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Is it Possible to Determine the Soil Shear Strength and Deformation Characteristics from the Studies of Pressuremeter Tests?

Est-il possible de déterminer la résistance au cisaillement et les caractéristiques de la déformation du sol avec des essais pressiométriques?

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ABSTRACT: The paper deals with an application of the cavity expansion theory for the determination of soil strengths and nonlinear deformation parameters using pressuremeter tests. The developed cavity expansion theory takes into consideration the facts that even the initial soil stress-strain state itself is anisotropic, and that due to expansion soil density increases. By having introduced the deformation modulus, we have introduced two soil constants; (E_O) that is the basic deformation modulus, and (a) an exponent. The soil strength parameters, namely cohesion (c) and angle of friction (ϕ), as well as the deformation parameters represent the soil properties. We can determine only the combination of the interrelated and suitable soil parameters from the pressuremeter test. The paper presents an example, and proves that the measured diagram very well approximates the theoretically calculated diagrams with different cohesion - basic deformation modulus combinations.

RÉSUMÉ : L'auteur s'occupe de l'application de la théorie de l'expansion d'une cavité pour déterminer la résistance du sol et les paramètres de la déformation non-linéaire du sol par des essais pressiométriques. La théorie avancée de l'expansion d'une cavité tient compte du fait, que l'état contrainte-déformation d'origine est anisotrope, et la densité du sol s'accroît à cause de l'expansion. En introduisant le module de déformation, deux constantes caractérisant le sol ont été introduites: le module de base de déformation (E_0) et l'exposant (a). Les valeurs déterminant la résistance du sol, c'est à dire la cohésion (c) et l'angle de frottement interne (ϕ) ainsi que celles de la déformation reflètent les propriétés du sol. Avec l'essai pressiométrique on peut déterminer seulement une combinaison de certains paramètres du sol qui sont liés entre eux. Un exemple est présenté qui prouve, que la courbe reflétant les résultats des essais pressiométriques s'ajuste bien aux courbes théoriques calculées en utilisant différentes combinaisons cohésion - module de base de déformation.

KEYWORDS: Cavity expanding theory, pressuremeter test, nonlinear deformability of soil.
MOTS-CLÉS : théorie de l'expansin d'une cavité, essai pressiométrique, déformation non-linéaire des sols

1 INTRODUCTION

The pressuremeter test covers the in situ measure of the deformation of soils and weak rock based on the expansion of a cylindrical flexible membrane under pressure.
The pressuremeter is recognized as a worldwide field test with good potential to be used together with analytical interpretations, in establishing constitutive models for soils.
The expansiometric characteristic of the test has a good agreement with the expansion of a cylindrical cavity. The parameters identification by inverse analysis of pressuremeter test for soil strength and deformation parameters offers good possibility to interconnect the conventional geotechnical models to the in situ tests. The pressuremeter test may be the most suitable method for ground which is difficult to sample.
Pressuremeter technology has been greatly affected by developments in measurement technology and computer technology. It is important that the basic principles forthe design of pressuremeters, the measurement procedures and the analysis of the data resulting from the tests should always be based on the same internationally accepted principles.
The Ménard type pressuremeter is popular in the geotechnical praxis. Two basic test procedures can be differentiated: a procedure to obtain a pressuremeter modulus E_M, and limit pressure p_{LM}, that may be used in design procedures formulated for the Ménard pressuremeter; and another procedure to obtain other stiffness and strength parameters.

2 CAVITY EXPANDING THEORY- SOIL PARAMETERS

2.1 Basic assumptions

The determination of the soil parameters from the cylindrical cavity expansion - cavity stress relationship curve is not an easy task, because the soil deformation and strength parameters are in combination with each other. We *can only determine the combination* of the interrelated and suitable soil parameters.

The specific deformations (strains) are defined as the compression/dilation of a layer of soil of unit thickness. By convention, compression of the soil is taken as a positive value, while loosening (expansion) will have a negative sign. Strains are dimensionless quantities mostly expressed as percentages but for calculations used as ratios. The specific deformations are always conceived as the changes in the dimensions of a soil mass, i.e. as macro-variations and not micro-variations. Clearly, the change in density due to changes in the complex state of stress results from the micro-movements of the individual soil grains. The micro-movements of the grains are determined by themselves and occur at random, but as the resultant of the cumulative movements they become apt for engineering calculations.
In the case of granular soils and soils of low cohesion relationships based on tests can be used. In the case of materials exhibiting high cohesion the structure of the material becomes decisive since under heavy load the structure collapses.

