A Novel Method for Pressuremeter Test Interpretation: Accounting for Membrane Deformation Effects

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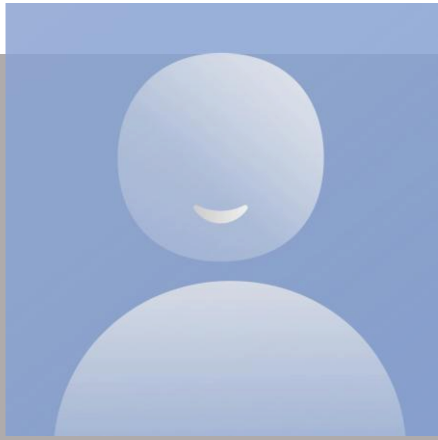


1. Introduction

The various pressuremeter standards (AFNOR, 2015; ASTM, 1994) require only two corrections to be applied to raw measurements: one for apparatus expansion and the second for membrane stiffness.

This approach:

- Neglects the effect of membrane thickness.
- Assumes that the pressuremeter probe deforms as a perfect cylinder.

We present two additional corrections that:

- take into account the actual thickness of the membrane (and of the slotted tube, where present)
- take into account the probe deformation during loading, similar to that of a beam on two simple supports or fixed at both ends.

A theoretical correction is proposed and verified by a finite-element calculation.

Two applications are carried out ; one on the cross-tests performed by Fondasol for the ARSCOP research project at the Messange site; the second on two soils on the Rhone valley

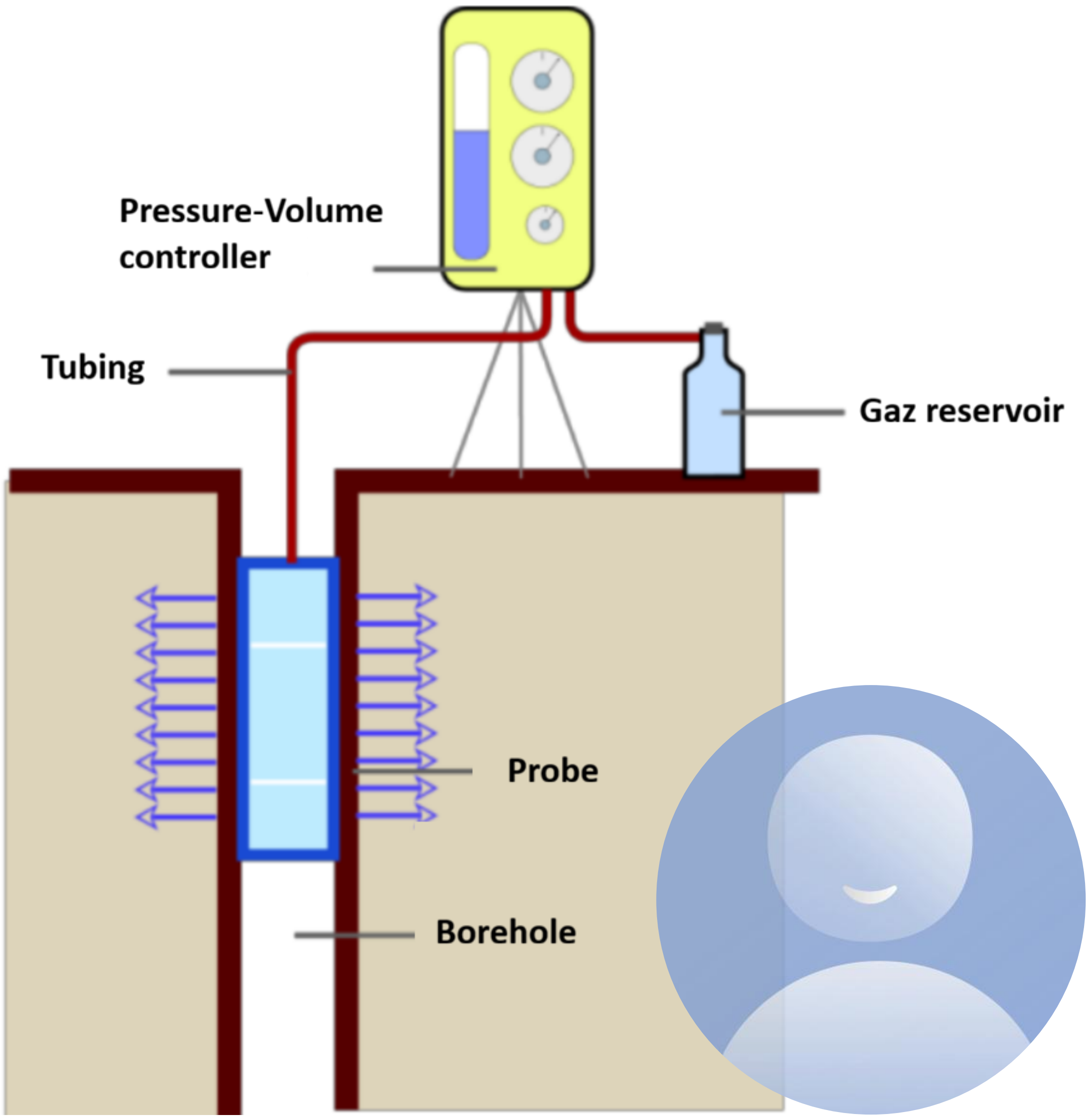


Fig 1 : The pressuremeter test

2.1 Membrane thickness

$$p_i.r_i.d\theta = p_e.(r_i + e).d\theta = p_e.r_e.d\theta \qquad (1)$$

$$(p_i - p_{ie}).r_e.d\theta = p_e.(r_i + e).d\theta = p_e.r_e.d\theta \qquad (2)\ \text{Fig.2.b}$$

The pressure–volume controller of the pressuremeter applies an internal pressure p_i to the probe (using water pressure), and the soil reacts with an external reaction pressure p_e on the probe.

Equation (1) gives the relationship between p_i and p_e without the membrane-stiffness correction, while equation (2) gives the relationship between p_i and p_e with the membrane-stiffness correction.

