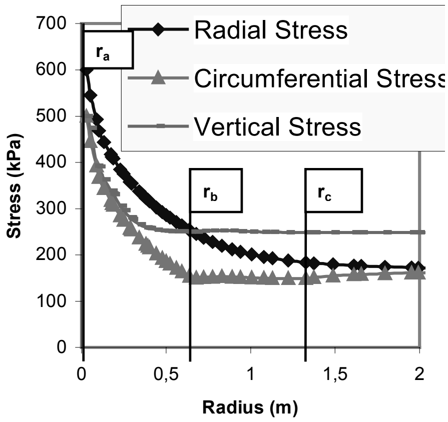

Fig. 1. Plastic areas around pressuremeter

Three different areas of soil are considered from the borehole wall to the infinite radius (figure 1). Plasticity appears between the radial stress σ_r and the circumferential stress σ_θ in the first zone. This first plastic area extends between the radius r_a (borehole wall) and r_b (external radius of the first plastic area). For a cohesive soil the plasticity may appear in the vertical plane (WOOD and WROTH [8]) between the vertical stress σ_z and the circumferential stress σ_θ in an area between the radii r_b and r_c (external radius of both plastic areas). An elastic area extends beyond the radius r_c.

2.2. EQUILIBRIUM CONDITION

In the horizontal plane and in the vertical plane, the equilibrium of an element of soil is given by:

$$\sigma_r - \sigma_\theta + r.\frac{d\sigma_r}{dr} = 0\,, \tag{2}$$

$$\frac{d\sigma_z}{dz} = \gamma \tag{3}$$

probe found by numerical analysis.

2.3. PRESSUREMETER RELATION WITH TWO PLASTIC AREAS

MONNET and CHEMAA [6] have shown that the continuity for the stress between the three different areas allows finding the constant C_1, and the relation between the pressure applied by the pressuremeter probe and the displacement at the borehole wall:

$$\ln\left[\frac{u_a}{r_a}-\frac{C_1}{2}\right]=\frac{1}{c_u}.p-\frac{\gamma.z}{c_u}+\ln\left[\frac{\gamma.z}{2.G}.(1-K_0)-\frac{C_1}{2}\right] \tag{4}$$

with

$$C_1=-\frac{c_u}{G}. \tag{5}$$

The value of coefficient C_1 is usually equal to the hundredth of the radial strain. This is very small and can be neglected. Equation (4) shows a linear relation between the logarithm of the radial strain at the borehole wall and the pressure applied by the pressuremeter as previously found (GIBSON and ANDERSON [4]). Such a relation allows the unique and accurate determination of the shear strength c_u by the slope of the straight line between the variables.

2.4. PRESSUREMETER RELATION WITH ONE PLASTIC AREA

The continuity of stress between the two different areas gives a null constant C_1. The general equilibrium condition between stress and strain is:

$$\ln\left[\frac{u_a}{r_a}\right]=\frac{1}{c_u}.p-\left[\frac{K_0.\gamma.z}{c_u}\right]-1+\ln\left[\frac{c_u}{2.G}\right]. \tag{6}$$

The proportionality between the axial strain at the borehole wall and the pressure applied by the pressuremeter is also obtained. The difference between the two cases is linked with the value of the radial stress for the radius of the external area of plasticity r_c.

The difference between the two cases is linked with the value of the radial stress for the radius of the external area of plasticity r_c. In the second case (failure between r–θ only), the value of the radial stress must be greater than the vertical stress $\sigma_{rc} > \sigma_z$ and a condition between K_0 and c_u is derived:

$$K_0 \ge 1-\frac{c_u}{\gamma.z}. \tag{7}$$

2.5. CONVENTIONAL LIMIT PRESSURE WITH TWO PLASTIC AREAS

In the two cases, we obtain the conventional limit pressure p_{lM} with the assumption of a volume of the probe which is double the initial one and a radial equal to

$\sqrt{2}-1$. The main advantage of this conventional pressure is that it can be directly measured in the pressuremeter test, which is not the case of the theoretical limit pressure found by an extrapolation for an infinite expansion of the cavity. This particular value of the radial strain is inserted in equation (4) and we obtain the conventional limit pressure:

$$p_{lM} = \gamma.z + c_u.\ln\left(\frac{2.G.(\sqrt{2}-1)+c_u}{(1-K_0).\gamma.z+c_u}\right). \tag{8}$$

