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A new tool for soil characterization

T. Besson
Fondasol, Avignon, France, theo.besson@fondasol.fr

M. Rispal[1], C. Jacquard[2]
Fondasol, Avignon, France, michel.rispal@fondasol.fr[1], catherine.jacquard@fondasol.fr[2]

P. Reiffsteck, F. Szymkiewicz
Univ. Gustave Eiffel, IFSTTAR, Marne-la-Vallée, France

ABSTRACT: This paper will present a new ground investigation apparatus that is aimed to perform pre-bored expansion tests similarly to Ménard pressuremeter tests. This apparatus consists of two rigid and semi-cylindrical metallic parts which are spread in the soil. A comparative numerical study between the expansion of a cylinder and the penetration of punches of various shapes has enabled to design the probe: it appeared that a curvy punch with a horizontal length of 30mm embedded in a cylinder with a diameter of 60mm enables to measure an initial rigidity of the soil very close to the one measured with the Ménard expansion test. In parallel, we introduce elastic theories that could be used to define a linear deformation modulus.

Keywords: modulus; in-situ test; Ménard pressuremeter; borehole expansion test.

1. Introduction

A borehole expansion test consists in a radial dilatation of a cylindrical probe and in measuring the pressure applied on the soil as well as the volume of fluid injected and/or the displacement of the borehole wall. This in-situ test is one of the very few that enables to measure the deformability and the strength of any type of soil and rock mass.

Indeed, in situ tests such as the cone penetration test or the standard penetration test are designed to provide only a strength parameter. Generally, they only provide an approximation of the soil's deformability using correlation with laboratory tests. The cone loading test shows promising results at calculating a deformation modulus, but questions remain on its applicability to a large variability of soils (Teyssier et al. [12]). Deformability tests such as the lateral penetrometer (sort of plate loading test in a self-boring probe) or the flat dilatometer test do not strain the soil sufficiently to reach its limit pressure [2,10]. Plus, the flat dilatometer operates at only one deformation rate and cannot be used in hard soils and rocks due to its mode of insertion.

The Ménard test is a widespread in-situ expansion test, especially in France. The probe is made of a steel body covered by a Nitrile rubber sheath creating three cells inflated with water for the central measuring cell and with gas for the two guard cells. This arrangement creates a cylindrical stress field around the measuring cell. The volume of water injected is measured by a control unit at the surface, as the pressure is applied to the borehole's walls. After several corrections, one can have access to the limit pressure $p_{\ell M}$ and the Ménard modulus E_M[5]:

$$E_M = 2(1+\upsilon)\left[V_S + \frac{V_1+V_2}{2}\right]\frac{p_2-p_1}{V_2-V_1} \quad (1)$$

where V_S is the initial volume of the measuring cell, and V_1, V_2 and p_1, p_2 are respectively the volumes injected and the pressures applied that delimitate the pseudo-elastic part of the pressuremeter curve.

Thanks to these advantages, the Ménard test has enabled to develop reliable and precise methods of foundation design both for resistances and displacements issues.

However the Ménard test suffers from some drawbacks such as the high influence of the quality of the borehole on the test representativeness, the complexity of the equipment and the frequent bursting of the probe: the rubber membrane badly resists to the soils heterogeneities when the pressure and the volume of the probe increase, and the limit pressure is rarely reached with the current Ménard test. Furthermore, the use of pressurized gas raises a number of safety concerns.

For these reasons, Fondasol is seeking to develop a new borehole expansion test, fast and easy to use for medium-sized construction project. It should be able to measure a modulus and a limit pressure as the Ménard pressuremeter test.

If it seems difficult to avoid the influence of the quality of the borehole, the new test should overcome some of the drawbacks of the Ménard test by:

- limiting the complexity of the control unit and the probe by trying to prevent the use of a pressurized gas;
- preventing the probe bursting even if it leads to give up the use of a flexible membrane;
- preventing the head loss in the tubing when the variation of the volume injected is too high;
- avoiding the need for corrections due to the rubber sheath resistance and the control unit deformation under pressure.