These equations show that p_e is always lower than p_i.

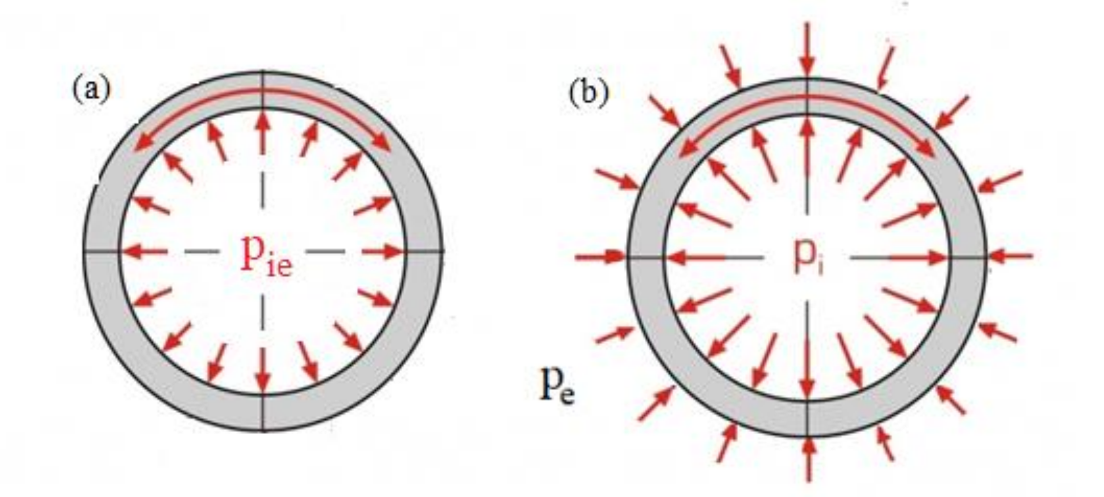


Fig. 2 – Differences between the internal pressure p_i and the external pressure p_e at the pressuremeter probe

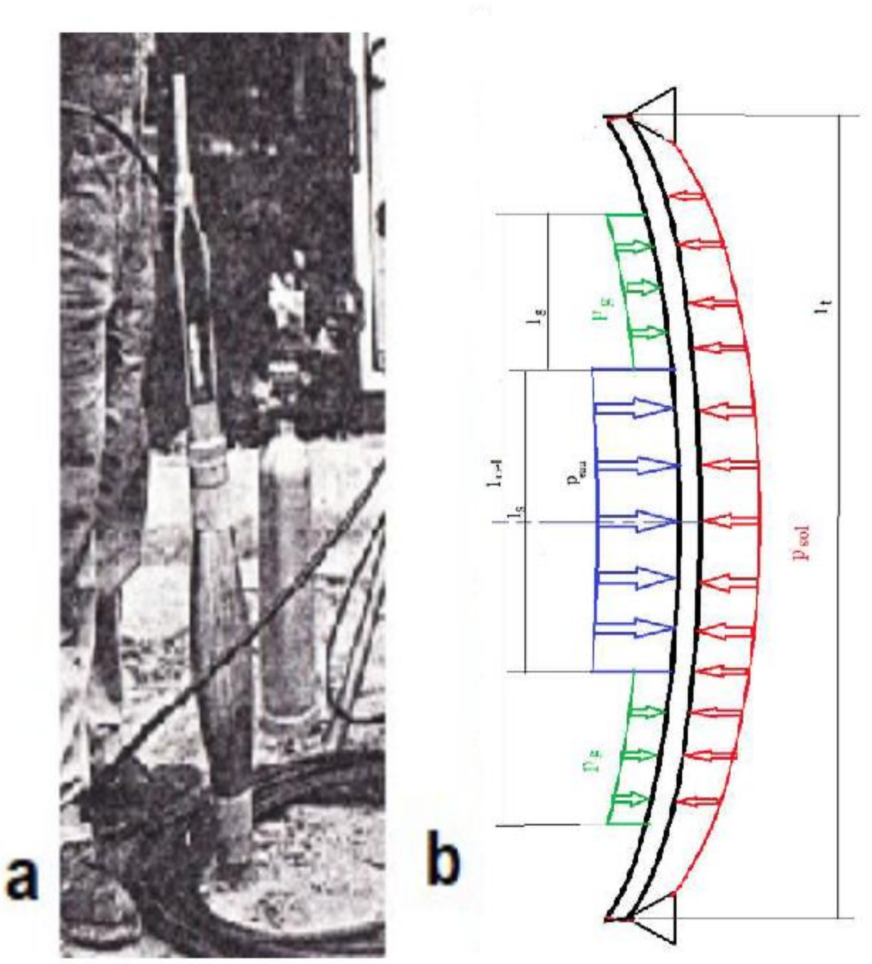


Fig. 3 Deformation and model of the bare G probe membrane

2.2 Deformation of the bare G probe

The membrane deforms as a like rugby ballon (Fig. 3.a) and can be model as beam on two simple supports (Fig.3.b). The deformed radius is given by equation (3).

The soil reaction outside the probe is proportional to the radial displacement according to equation (4).

$$r_y = r_{max}.\,[4.\,(r_0/r_{max} - 1).\,(y/l_t)^2 + 1] = [4.\,(r_0 - r_{max}).\,(y/l_t)^2 + r_{max}] \quad (3)$$

$$p_y = p_{max}.\,[4.\,(p_0/p_{max} - 1).\,(y/l_t)^2 + 1] = [4.\,(p_0 - p_{max}).\,(y/l_t)^2 + p_{max}] \quad (4)$$

Integrating the deformed radius radially (3) makes it possible to determine the internal volume of the probe, the maximum deformation r_{max} , and the mean radius r_{moy} (5).