We are supposing axially symmetric stress condition in normally consolidated soil with incompressible soil grains.
The developed cavity expanding theory takes into consideration that already the initial soil stress-strain state is anisotropic, at the initial stage we can find the compressive stresses in vertical direction (σ_v), and earth pressure at rest in horizontal direction (σ_H)

Practical application of the expansion pressure has to follow some time-dependent rate. If the loading rate is faster than what the soil may endure, a consolidation process arises and the deformation of the soil mass extends to longer periods. This is particularly influenced by the dissipation of the pore-water pressure. The model deals with the ultimate rate of deformations.

The expansion of the cylinder has a complex effect on the stresses, the displacement of soil particles and the soil compaction as well; the cavity stress/strain diagram is obtained as a resultant and consequence of these effects. In this diagram, we can't distinguish elastic or plastic sections, nevertheless, professional engineering literature often refers to the initial section of the diagram as 'quasi elastic'.

If we want to determine the diagram demonstrating the expansion process on the grounds of the basic (not derived) properties of the soil, we need to carry out a detailed analysis of the volumetric changes of the soil and the changes in soil stresses exerting in different directions.

Special attention must be paid to the fact that the cylinder is surrounded by a soil mass of infinite extent. The movement of particles is impeded by the gradually compacting soil mass. The compaction is mainly due to the limited expansion in the hoop direction.

2.2 Summary of the elements of the model

a) Application of the Mohr-Coulomb condition;
b) Force equilibriums;
c) Non-linear relationships between the increasing soil stress and soil strains;
d) Assuming elastic behaviour if the soil stress is decreasing;
e) The volumetric strain (change in density) of the soil, is obtained as the resultant of strains in three mutually perpendicular directions.

a.) Application of the Mohr-Coulomb condition

The Mohr-Coulomb condition expresses a constant ratio between the principal stresses $(\sigma_1 = \sigma_r, \sigma_3 = \sigma_t)$, in a manner, whereby, in the case of the maximum principal stress, its value is reduced by the unconfined compression strength (σ_u).

$$\frac{\sigma_3}{(\sigma_1 - \sigma_u)} = \underbrace{\frac{1 - \sin\phi}{1 + \sin\phi}}_{\xi} \quad (1) \qquad \text{where} \qquad \sigma_u = \frac{2 \cdot c}{\sqrt{\xi}} \quad (2)$$

This means that the increase of external actions provokes a situation whereby the alterations ensue along a minimum but constant ratio of the reduced principal stresses.

b) Force equilibriums

The force equilibrium differential equations on the basis of the balance of forces exerted on the element of soil:

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_t}{r} = 0 \quad (3)$$

σ_r, σ_t are radial and tangential (hoop) directions stress on the horizontal plane

b.) Non-linear relationships between the increasing soil stresses and soil strains

Being on the basis of the Mohr-Coulomb condition, the increments of the radial and hoop stresses are in linear relationship with each other, therefore, the correlation between the average soil pressure and the volumetric deformation of the soil is similar to the correlation that evolves between the radial pressure and the radial specific deformation.
With increasing the external pressure continuously on the wall of the cylinder, the pressures in the elementary soil cube also increase proportionally and the soil becomes ever denser and less compressible.

Based on the above defined relationships, the relation between specific deformation and average soil pressure can be approximated by introducing an exponential equation which incorporates a term for equating the dimensions.
So, the relation between specific radial deformation and radial soil stresses can be described in the following form:

$$\varepsilon_r = a_1 \cdot \left(\frac{\sigma_r}{\sigma_e}\right)^{a_2} \quad 0 < a_2 < 1 \quad (4)$$

where $\sigma_e = 100\text{kN/m}^2$ is the reference stress introduced to restore dimensional consistency between the two sides of the equation.
By derivation and inversion we get the deformation modules:

$$E_r = \frac{d\sigma_r}{d\varepsilon_r} = \underbrace{\frac{\sigma_e}{a_1 \cdot a_2}}_{E_o} \cdot \left(\frac{\sigma_r}{\sigma_e}\right)^{\overbrace{1-a_1}^{a}} = E_o \cdot \left(\frac{\sigma_r}{\sigma_e}\right)^{a} \quad \text{and } a<1 \quad (5)$$

From (5) it follows that the deformation modulus is not in linear relationship with soil pressure.
By having introduced the deformation modulus, we have introduced two soil constants:
- (E_o): the initial deformation modulus, and
- (a): the stiffness exponent, named as stiffness index.

