Assessing the influence of the slotted tube on modulus calculations, from theory to field tests

Evaluation de l'incidence du tube fendu sur le calcul du module, approche théorique et validation expérimentale

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ABSTRACT

In the current French practice, the use of a 44 mm probe inserted inside a slotted tube is very common and tends to extend beyond the initial scope of use, whether it is by driving the tube into loose soils or inserting the tube in a prebored borehole. Besides the obvious effects of driving the tube on the soil, the mere presence of the slotted tube influences the way the probe applies pressure and volume change on the cavity. To take this into account, Hansbo (1990) has proposed a formula to derive the Ménard modulus that accounts for the tube's thickness, which is now used in EN ISO 22476-4 standard.
In this paper we examine the influence of the slotted tube on the expansion of the cavity from a theoretical standpoint and the expected effects on the derived modulus. We then confront this analysis with the field results obtained at the Messanges test site during ARSCOP works, where comparative Ménard pressuremeter tests were carried out in medium dense to dense sands, with 60 mm probes with a flexible cover alongside 44 mm probes inside a slotted tube, both performed in prebored boreholes.

RESUME

Dans la pratique française, l'utilisation de sondes de 44 mm dans un tube fendu est très répandue, et dépasse assez largement le domaine d'application initial, que ce soit avec une mise en oeuvre par battage dans les sols laches ou par insertion dans un forage préalable. En dehors des effets liés à une mise en oeuvre par battage, la simple présence du tube fendu modifie l'application de la pression et les variations de volume imposés à la cavité. Afin de tenir compte de ces effets, Hansbo (1990) a proposé une formule pour calculer le module pressiométrique qui tient compte de l'épaisseur du tube, et qui est reprise dans la norme EN ISO 22476-4.
Dans cet article, on étudie l'impact du tube fendu sur l'expansion de la cavité d'un point de vue théorique et les effets induits sur le module calculé. On confronte ensuite cette analyse aux résultats des essais croisés obtenus sur le site de Messanges dans le cadre des travaux du PN ARSCOP. Sur ce site, un ensemble de sondages et essais ont été réalisés, dans des sables moyennement dense à dense, pour partie avec des sondes à gaine souple de 60 mm de diamètre et pour partie avec des sondes de 44 mm dans divers modèles de tubes fendus, mais toujours dans des forages préalables.

Keywords: comparative testing; Ménard modulus; slotted tube.

1. Introduction – the available approaches

When interpreting a Ménard pressuremeter test, a stiffness modulus is estimated during the pseudo-elastic phase of the test using the following formula:

$$E_M = 2\,(1+\nu)\,\left(V_c + \frac{V_1+V_2}{2}\right)\frac{P_2-P_1}{V_2-V_1} \qquad (1)$$

where V_c is the initial volume of the central measuring cell and P_1, P_2, V_1, V_2 correspond to the corrected pressures and injected volumes defining the range where the modulus is calculated.

In the rest of this paper, all pressures and volumes are assumed to be corrected through adequate pressure and volume loss tests. We will also use $V_m = (V_1 + V_2) / 2$ for the average value of injected volume during the pseudo elastic phase, $\Delta P = P_2 - P_1$ and $\Delta V = V_2 - V_1$.

This formula is derived from the expression of the radial expansion of a cylindrical cavity in an elastic material (Lamé, 1852):

$$\Delta V = V\,\frac{\Delta P}{G} \qquad (2)$$

When deriving the modulus for a test where a 44 mm probe inserted in a slotted tube is used, there is an old debate as to whether the tube should be considered as part of the probe or as part of the soil. We can list 3 different points of view:

- Louis Ménard in his D60 documentation (Ménard, 1967) calculates the modulus using the same initial volume of the AX probe measuring cell whether it is placed inside a slotted tube or directly into a small diameter borehole (46 to 52 mm). In this paper we will use Vc for the initial volume of the measuring cell (44 mm probe including membrane and flexible cover, but not the slotted tube).

- In 1991, the first French standard (NF P94-110) takes the opposite stance using the volume obtained from a volume loss calibration test, thus including the slotted tube, as the initial volume of the measuring cell. In this paper we will use Vt to indicate the initial volume of the measuring cell including all covers and the slotted tube.
  It should be noted that with a 63 mm slotted tube this volume is about twice that of the 44 mm probe and using Vt in place of Vc in Eq. (1) results in much larger values for E_M.
- Around the same time, Hansbo from Chalmers University of Technology in Sweeden proposed a compromise using a geometric average (Hansbo, 1990), as follow:

$$E_m = 2\,(1+\nu)\,\sqrt{(V_c+V_m)(V_t+V_m)}\ {}^{\Delta P}/_{\Delta V} \tag{3}$$

To understand where these different points of view come from, we will first study what happens around the slotted tube during the expansion of the probe.