This relation is quite different from the Ménard experimental correlations, proposed by the European Regional Technical Committee (AMAR et al. [1]):

$$p_{lM} = 5.5.c_u + K_0.\gamma.z \quad \text{if } p_{lM} - K_0.\gamma.z < 300 \text{ kPa}, \tag{9}$$

$$p_{lM} = 10.(c_u - 25) + K_0.\gamma.z \quad \text{if } p_{lM} - K_0.\gamma.z > 300 \text{ kPa}.$$

The Ménard relation was a result of the experience in many pressuremeter tests at mean depth. Theoretical considerations show that the shearing takes place between the radial stress σ_r and the circumferential stress σ_θ, which lie in the horizontal plane. For a cohesive soil, the plasticity condition shows that the level of shearing is independent of mean stress. In the pressuremeter test, the mean stress is proportional to the vertical stress and the level of shearing must be independent of σ_z. Equations (7) and (8) show that the net conventional limit pressure is not linked with a particular value of the vertical stress.

2.6. CONVENTIONAL LIMIT PRESSURE WITH ONE PLASTIC AREA

The particular value of the radial strain is inserted in equation (6) to infer the conventional limit pressure. It appears that the net conventional limit pressure is independent of the vertical stress:

$$p_{lM} = K_0.\gamma.z + c_u.\left[1+\ln\left(\frac{2.G.(\sqrt{2}-1)}{c_u}\right)\right]. \tag{10}$$

3. NUMERICAL VALIDATION OF THE ELASTOPLASTIC THEORY

The theoretical expressions for the conventional limit pressure in the cohesive soil depend on the vertical stress, the coefficient of pressure at rest, the shearing modulus and the shear strength. We use the finite element program Plaxis with the Tresca model to compute the value of the conventional limit pressure, which is compared with theoretical results. The model used is elastoplastic with a constant shearing modulus and five parameters (Young modulus and Poisson ratio, undrained shear strength, no friction angle, no dilatancy angle). The method used for the validation is a variation of only one parameter when the other ones stay constant. The evolution of the numerical conventional limit pressure is compared with the value found by means of the theoretical expression. The values of the mechanical characteristics are shown in the table. The mesh (figure 2) is composed of 9199 nodes with 1013 triangular elements of 15 nodes. The mesh is refined close to the borehole to have a correct numerical evaluation of the radial stress in the plastic area. The left limit is the borehole wall placed at 3 cm from the axis to simulate a 6 cm diameter borehole and no horizontal displacement are allowed above the pressuremeter probe, but vertical displacements are allowed. The right limit is placed at a radius of 5 m from the axis with a horizontal at rest pressure and displacements allowed in both directions. The lower limit is the horizontal plane, which intersects the probe at its mid-length with vertical displacements not allowed. The upper limit is an horizontal plane at 2 m from the mid-length of the probe. The ratio of L/D = 7.5 is adapted to the dimension of the apparatus, which is commonly used.

Table

The values of the mechanical parameters used in the numerical analysis

Parameter	G MPa	K_0	σ_z kPa	c_u kPa	E MPa	ν
σ_z 1 zone	13.3	0.667	100–300	100	40	0.499
σ_z 2 zones	13.3	0.667	300–600	100	40	0.499
G 1 zone	3–67	0.667	250	100	10–200	0.499
G 2 zones	3–67	0.4	250	100	10–200	0.499
c_u 1 zone	13.3	0.667	250	100–700	40	0.499
c_u 2 zones	13.3	0.667	600	80–200	40	0.499
K_0 1 zone	13.3	0.65–1.0	250	100	40	0.499
K_0 2 zones	13.3	0.3–0.55	250	100	40	0.499