On the basis of our investigations and having been confirmed through the evaluation of accomplished in situ tests we may suppose that the value of the exponent (a) might be brought in connection with the roughness of the soil grains (consequently it depends mostly on the internal friction angle), while the value of the initial deformation modulus might be connected to the initial density of the soil and the cohesion.

c.) Assuming elastic behaviour if the soil stress is decreasing

If the initial compressive stress decreases, expansion develops in the soil, and we may describe it more closely as elastic behaviour. For the hoop direction on the horizontal plane the soil strain is:

$$\Delta\varepsilon_{\%} = \underbrace{-\frac{\Delta\sigma}{E_o \cdot \sigma_H{}^a} \cdot 100}_{\text{Expansion linear}} \quad (6)$$

It is valid if the soil stress value is less than the initial stress.

d.) The volumetric strain (change in density) of the soil

The volume change of the soil (the change in density) can be derived from its specific deformations. We can approximately calculate with the sum of three specific deformations changes determined at right angles to one another.

$$m_s = \frac{V_i - V_o}{V_o} = (1+\Delta\varepsilon_r)\cdot(1+\Delta\varepsilon_t)\cdot(1+\Delta\varepsilon_v) - 1 \approx \Delta\varepsilon_r + \Delta\varepsilon_t \qquad (7)$$

If $\sigma_t > \sigma_H$ then $\Delta\varepsilon_v > 0$ compacting the soil in the vertical direction too.

Unit weight of the soil is:

$$\gamma_s = \frac{\gamma_o}{1 - m_s} \quad \text{where } \gamma_o \text{ is in the initial state} \qquad (8)$$

2.3 Conditions applied for the model

Possible effects applied to the area outside the plastic stress zone (compaction zone):

- Force equilibrium differential equation,
- Nonlinear relation between radial deformations and stresses (compression),
- Linear relation between hoop stresses and deformations (expansion),
- There is no volume change, no density change of soil

At the border of the plastic stress zone:

- The same effects apply as for the area outside the zone, but they are supplemented
- The Mohr-Coulomb relation has an effect.

Effects applied within the plastic stress zone:

- Force equilibrium differential equation,
- The Mohr-Coulomb relation,
- Nonlinear relation between radial deformations and stresses (compression),
- Nonlinear or linear relation between stress and deformation depending on whether the stresses exceed the initial stress.

2.4 Pressures at the boundary of the compacted zone (r=ρ)

Because at the boundary of the compacted zone the soil does not change in volume (m_s=0, no change in the density of the soil) we can determine the radial stresses which develop at the boundary of the plastic stress zone.

$$0 = \underbrace{\frac{\sigma_{\rho_H}{}^{1-a} - \sigma_H{}^{1-a}}{(1-a)\cdot E_o}}_{\Delta\varepsilon_r} - \underbrace{\frac{\sigma_H - \overbrace{\xi\cdot(\sigma_{\rho_H} - \sigma_u)}^{\sigma_t \Leftarrow \text{Mohr-Coulomb}}}{\sigma_H{}^a \cdot E_o}}_{\Delta\varepsilon_t\ (\Delta\varepsilon_v = 0)} \Rightarrow \sigma_{\rho_H} \qquad (9)$$

Compression Expansion

Where ρ is the radius of the compacted (plastic stress) zone, and $\sigma_{\rho_H} = K_{\rho_H}\cdot\sigma_H$ is the soil stress at the radial direction.

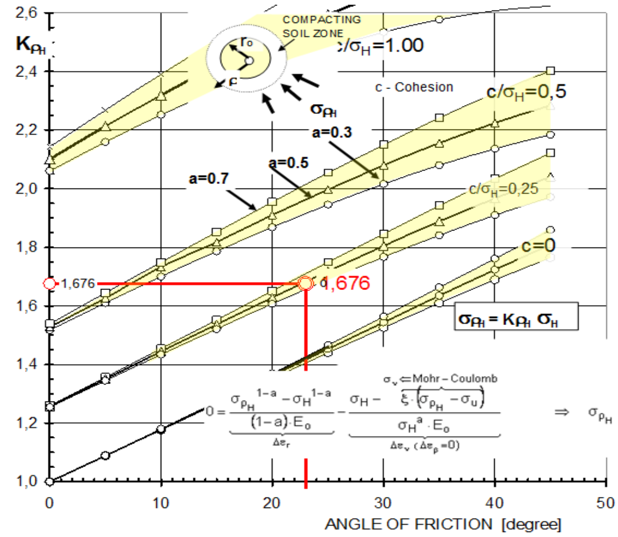

Figure 1. Diagram for the determination of the radial stresses at the boundary of the compacted zone. (r=ρ)

For practical calculation, Fig. 1. shows the diagram to be used for the determination of the radial stresses at the boundary of the compacted zone. It should be noted that the stresses developing at the boundary of the compaction zone do not depend on the size of the compaction zone, nor on the value of the basic deformation modulus.