The equilibrium of the internal forces (water and gas pressure) with the external forces (soil reaction force and groundwater counterpressure) makes it possible to determine the maximum pressure p_{max} and the mean pressure p_{moy} (6)

$$r_{moy} = r_{max} - (r_{max} - r_0).\,l_s^2/(3.\,l_t^2)$$

$$dr/r_0 = (r_{moy} - r_0)/r_0 \quad (5)$$

$$p_{moy} = p_{max} - (p_{max} - p_0).\,l_s^2/(3.\,l_t \quad (6)$$

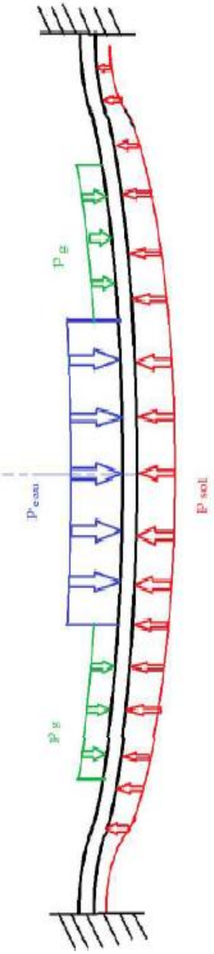


Fig. 4 Deformation and model of the slotted tube probe

2.3 Deformation of the probe with the slotted tube

The membrane behaves like a beam on two fixed supports, and the deformed radius is given by (7).

The soil reaction outside the probe is proportional to the deformation according to (8).

$$r_y = 16(r_{max} - r_0)\{[(2y + l_t)/(2.l_t)]^2 - 2[(2.y + l_t)/(2.l_t)]^3 + [(2.y + l_t)/(2.l_t)]^4\} + r_0 \quad (7)$$

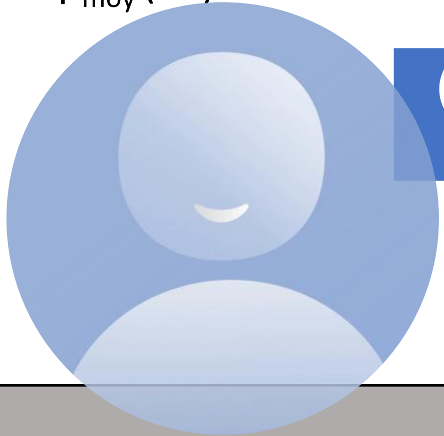
$$p_y = 16.(p_{max} - p_0).\{[(2y + l_t)/(2.l_t)]^2 - 2[(2.y + l_t)/(2.l_t)]^3 + [(2.y + l_t)/(2.l_t)]^4\} + r_0 \quad (8)$$

Integrating the deformed radius radially makes it possible to determine the internal volume of the probe, the maximum deformed radius r_{max}, and the mean radius r_{moy} (9)

$$r_{moy} = 16.r'_{max}/L_s.(I_{10} - I_{11} + I_2) + r_0 \quad (9)$$

The equilibrium of the internal forces (water and gas pressure) with the external forces (soil reaction force and groundwater counterpressure) makes it possible to determine the maximum pressure p_{max} and the mean effective pressure p_{moy} (10)

$$p_{moy} = \{256.(p_{max})^{\cdot}.(r_{max})^{\cdot}.[I_2 + I0_3 + I_4 - 2.I_5 - 2.I_6 + 2.I_7] + 16.(p_{max})^{\cdot}.r_0[I_8 - I_9 + I_{10}]\} / \{16.(r_{max})^{\cdot}.[I_8 - I_9 + I_{10}] + r_0.L_s\} \quad (10)$$



- The calculation is conducted with an anisotropic membrane of 2 layers of T16 (and a slotted tube of 2 layers of T16) with axisymmetric condition (Fig. 5)
- The soil is calculated in isotropic elasto-plasticity
- The thickness of the slotted tube is fitted by stiffening element each 2cm of height
- The dimension of the probe is shown (Table 1)
- The parameters used are shown (Table2)

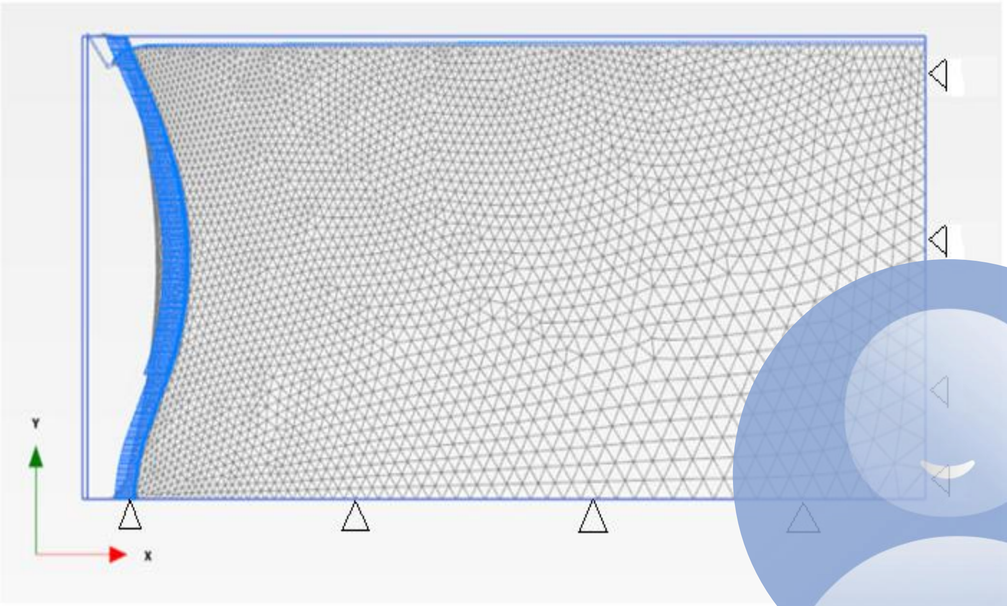


Fig. 5 – The mesh used

Table 1: Geometry of the probes

	Bare G probe	Slotted Tube
L_{cel} (mm)	450	590
L_s (mm)	210	370
L_g (mm)	120	110
L_m (mm)	-	870
E_{peau} (mm)	6	12
D_{ext} (mm)	60	63