2. Theoretical analysis of the effect of the slotted tube

Considering that the formula used to calculate the Ménard modulus derives from the expansion of a cylindrical cavity, it would seem logical to include the slotted tube in the volume of the measuring cell. However, ΔP and ΔV as read on the pressure volume controller actually correspond to what happens inside the slotted tube. We need to look at how these variations are transferred to the soil by the slotted tube.

2.1. Applied pressure

When an increment of pressure ΔP_{int} is applied on the inner side of a strip from the slotted tube, what is transferred to the other side is actually an equal force and not an equal pressure. For the complete slotted tube, we then have:

$$\Delta P_{int}\ 2\pi\ R_{int} = \Delta P_{ext}\ 2\pi\ R_{ext} \tag{4}$$

where R_{int} and R_{ext} correspond to the inside and outside radius of the slotted tube. Which then gives:

$$\Delta P_{ext} = \Delta P_{int}\ \frac{R_{int}}{R_{ext}} \tag{5}$$

The discontinuity of the slotted is not accounted for in the above equation, but we assume that irregularities of the pressure increment are smoothed quickly within the encasing soil.

2.2. Volume variation

If we apply the same analysis for volumes, an increment of volume ΔV_{int} inside the slotted tube will produce an increment of radius ΔR of the slotted tube, which will be the same for the inner side and the outer side of the tube. If we assume that ΔR is relatively small compared to R (which seems reasonable during the pseudo-elastic phase), we can then approximate:

$$\Delta V_{int} = \Delta R\ 2\pi\ R_{int} \tag{6}$$

$$\Delta V_{ext} = \Delta R\ 2\pi\ R_{ext} \tag{7}$$

which then gives:

$$\Delta V_{ext} = \Delta V_{int}\ \frac{R_{ext}}{R_{int}} \tag{8}$$

The volume increment on the outside of the slotted tube is greater than the volume increment inside; the difference between the two corresponds to the volume that is created by the slots opening during the expansion.

This effect transfers to the soil around the slotted tube only if the slots do not get filled by soil, or if stress arches develop above the slots so that the full volume displacement is applied to the encasing soil (even if some soil would fall in the slots).

2.3. Compounded effect

As we have shown above, if we consider the full volume of the borehole as the volume of the cavity, the values of ΔP and ΔV measured inside the tube should be adjusted to obtain the increments that are applied to the soil by the slotted tube.

Depending on whether we consider that the volume created by the slots opening is entirely filled with soil or not, only ΔP or both ΔP and ΔV should be corrected, thus the correction factor applied to $\Delta P/\Delta V$, and in the end E_M, should be either R_{int}/R_{ext} or $(R_{int}/R_{ext})^2$.

Interestingly enough, if we apply the correction factor of $(R_{int}/R_{ext})^2$ to the volume of the cavity (instead of $\Delta P/\Delta V$) in the middle of the pseudo-elastic phase we obtain the volume of what is inside the slotted tube at that point, hence $Vc + Vm$. This corresponds precisely to the original calculations proposed by Ménard.

And if we only apply a factor of R_{int}/R_{ext} to the volume of the cavity, we obtain an intermediate value, somewhat similar to what Hansbo proposed.

In any case however, the calculation with Vt that was used according to the French standard from 1991 to recent years seems overly optimistic.

The above analysis is not new, and François Baguelin already wrote (Baguelin et al. 1978): "*This analysis points out the complexity of the problem of trying to rationalize what happens around the slotted tube. The problem is so complex that only comparative tests between probes in direct contact with the soil and probes inside the slotted tube can hope to resolve the problem*». Fig. 1 taken from that same book illustrates the volume created by the slots opening during the test.

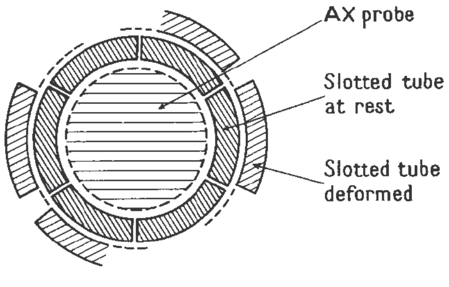

Figure 1. Illustration of the volume created by the opening of the slots during the test (from Baguelin et al. 1978).