2.5 Distributions of the radial stresses near the cylinder

The distribution of soil stresses within the compacted zone is statically determined from the force equilibrium and the Mohr-Coulomb condition:

In horizontal radial direction of expanding, if r<ρ:

$$\underbrace{\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_t}{r} = 0}_{\text{force equilibrium}} \Rightarrow \underbrace{\sigma_t = \xi\cdot(\sigma_r - \sigma_u)}_{\text{Mohr-Coulomb}} \Rightarrow \sigma_r \qquad (10)$$

$$\Rightarrow \sigma_r = \left(\underbrace{K_{\rho H}\cdot\sigma_H}_{\sigma_{\rho H}} + \frac{c}{\tan\phi}\right)\cdot\left(\frac{\rho}{r}\right)^{\frac{2\cdot\sin\phi}{1+\sin\phi}} - \frac{c}{\tan\phi} \qquad (11)$$

if r>ρ $\Rightarrow$ no volume change in the soil

$$\sigma_r \approx (\sigma_{\rho H} - \sigma_H)\cdot\left(\frac{\rho}{r}\right)^2 + \sigma_H \qquad (12)$$

If we know the magnitude of the radial stress exerted on the initial surface, the extension of the compaction zone can be calculated from Eq. 11, where r_o is the initial radius of the cylinder.

$$\rho = r_o \cdot \left(\frac{\sigma_{ro} + c/\tan\varphi}{\sigma_{\rho H} + c/\tan\varphi}\right)^{\frac{1+\sin\varphi}{2\cdot\sin\varphi}} \qquad (13)$$

2.6 Determination of the aggregate soil compaction

The soil displacements are interconnected with the soil strains, in that they are the integrated values of the strains.

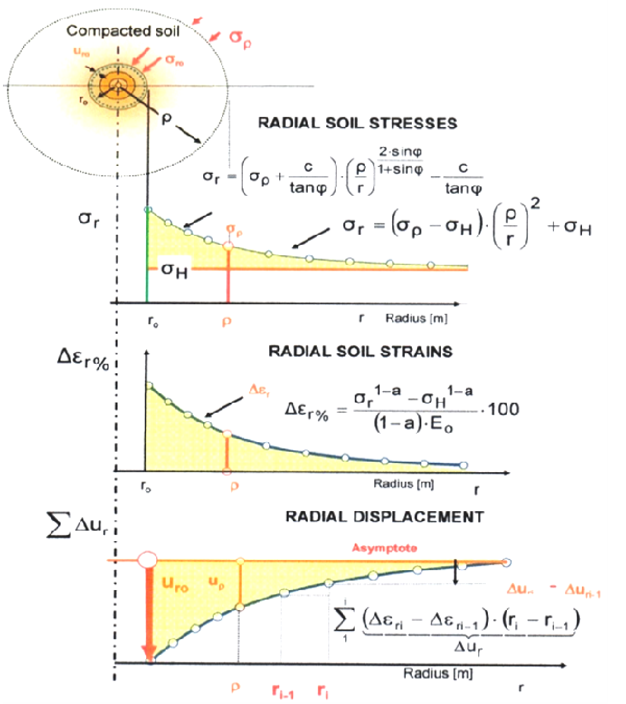

Figure 2. Determination of soil strain and displacements

The radial displacement vector is:

$$u = \underbrace{\int_{r_o}^{\rho} \frac{\overbrace{\sigma_r^{1-a}}^{\text{Mohr-Coulomb}} - \overbrace{\sigma_H^{1-a}}^{\text{initial}}}{(1-a)\cdot E_o}\cdot dr}_{\text{inside of the comp. zone}} + \underbrace{\int_{\rho}^{\infty} \frac{\overbrace{\sigma_r^{1-a}}^{m_r=0} - \overbrace{\sigma_H^{1-a}}^{\text{initial}}}{(1-a)\cdot E_o}\cdot dr}_{\text{outside of the comp. zone}} \qquad (14)$$

This relationship also means that the total compression of the soil is equivalent to the area of the diagram showing the radial distribution of radial strains.