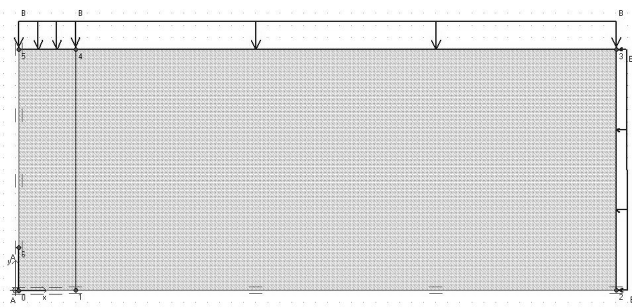

Fig. 2. The limit conditions of the mesh used

3.1. INFLUENCE OF THE VERTICAL STRESS

The theory takes into account the vertical stress as the intermediate stress between the radial and the circumferential stresses. It shows that shearing takes place mainly in the horizontal plane. For cohesive soil, the net conventional limit pressure (the difference $p_{lM} - p_0$) is independent of the vertical stress as shown by equations (8), (10), where the vertical stress is an additive factor into the theoretical conventional limit pressure so that the increase of the vertical stress gives an equivalent increase of the conventional limit pressure. The FEM (figures 3, 4) shows the same variation of the conventional limit pressure with an underestimation in the range of 8%. The Ménard equation (9) assumes that the net conventional limit pressure does not depend on the vertical stress, with an overestimation in the range of 7%.

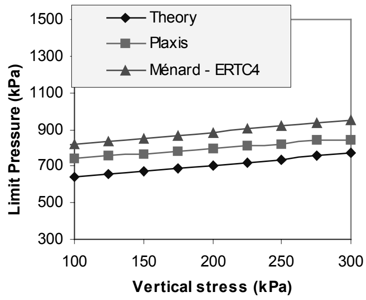

Fig. 3. Influence of the vertical stress σ_z on the conventional limit pressure in a test with one plastic zone

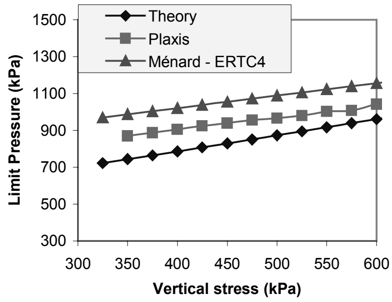

Fig. 4. Influence of the vertical stress σ_z on the conventional limit pressure in a test with two plastic zones

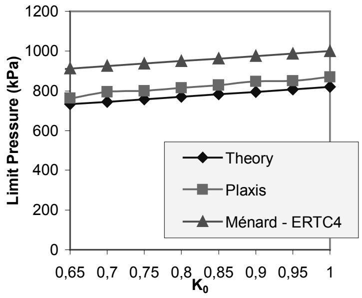

Fig. 5. Influence of the coefficient K_0 on the conventional limit pressure with one plastic zone

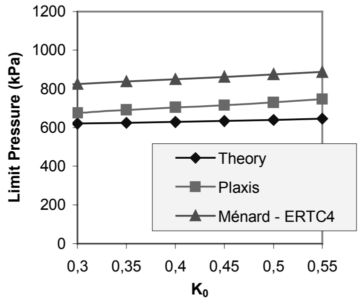

Fig. 6. Influence of the coefficient K_0 on the conventional limit pressure with two plastic zones

3.2. INFLUENCE OF THE COEFFICIENT OF PRESSURE AT REST K_0

The coefficient of pressure at rest K_0 should increase the horizontal pressure at rest and consequently should increase the conventional limit pressure. This evolution is found based on the theory for one plastic area (figures 3, 5) with an underestimation in the range of 6%. It can be seen that the relation proposed by Ménard gives more or less a larger difference compared with the Plaxis results with a difference in the range of 10%.

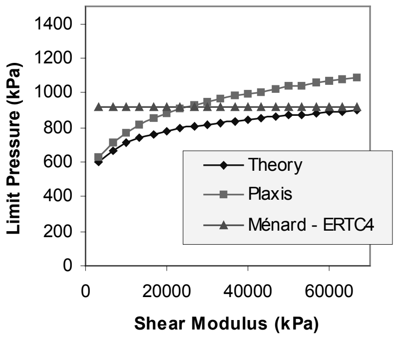

Fig. 7. Influence of the shear modulus on the conventional limit pressure in a test with one plastic zone