Table 2: Parameters used

	Sand 1	Sand 2	Membrane	Slotted Tube
E_X (kPa)	12673	60000	700	700
E_Y (kPa)	12673	60000	15.10^6	200.10^6
ν_x	0,3	0,3	0,4	0,498
ν_y	0,3	0,3	0,4	0,498
c (kpa)	0	0	-	-
Φ °	31	32	-	-

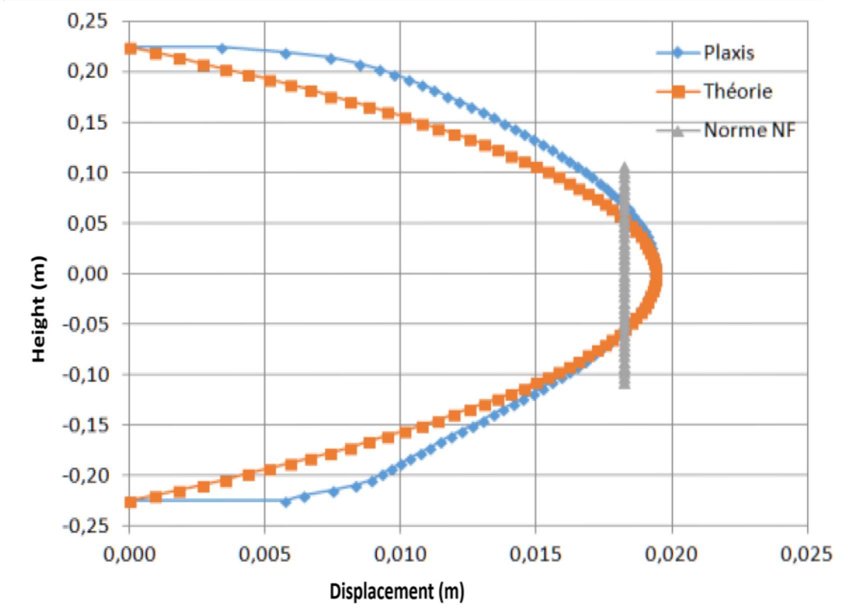


Fig. 6 Displacement, theoretical, analytical, and standard (bare G probe)

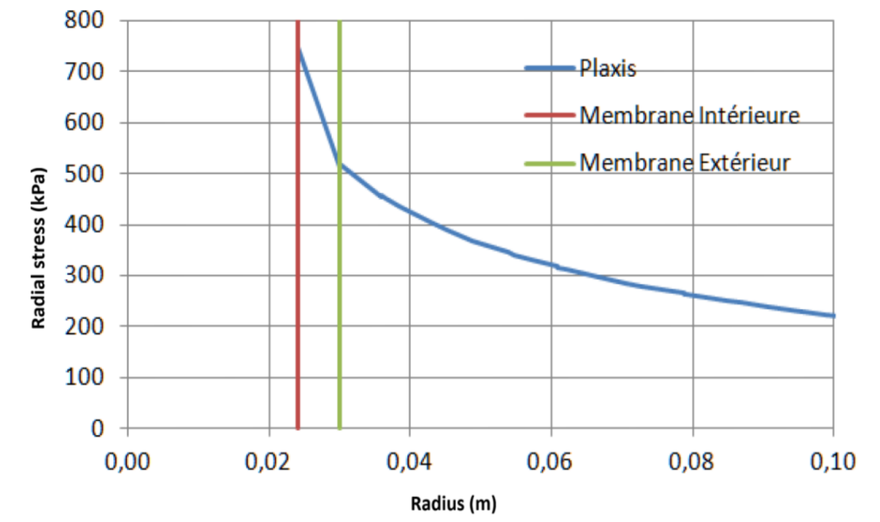
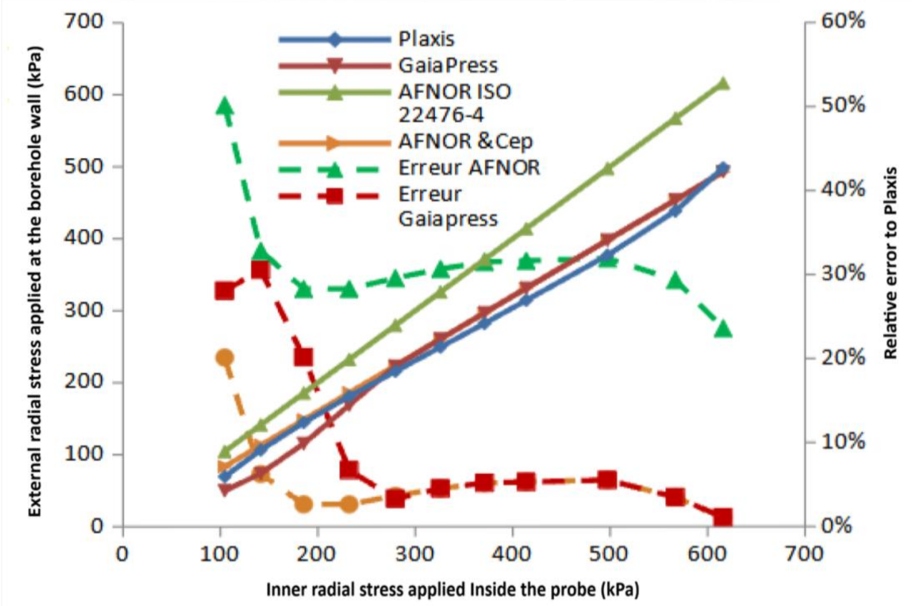


Fig. 7 Stress, calculated along radius (bare G probe)

- The calculation allows to check the correct value of the shape of the probe (Fig.6) close to the theory
- it allows to find the lost of pressure linked to the thickness of the membrane (Fig.7)
- It allows to control the correct value of the theoretical mean pressure along the test (Fig.8), and the overestimation of the standard pressure (24%)



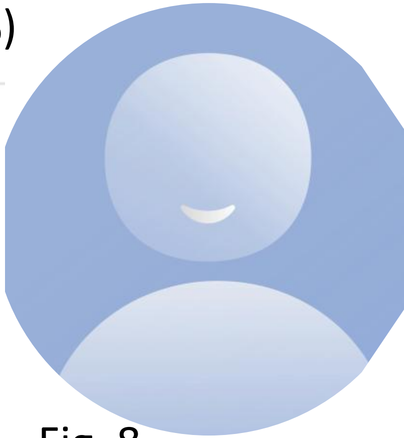


Fig. 8 Pressures along the test (bare G probe)