We thought it useful to perform calculations in Excel form and present tabulated results in graphs which may greatly help perception.

The compression of a given (r_i - r_{i-1}) segmentation of the radius can be composed of the specific compressions, and the aggregate value is composed of the individual segments.

The compression of the soil in a radial segment:

$$\Delta u_{r_i} = \left(\frac{\Delta\varepsilon_i + \Delta\varepsilon_{i-1}}{2}\right)\cdot(r_i - r_{i-1}) \qquad (15)$$

The total radial settlement is:

$$u_{r_o} = \sum_{i=1}^{n}\left(\frac{\Delta\varepsilon_{r_i} + \Delta\varepsilon_{r_{i-1}}}{2}\right)\cdot(r_i - r_{i-1}) \qquad (16)$$

where *n* is the number of the segmentation of the radius.

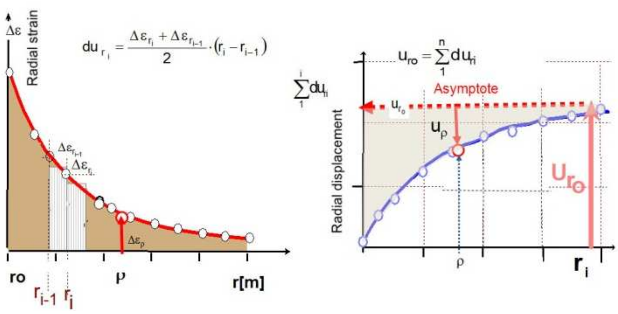

Figure 3. Determination of soil strain and displacements

It is practical to represent the sum of the compression of the individual soil hoops beginning at the initial radius, because it is clear that beyond a certain range the extent of soil compression is not considerable; therefore we can draw an asymptote to the curve of the aggregate compression values.

It should be noted that the distribution of stresses along a radius theoretically extends to infinity, but for practical purposes stress increments beyond a distance of 5 to 6 times the cavity radius diminish to an insignificant value.

2.7 Infinite length vs. finite length problem of the cylinder

The interpretation of the pressuremeter test data is based on the assumption of a cylinder of infinite length expanded in the soil, while in reality the expanded cylinder has finite length. At the ends of the probe the strain conditions do not exhibit axial symmetry. In order to minimize this effect it is required that the dimensions of the probe L/D>6.5, the guard cells (See Fig.4) are included in the length of the probe.

At the beginning of the expanding process *in the horizontal plane* the radial stress gradually increases, while the hoop stress decreases, and *in the vertical direction the soil stress does not change*. If the ratio of the hoop stress to the reduced radial stress arrive at the minimum value, after the hoop stress also continuously increases, the soil compaction begins in accordance with the Mohr-Coulomb condition. Because the initial soil stress on the vertical direction is limited, and in the horizontal plane both radial and hoop stress together increase, we arrive at the limit radial stress. After the limit radial stress is reached, the cavity strain progressively increases.

We suggested that this limit radial stress acting on the cylinder wall may approximate that in the loading process the hoop stress achieves the initial vertical stress.

We provide the multiplication factor κ for the initial hoop stress. This parameter depends on the boundary condition of expanding cylinder. (For example it is different for bored pile and driven pile.)

Accordingly, the value of the limit stress can be obtained by the following expression.

$$\underbrace{\kappa\cdot\sigma_H = \xi\cdot\left(\sigma_{r_{olimit}} - \sigma_u\right)}_{\text{Mohr-Coulomb}} \Rightarrow \sigma_{r_{olimit}} = \frac{\overbrace{\kappa\cdot\sigma_H}^{\sigma_V}}{\xi} + \sigma_u \qquad (17)$$

3 THE PRESSUREMETER TESTS

The pressuremeter

The pressuremeter consists of three main parts:

- an expandable cylinder (probe);
- tubing;
- measuring/monitoring/control unit.

Calibration

Before each test series, the correction factors deriving from the deflection of the membrane of the probe, the monitoring panel and the manometers must be determined by calibrating the probe.

It determines the resistance of the membrane and is performed by inflating the probe in the open air.

Hydrostatic pressure must also be considered when evaluating test results. The value of hydrostatic pressure is to be measured at the middle of the probe.