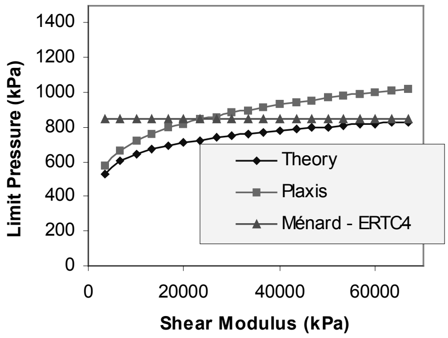

Fig. 8. Influence of the shear modulus on the conventional limit pressure in a test with two plastic zones

3.3. INFLUENCE OF THE SHEARING MODULUS

As to the conventional limit pressure value it can be inferred that if the soil is stiffer, then its deformation should be smaller, and should reach twice the initial volume for a high value of the pressure. On the other hand, for a soft soil and for a definite value of the pressure, the deformation of the soil should be larger, and should reach twice the initial volume for a low value of the pressure. This evolution is described by the theory, and we can see (figures 7, 8) that the shearing modulus has an increasing influence on the conventional limit pressure. As the shearing modulus increases, the conventional limit pressure increases. Furthermore, the theory can predict with the accuracy of 14% the conventional limit pressure obtained by the Plaxis program. But if we consider the correlative relation of the Ménard equation (8) we find that there is no influence of the shearing modulus on the conventional limit pressure. The new theory improves the interpretation of the pressuremeter test by the use of the Young modulus as a parameter of the limit pressure.

3.4. INFLUENCE OF THE SHEAR STRENGTH

The shear strength acts as a resistance factor for the soil deformation, and when the shear strength increases the conventional limit pressure increases as well. This is found by the theory of the expansion of the pressuremeter probe with a conventional limit pressure, which is the function of the shear strength. This variation is also obtained by the finite element analysis carried out by Plaxis. It can be seen (figures 9, 10) that the evolution of the limit pressure is in the same range as the numerical results with a mean difference of 70 kPa for the limit pressure, which validates the theory for the variation of the shear strength. If we consider now the correlative relation of Menard, we find an increasing difference with the numerical results of Plaxis and a serious underestimation of the shear strength as the shear stress increases with a mean difference of 360 kPa.

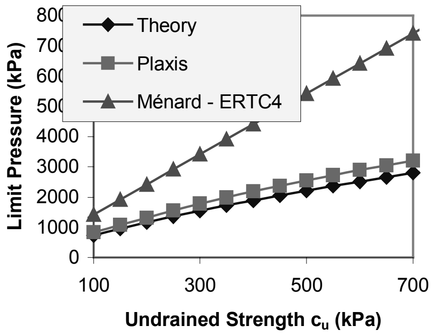

Fig. 9. Influence of the undrained strength on the conventional limit pressure in a test with one plastic zone

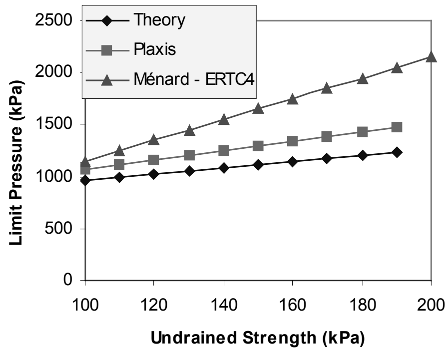

Fig. 10. Influence of the undrained strength on the conventional limit pressure in a test with two plastic zones

4. CONCLUSION

We present the numerical validation of a theory which takes into account a three--dimensional state of stress around the pressuremeter, the plasticity which occurs between the radial stress and the circumferential stress, and the plasticity which occurs between the vertical stress and the circumferential stress.

The theory shows that the linearity between the radial stress and the logarithm of radial strain at the borehole wall allows the measurement of the shear strength. This value can be controlled by the comparison between the theoretical and experimental pressuremeter curves and by the comparison between the theoretical and experimental conventional limit pressures.

The theory shows that four mechanical parameters have an influence on the conventional limit pressure (vertical stress, shearing modulus, shear strength, coefficient of pressure at rest). The numerical calculation of the pressuremeter test by Plaxis software has been made with a variation of one of these variables, while the other ones remained unchanged. The theory shows the same variation of each variable as the numerical results and a close agreement with Plaxis. This allows the validation of the theory in the range of variation for the four variables identified.

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