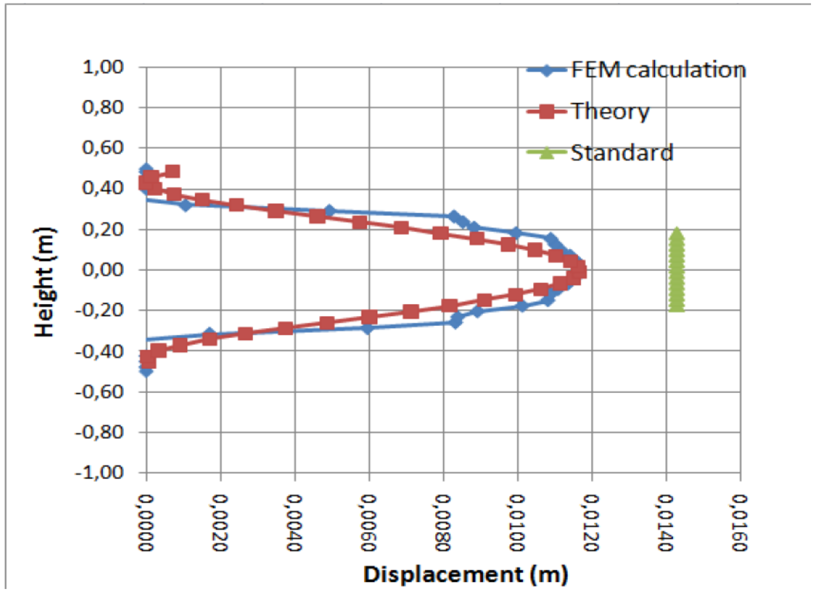


Fig. 9 Displacement, theoretical, analytical, and standard (slotted tube)

- The calculation allows to check the correct value of the shape of the probe (Fig.9) close to the theory
- it allows to find the lost of pressure linked to the thickness of the membrane (Fig.10)
- It allows to control the correct value of the theoretical mean pressure along the test (Fig.11), and the overestimation of the standard pressure (62%)

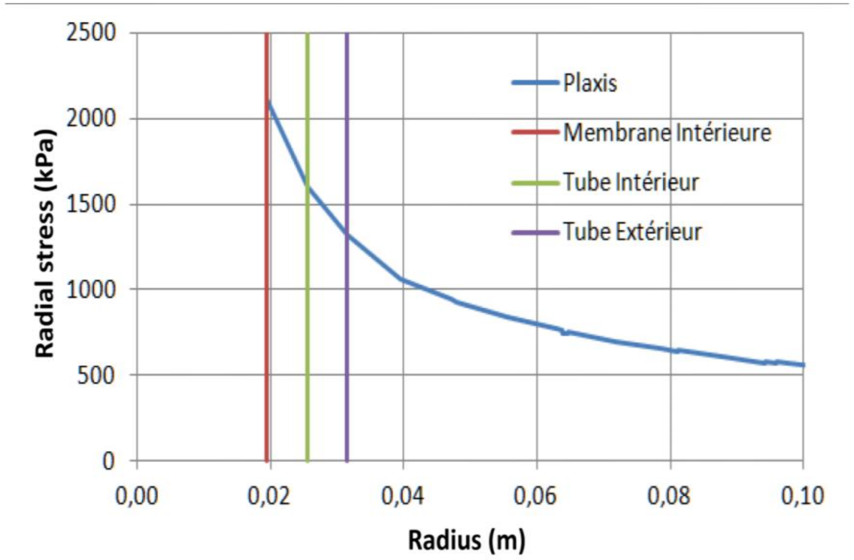


Fig. 10 Stress, calculated along radius (slotted tube)

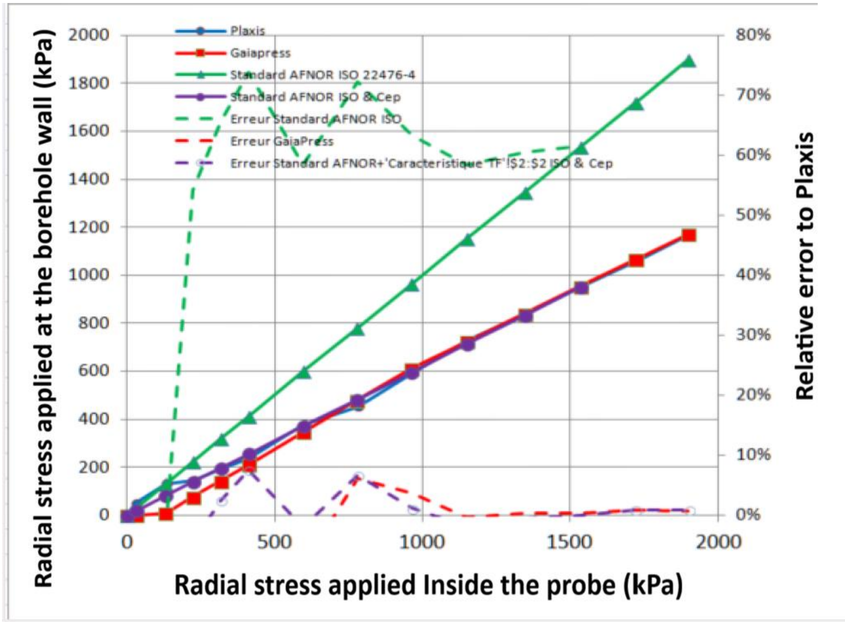


Fig. 11 Pressures along the test (Slotted tube)

Fig. 11 Pressures along the test (slotted tube)