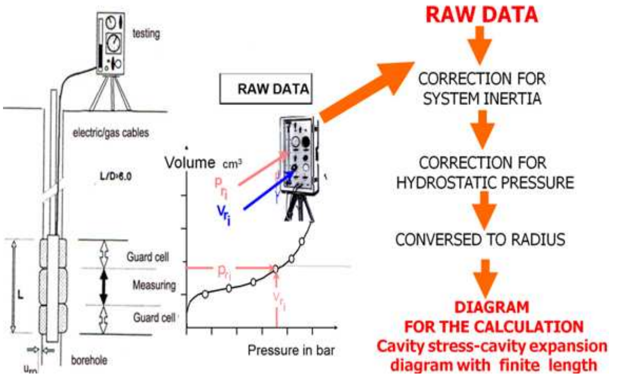

Figure 4. The calibration process of the pressuremeter test.

The original volume must be determined before the probe is inserted into the borehole (V_o).
V_o is the volume measured in the unloaded probe at atmospheric pressure.

4 DETERMINATION OF THE SOIL PARAMETERS

We are using two measured values of every step during the loading process for the determination of the soil parameters. These are: the measured pressure acting of the membrane, and the displacement of the membrane due to the pressure. The test is carried out iteratively using the computer program.

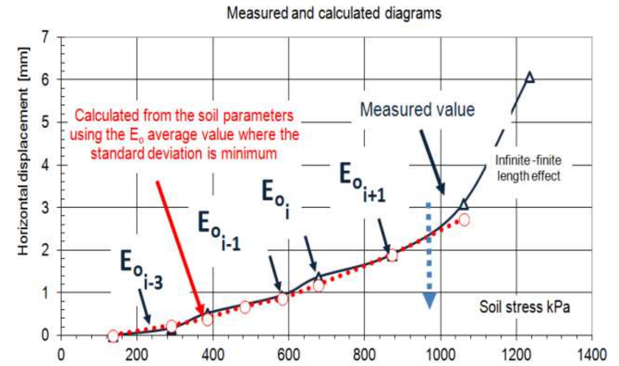

Figure 3. The approximation of the measured cavity expansion diagram with the theoretical curve, which is composed of the soil strength and deformation parameters.

The essence of the method is as follows:

Choosing the soil physical parameters, namely strength parameters (ϕ,c) and rigidity index (a), but only the value E_o will be unknown. For every point (i) of the measured diagram, we can determine E_{oi} value. We have N number of the E_{oi} values.
We assume that for all of the measured points (N) the E_{oi} are constant, and we use the average value of $\overline{E_o}$ for determining the theoretical cavity stress-cavity expanding diagram. See Fig.3. The best fit to the measured diagram is that where the standard deviation of E_{oi} is minimum.
The calculation process is easy using computer program.

a.) Using of the pressure acting on the cylinder wall

The measured pressure, that is equivalent to the soil pressure acting on the cylinder wall, can be determined with the combination of the soil strength parameters. If we know the pressure at the cylinder wall, we can determine the radius of the compacted zone (Eq 11), and the distributions of stresses near the cylinder.

$$\underbrace{p_i}_{\text{measured}} \equiv \sigma_{r_o} = \left(\underbrace{K_p \cdot \sigma_H}_{\sigma_p} + \frac{c}{\tan\phi} \right) \cdot \underbrace{\left(\frac{\rho}{r_o} \right)^{\frac{2\cdot\sin\phi}{1+\sin\phi}}}_{\text{determine}} - \frac{c}{\tan\phi} \tag{18}$$

b.) Using of the measured cavity expansion.

$$\sum_1^n A_i = \sum_1^n \left(\left(\underbrace{\frac{\sigma_{r_i}^{1-a} - \sigma_H^{1-a}}{1-a}}_{\Delta\varepsilon_r} \right) + \left(\underbrace{\frac{\sigma_{r_{i-1}}^{1-a} - \sigma_H^{1-a}}{1-a}}_{\Delta\varepsilon_{r_{i-1}}} \right) \right) \cdot \frac{r_i - r_{i-1}}{2} \tag{19}$$

where n is the number of the sections of the radius.
The measured soil displacements at the pressuremeter surface are:

$$\underbrace{u_{ro_i}}_{\text{measured}} \cdot E_{o_i} = \sum_1^n A_i \Rightarrow \tag{20}$$

$$E_{oi} = \frac{\overbrace{\sum_1^n A_i}^{\text{Calculated}}}{\underbrace{u_{roi}}_{\text{measured}}} \tag{21}$$

that is only one measured point, and we have N determined E_{oi} parameters.