3. The Messanges field tests

The field works of the national project ARSCOP included a series of comparative tests on the Messanges site, in the Landes (Fig. 2). This site is a sand quarry, and the soil is composed of medium dense to dense Quaternary sand to the full depth of the investigations (approx. 11 m from ground level).

Figure 2. Messanges test site location.

A total of 13 boreholes and 103 pressuremeter tests have been carried out over two investigation phases in 2019 and 2021. The comparative tests used various equipment including different type of probes, different rubber sleeves, different slotted tubes, etc. All tests were carried out in prebored boreholes supported by a bentonite fluid (no driving of the slotted tubes).

In this paper, we split the results into 2 groups: those obtained from a Ménard tri-cellular 60 mm probe with flexible cover on one side and those obtained from 44 mm probes inside slotted tubes on the other.

3.1. Tests with 60 mm flexible cover probes

A total of 33 tests have been carried out in 5 boreholes with 60 mm probes. The Ménard moduli range from 2 to 32 MPa with most values between 5 and 15 MPa corresponding to medium dense to dense sands. The average value for the modulus is 10.5 MPa, with a coefficient of variation CV of 66%. Fig. 3 below plots all the results, and some increase with depth can be discerned.

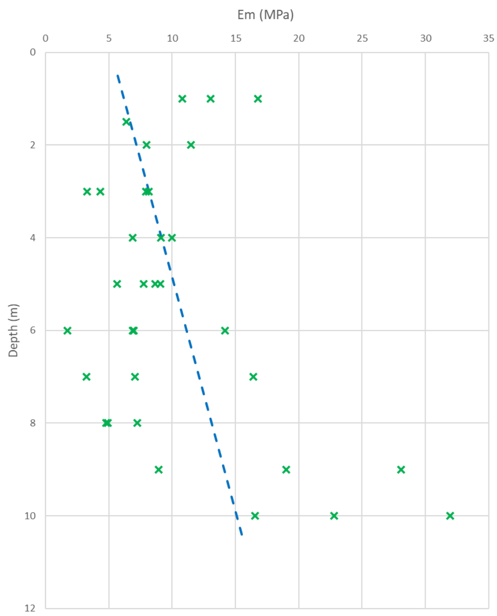

Figure 3. Test results from 60 mm probe.

A regression can be plotted: $E_M = 0.99\ z + 5.2$ with z depth from the surface (in meters) and E_M in MPa, but the scatter is notable. For the comparison with the 44 mm probes, this variation with depth is ignored and all results are compared in bulk.

3.2. Tests with 44 mm probes in a slotted tube

A total of 70 tests have been carried out in 8 boreholes with 44 mm probes (including short and long measuring cells) inserted into different slotted tubes (46/60 mm and 48/63 mm).

Here the results obviously depend on the formula used to calculate the modulus. Table 1 below gives the average value and CV obtained with the 3 different approaches:

- The one from Ménard's D60 where Vc in Eq. (1) corresponds to the volume of the 44 mm probe.
- The one used in the French standards from 1991 to 2015 where Vt is used in place of Vc in Eq. (1) and includes the volume of the slotted tube.
- And finally, Hansbo's intermediate proposition.

Table 1. Modulus derived from the 3 formulas

Formula	Average (MPa)	Coefficient of variation
Ménard	12.5	55%
NF P94-110	22.9	59%
Hansbo	16.9	57%

We can immediately see that the modulus obtained with the 44 mm probes in slotted tubes are overall higher than those obtained with 60 mm probes, and the closest fit is obtained using Vc in Eq. (1) as initially proposed by Ménard. Fig. 4 below shows the corresponding test results for comparison with Fig. 3.

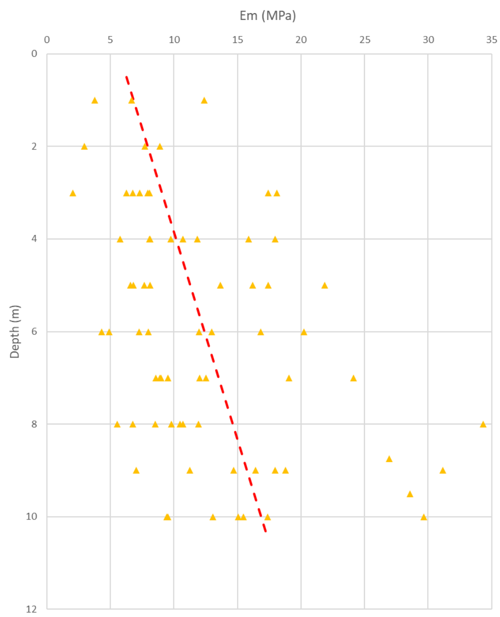

Figure 4. Test results from 44 mm probe (D60 interpretation).