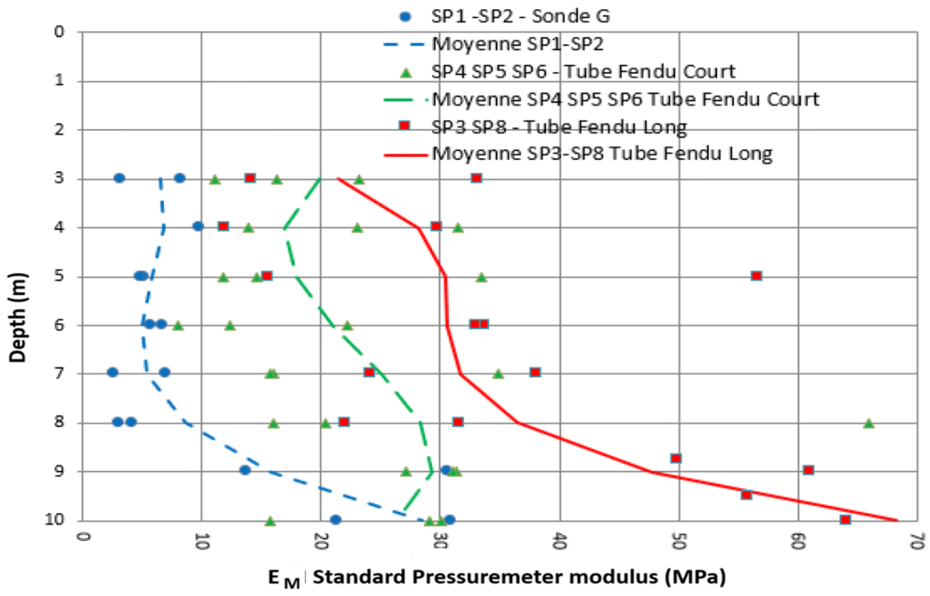


Fig.12 Pressuremeter modulus **without** proposed corrections

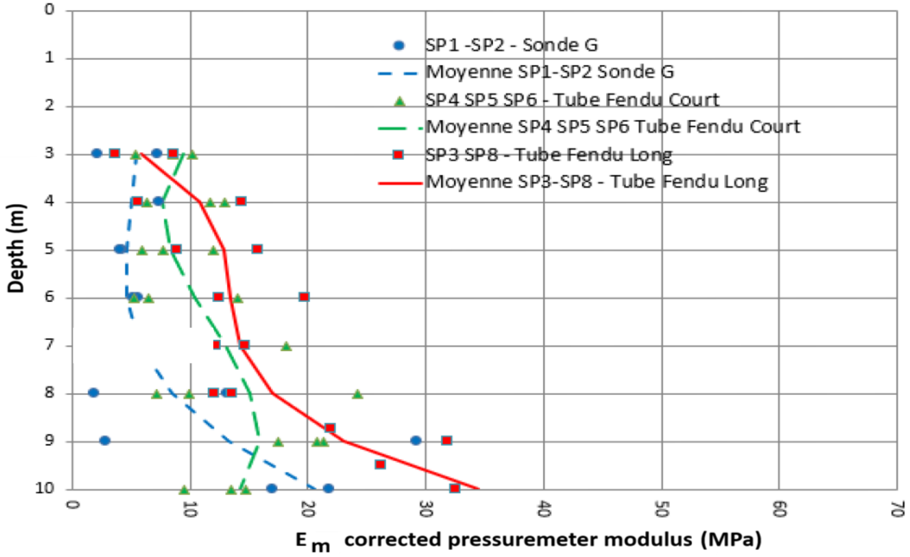


Fig.13 pressuremeter modulus with membrane correction

The ARSCOP National Project funded 59 pressuremeter tests using 3 different probe types (bare G probe; short slotted tube; long slotted tube) in a medium-dense sandy soil (0–8 m), then dense soil (9–10 m).

- The results show a strong dependence of the pressuremeter modulus E_m (Fig. 12-13) on the type of probe used (E_m_TFC ≈ 3·E_m_G; E_m_TFL ≈ 2·E_m_G). The pressuremeter moduli corrected for the membrane effect are less dependent on the probe type (E_m_TFC ≈ E_m_G; E_m_TFL ≈ 1.5·E_m_G) and show lower scatter.