The average and standard deviation are:

$$\overline{E_o} = \frac{\sum_1^N E_{o_i}}{N} \Rightarrow s = \sqrt{\frac{\sum_1^N \left(E_{o_i} - \overline{E}_o \right)^2}{N-1}} \quad \text{minimum!} \tag{22,23}$$

Note: Different are n, the number of the segment of the radial strain section, and N, the number of the measured points. The best fit to the measured diagram is that where the standard deviation of E_o is minimum.

Example

The initial data source is : Reiffsteck P. (2005) in ISP5-Pressio 2005 Symposium international, 50 ans de pressiomètre. Marne-la Vallée 22-24 août 2005. Edited by M. Gambin, J.P. Magnan, P. Mestat ISBN 2-85978-417-9 Volume 2. pp. 521-535

Table 1. Some details of the pressuremeter analysis

Borehole No 100 Gprobe		z=12.0 m		H=0.80 m		GWL=1.0 m	
Measured diagram							
Pressure (bar)		2.00	3.00	5.00	6.00	8.00	10.00	12.00
V_i		104	122	136	154	177	230	370
Pressure loss diagram								
Pressure (bar)		0	20	50	70	100	120	150
Volume (cm^3)		0	65	156	240	398	515	699
Transformed for the cavity stress- cavity strain diagram from the measured data								
Δp	(kPa)	38,8	43,4	46,9	51,2	56,5	67,9	95
$p_{corrected}$	(kPa)	289,2	384,6	581,1	676,8	871,5	1060,0	1233,0
Di (diameter)	(mm)	62,24	63,11	63,78	64,63	65,70	68,10	74,07
$U_{ro\ corr}$	(mm)	0,17	0,61	0,94	1,37	1,90	3,10	6,09
D_o	(mm)	61,9 mm	Initial horizontal soil stress σ_H=136 kPa					

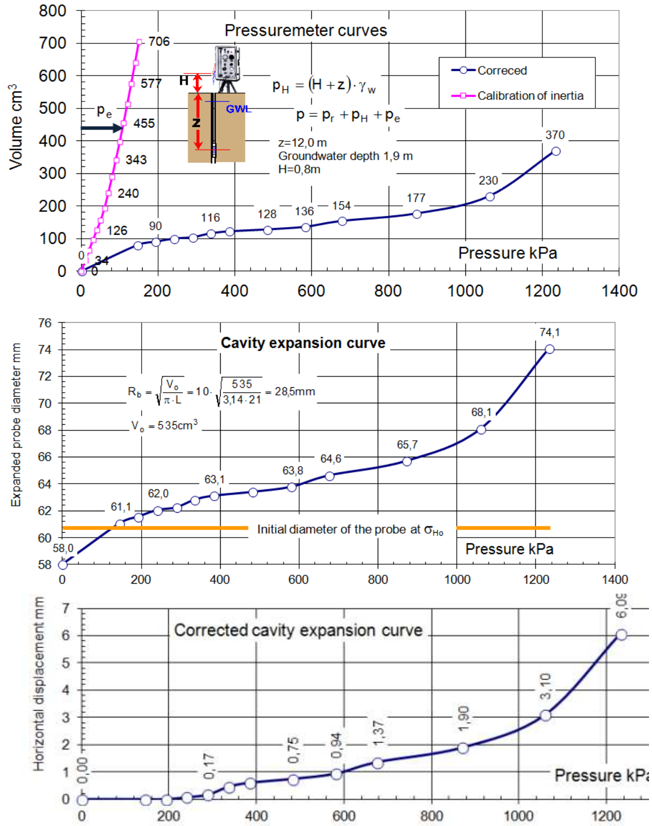

Figure 6. Correction of the measured pressures, and conversion of the volume to radial displacement

Table 2. Determination of the soil physical parameter combination from the measured pressuremeter diagram

Borehole Number No100	Angle of friction ϕ=23,4 deg			Cohesion c=102 kPa			
Depth z=12 m	Power index (Rigidity index) a=0,42						
σ_{pH} [kN/m^2] Eq(9)	256,37 kN/m^2		From one of the best combinatios				
$p_{corrected}$	289,2	384,6	483,0	581,1	676,8	871,5	1060,1
ρ[mm] Eq(13)	34,7	46,5	60,3	75,5	91,7	128,9	169,9
ΣAi Eq(20)	718,0	953,0	1640,0	2104,0	2868,0	4609,0	6626,0
E_o (calculated)	24,4	11,7	16,6	17,0	15,9	18,4	16,2
u_{ro} (calculated)	0,23	0,4	0,68	0,87	1,19	1,91	2,75