Another representation can be established in the form of cumulative frequency diagrams to compare the different interpretations for the modulus on the full distribution. As we can see in Fig. 5 the interpretation using the volume of the 44 mm probe for Vc in Eq. (1), in orange, as initially proposed by Ménard, presents a relatively good fit to the reference distribution obtained with standard 60 mm probes. The slight offset could simply be attributed to the lower number of tests of that series.

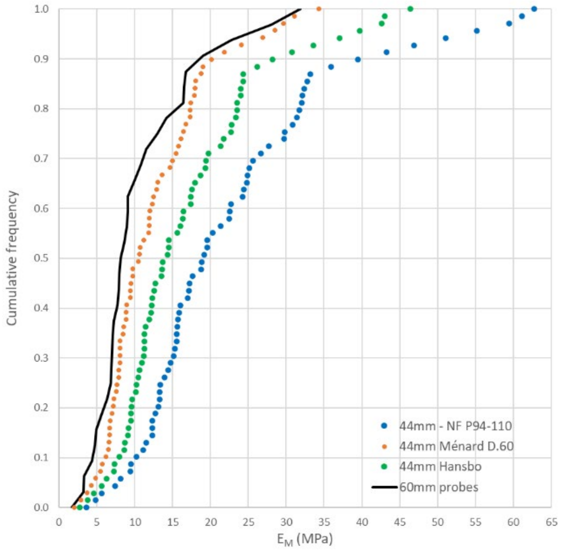

Figure 5. Cumulative frequency diagram of the different formulas for deriving E_M with a slotted tube compared to the results obtained with 60 mm probes.

Based on the Messanges test results it seems that the best consistency in terms of modulus, between standard 60 mm probes and 44 mm probes in slotted tubes, is obtained by using Vc in Eq. (1). This would imply that in the theoretical analysis presented in 2.1 and 2.2 both effects do apply, i.e. a reduced pressure and increased volume increment. This could be explained in two ways: either not much soil fills the slot as they expand, or stress arches form in the sand that bridge those gaps.

In both case the correction factor is $(R_{int}/R_{ext})^2$ which, if applied to the volumes instead of $\Delta P/\Delta V$, brings us back to the volume that is inside the tube. This is equivalent to considering that the slotted tube is part of the soil and not the probe.

In this case the value of Vc to use in Eq. (1) is that of the 44 mm probe, which can be derived from the volume loss calibration test (performed with the slotted tube) using the following formula:

$$Vc = 0.25\,\pi\, l_c\,(d_i - 2\,e_{TF})^2 - V_p \quad (9)$$

where l_c is the length of the measuring cell
d_i is the inner diameter of the calibration tube
e_{tf} is the thickness of the slotted tube
V_p is the conventionnal volume intercept obtained from the volume loss calibration test (see Fig. 6)

This volume could also be obtained by performing the volume loss calibration test without the slotted tube, but that would require a smaller calibration tube.

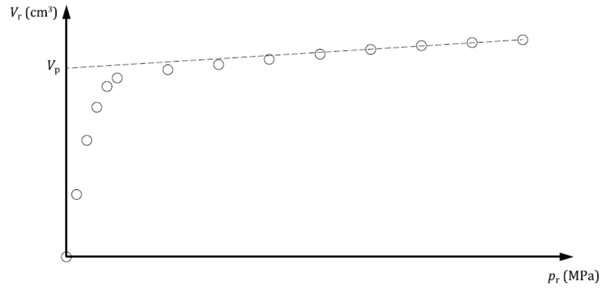

Figure 6. Definition of Vp in a volume loss calibration test.

4. Conclusions

In this paper we have shown, through a relatively simple analysis of how pressures and volume increments are applied to the soil through the slotted tube, that it is possible to use the values of ΔP and ΔV obtained from the pressure volume controller to derive the Ménard modulus when using a 44 mm probe in a slotted tube, as long as an appropriate value in considered for the initial volume of the measuring cell in Eq. (1).

The theoretical analysis and the field evidence both show that this volume should not include the full thickness of the slotted tube. In sands, the Messanges test results show that only the volume of the 44 mm probe should be used.

A different conclusion might however be obtained in clays, where Hansbo's proposition may or may not be more suitable, but further investigation would be needed to draw a definitive conclusion for fine soils.

A more detailed analysis (either through physical or numerical modelling) of the stress/strain fields around the slots of the tube could also help better understand the effects of the slotted tube.

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