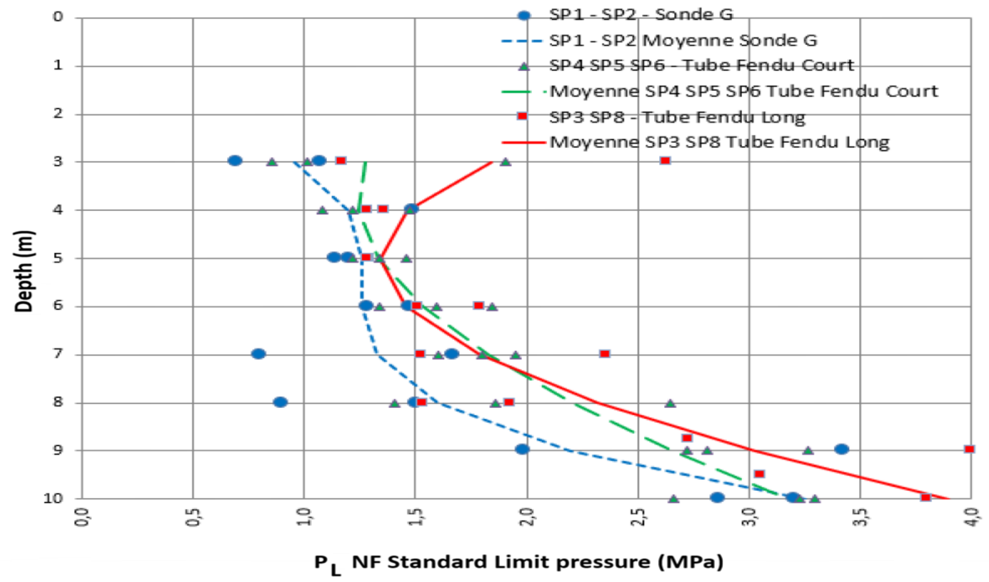


Fig.14 : Limit pressure p_L **without** membrane correction

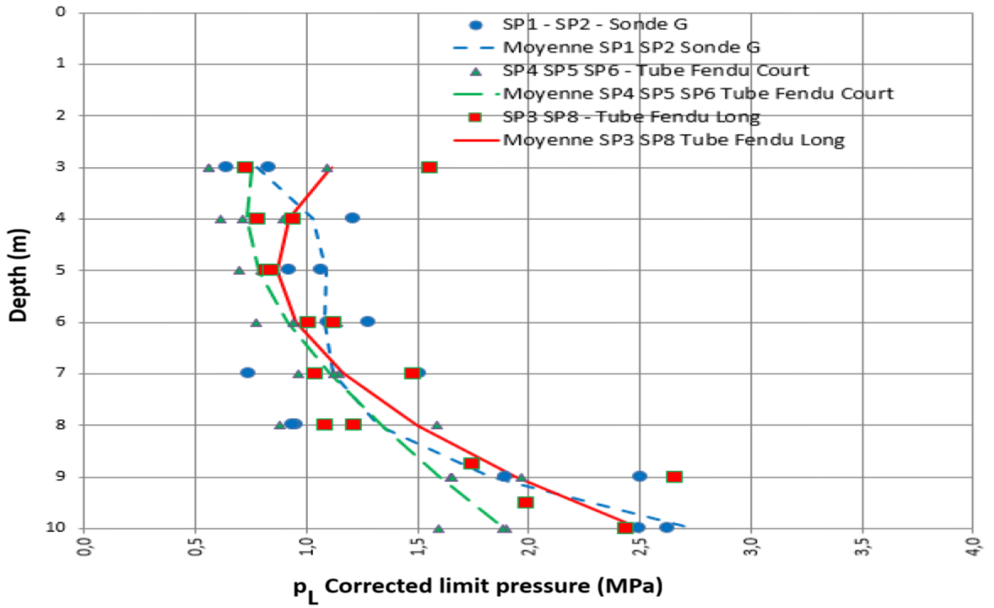


Fig. 15 corrected Limit pressure **with** membrane correction

- The standard limit pressure p_L depends highly (Fig.14-15) of the type of the probe ($p_{L\_CST} \approx 1.5p_{L\_G}$; $p_{L\_LST} \approx 1.7p_{L\_G}$) . The p_L with membrane correction is independant of the type of probe.

5. Using the new theory – determination of the friction angle

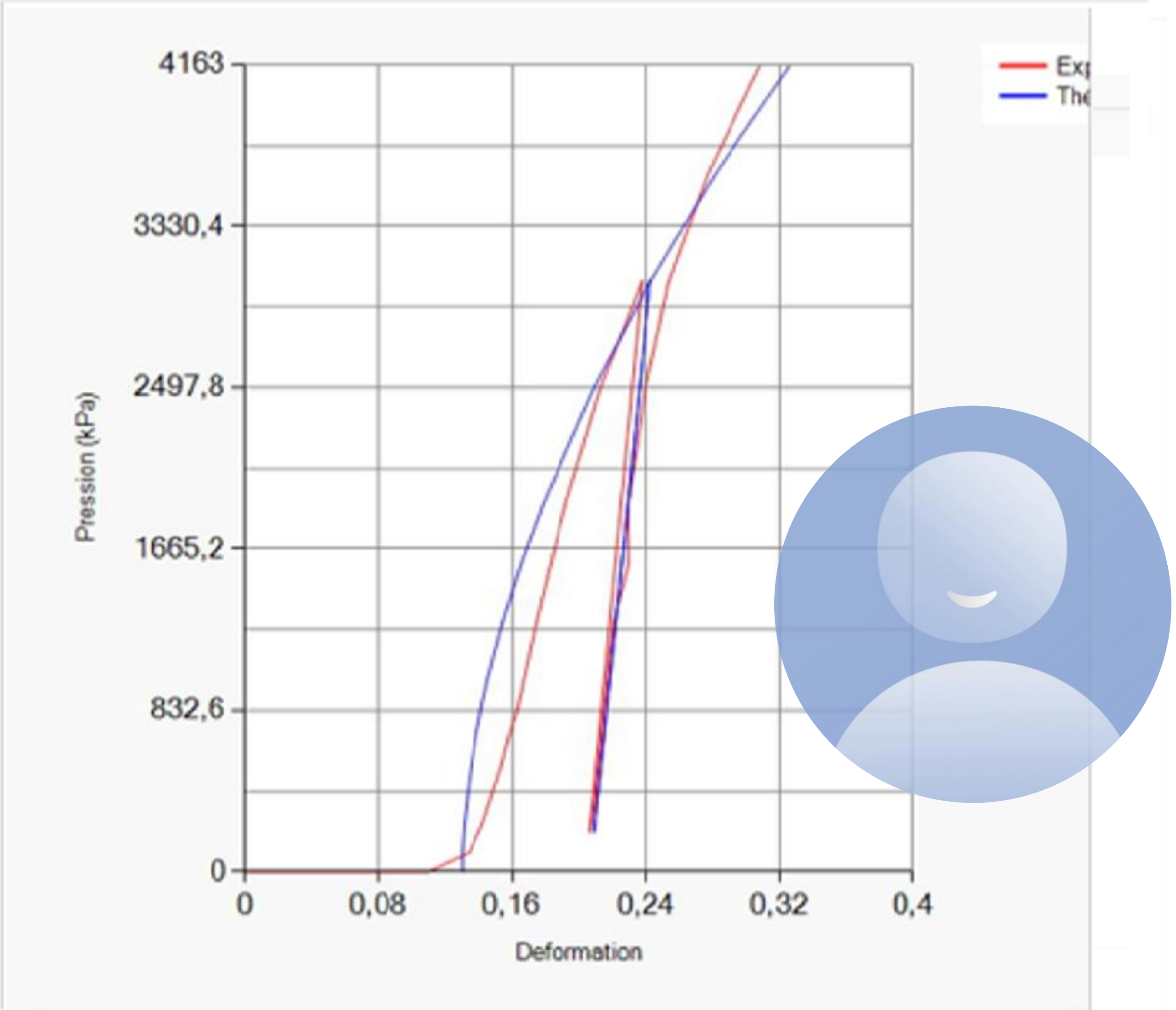


Fig.20 : Determination of the elastic modulus and friction angle by fitting the theoretical curve to experimental data