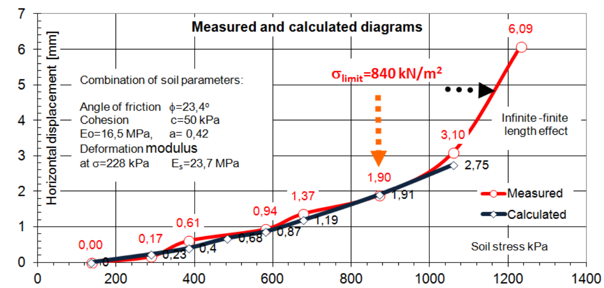

Figure 7. Approximation of the pressuremeter curve

Estimation of the limit pressure

We assume that if the hoop pressure reaches the initial vertical pressure, after progressive increases of the cavity expansion

$$\sigma_{r_o\,\mathrm{limit}} = \frac{228}{0{,}42} + \frac{2\cdot 102}{\sqrt{0{,}42}} \approx 840\mathrm{kN/m^2}$$

Soil properties trough laboratory and CPT in situ testing

The challenge was that we had to estimate the capacity of a bored pile, by providing the measurements of pressuremeter tests and soil test results. The laboratory and CPT tests carried out on soil samples obtained close to the pile location yielded relatively homogeneous physical parameters. The shear strength parameters were c'=57 kPa and ϕ'=23 degrees.
The results of the soil investigations are shown on Fig. 8.

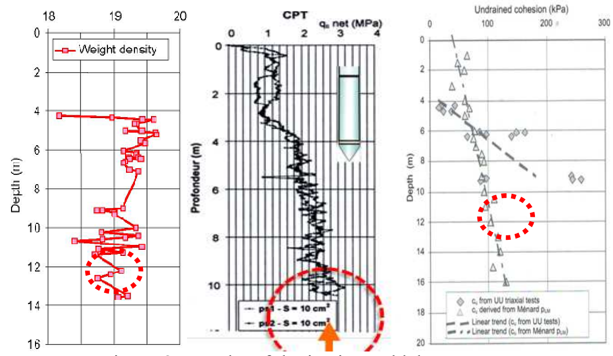

Figure 8. Results of the in situ and laboratory tests

Do results change for different radii of the cylinder

The radial soil stress depends on the ratio of the radii outside and those inside the compacted zone, and at the boundary of the compacted zone the radial and the hoop pressure are independent of the radii.
The cavity stress acting at the cylinder surface is:

$$\frac{\sigma_{r_o}}{\sigma_H} = \left(K_{\rho H} + \frac{c}{\sigma_H\cdot\tan\phi}\right)\cdot\left(\frac{\rho}{r_o}\right)^{\frac{2\cdot\sin\phi}{1+\sin\phi}} - \frac{c}{\sigma_H\cdot\tan\phi} \qquad (24)$$

The ratio of the extent of the compaction zone to the initial radius depends solely on the combination of the parameters of the soil. It means that in the same soil and at the same depth the ratio is the same. The cavity expansion is:

$$\frac{u_{ro}}{r_o} = \sum_{1}^{N}\Delta\varepsilon_r\left(\frac{r_2}{r_o} - \frac{r_1}{r_o}\right) \qquad (25)$$

It means that ~~in~~for the same soil and the same depth the calculated cavity pressure – cavity strain diagrams for different initial radii are equal.

5 CONCLUSIONS

The pressuremeter is well-known but in many countries it is not often used as an in-situ method.
The limitation of its application is that the classical civil engineering models do not use the pressuremeter parameters, and so far we did not have a reliable method for determining the shear strength and deformability parameters of the soil.
The investigation of stress - strain and volume changes which take place around the expanded cylindrical cavity in the soil raises a number of questions, but we can say that the investigation methods have gradually extended our knowledge of this type of problems and also turned the attention to the unsolved questions.
The developed cylindrical cavity theory renders it possible to determine more details of soil properties characteristics combinations.

The paper presents the major elements of the cavity expansion theory, namely based on the Mohr-Coulomb theory, nonlinear deformability of soils, and using these elements it presents a calculation model for determining the strength and deformation soil parameter combinations.

It is important to remark, that we determine ***parameters combinations,*** because the measured diagram accessible as cohesion and E_o is different with its value pair, or the friction angle and stiffness index pairs can be different.

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