This new approach was applied in the Rhône valley on a gravelly soil with a water table, using the drained theoretical pressuremeter curve (Monnet, 2012):

- The standard calibration (AFNOR, 2015) was employed (Fig.16)
- The standard expansion curve (AFNOR, 2015) assumes the probe remains undeformed while tubing and pressure-volume controller expand under pressure.(Fig.17)
- However, the assumption that expansion increases with tubing length is invalid (Fig.18); instead, probe inner volume expansion correlates with membrane compression, whose thickness decreases under pressure (Fig.19).
- This allows to use the theoretical model (Monnet, 2012) to determine Young modulus and friction angle. Elastic modulus 80815kPa ; Friction angle Φ 47° ; p_{LEXP} 5520kPa

5. Using the new theory – determination of the undrained cohesion

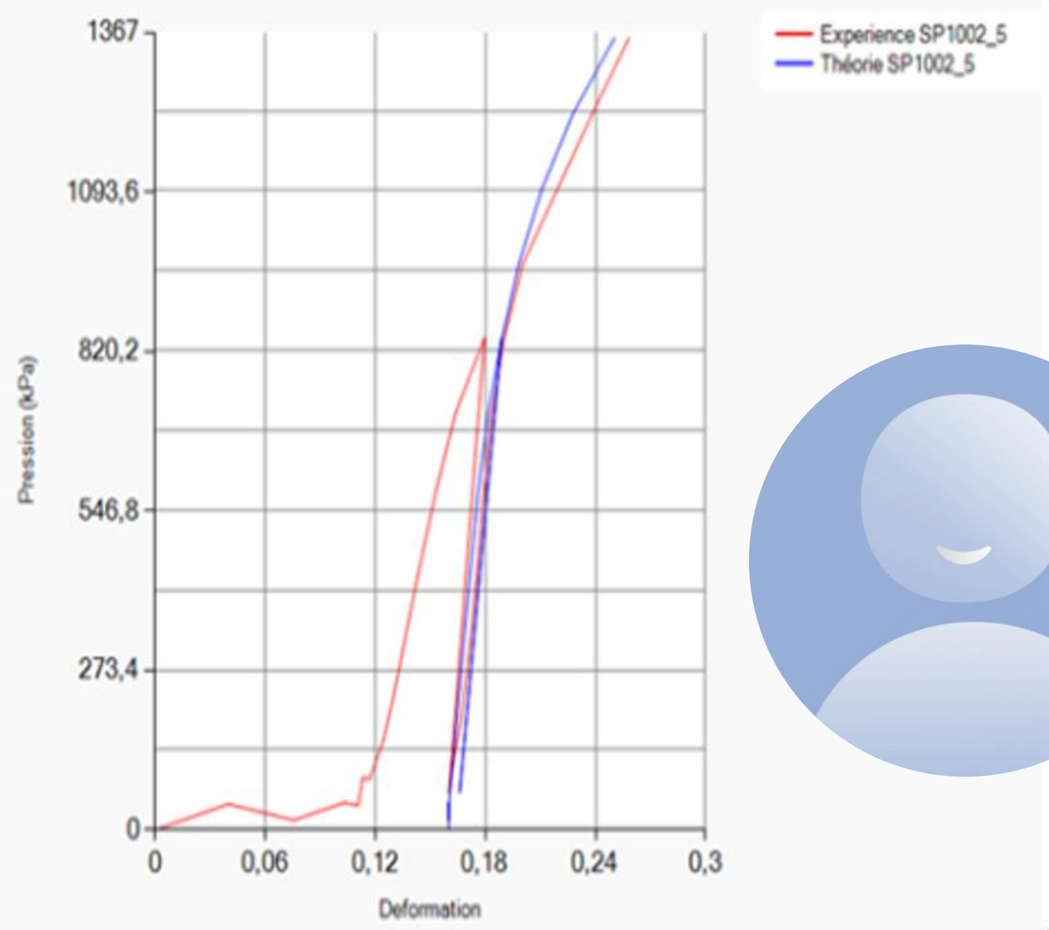


Fig.24 Determination of Elastic modulus and undrained cohesion by fitting the theoretical curve to expérimental data

This new approach has been used on a second site in Rhone valley where the soil is classified as a gravel marly soil (C1B5 class) with no water table. The undrained theoretical pressuremeter curve (Monnet, 2007) has been ussued. The interpretation use :

- The standard calibration (Fig.21)
- The standard expansion curve is not used (Fig.22)
- Instead the variable thickness of the membrane is used (Fig.23)
- At the end of the process, the determination of the Elastic modulus and the underdrained cohesion is made by fitting the theoretical curve (Monnet, 2007) to experimental data: Elastic modulus 109718kPa ; undrained Cohesion 1300kPa - ; p_{Ltheo} = 2042kPa ; p_{LEXP} = 2774kPa .
- A sample was tested in laboratory which gives c_u = 14200kPa

6. Conclusion

- The membrane thickness for the bare G probe and the Slotted Tube has been incorporated into a new theoretical correction. This correction models the membrane as an elastic beam supported at two points (either simply supported or fixed), with the soil reacting elastically to the deformation.
- This theoretical approach has been validated through Plaxis calculations, which enable the retrieval of theoretical deformations and pressures.
- When applied to Ménard pressuremeter tests, this theory reveals that pressuremeter results (E_m, p_L) are influenced by the type of probe used in the absence of membrane correction. However, with the membrane correction applied, the pressuremeter moduli (E_m) become nearly independent of the probe type.
- For limit pressures, discrepancies between the results obtained from different probes, as per standard procedures, are observed. These discrepancies vanish when the membrane correction is applied.
- It is recommended that, when using correlations between limit pressure (p_L) and the bearing capacity of foundations, the membrane correction be taken into account, particularly when employing a Slotted Tube.
- This new methodology has enabled the determination of the friction angle and undrained cohesion for two distinct soils in the Rhône Valley.

6. Conclusion

Thank You for your attention

7. References

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