2. Bibliographic review

Many expansion probes have only one cell that is assumed to be long enough to prevent end-effects. It is filled with water (as the Lateral Load Tester from Oyo or the Texam from Roctest) or gas (as the Tri-Mod from Roctest). The Texam does not require any gas as the fluid is pressurized in the cell via a piston [3].

Self-boring pressuremeters such as the Pressiomètre Auto-Foreur from the LCPC or the Camkometer from Cambridge in-situ offer better quality results than pre-boring pressuremeters by preventing the remodeling of the soil around the borehole. However, they involve a higher cost and complexity of the equipment. They are thus hardly used outside research laboratories.

Flexible dilatometers such as the Elastmeter from Oyo and the Probex from Roctest are actually very similar to pressuremeter probes even though they are designed to apply greater pressures to the soil. In contrast, rigid dilatometers have a completely different mechanism: they are made of two opposed rigid shells that are extended in the soil by the application of a hydraulic pressure to several small jacks between them. The Goodman borehole jack or more recently the Ettlinger borehole jack are such dilatometers [8, 4]. Rigid dilatometers are interesting in the sense that they do not need a membrane. However, they are currently only used in rocks and hard soils. The use of pistons to expand rigid punches in the ground requires a high borehole diameter (76mm for the Goodman and 101 or 146mm for the Ettlinger) which is incompatible with the range of the diameters currently used in French standards. It should be emphasized that there is no satisfactory theory that analyses the results of such tests. A deformation modulus is calculated using formulae derived empirically from other in-situ tests. On the contrary the Ménard pressuremeter test relies on the well-known cavity expansion theory that has enabled to rigorously define the modulus and the limit pressure.

In the light of this bibliographic review, the rigid dilatometer seems to be the most interesting solution even if the geometry of the shells should be reviewed to enable their use in soils, especially in terms of sealing. On this basis, a new apparatus has been developed (Fig. 1.).

It has a diameter of 60mm and is thus compatible with the borehole's standard size used in the French practice. The penetration in the soil at a user-defined rate is performed by two cylindrical and rigid punches. These parts can extend up to a probe's diameter of 90mm, diameter at which the Ménard probe approximately doubles its volume. The arms have been carefully designed so that the test results are the closest as possible to a Menard test. However, if the user wants to apply the formulas used for the Ménard procedure and apparatus, more insight must be performed on the relation between these two apparatuses.

Figure 1. The probe showing one of its two rigid punches diametrically opposed.

3. Numerical study of the Punch's shape

In this section, we compare the problem of the expansion of a cylindrical cavity with the penetration of punches of various shapes in a semi-infinite model. The purpose is to select the geometry that is in best agreement to the Ménard test results. The comparison is made using the finite element software Plaxis 2D. All models introduced here are squares of 3 meters. A too small model leads to overestimate the rigidity while a too large model implies larger elements and thus less reliable results. A zero-displacement condition at the surface enables to simulate borehole conditions. All models assume plane strains except model D which is axisymmetric. A K_0-procedure is performed in the initial stage with $K_0=1-\sin(\varphi)$ and an updated mesh analysis is carried out in the next stage. The elastic perfectly plastic model with a Mohr-Coulomb failure criterion is used. The parameters are listed in Table 1. All interfaces are set rigid.

Table 1. Soil parameters.

γ [kN/m^3]	E [MPa]	υ	c [kPa]	φ [°]	ψ [°]
17	10	0.3	15	25	0

Fig. 2. (a) shows a local view of the Plaxis model used for the pressuremeter test, model A. It consists in a half-cylinder that has a diameter of 60mm. A load is applied perpendicularly to the cavity's walls. Fig. 2. (b) shows a part of the mesh deformed in the last step of the program.

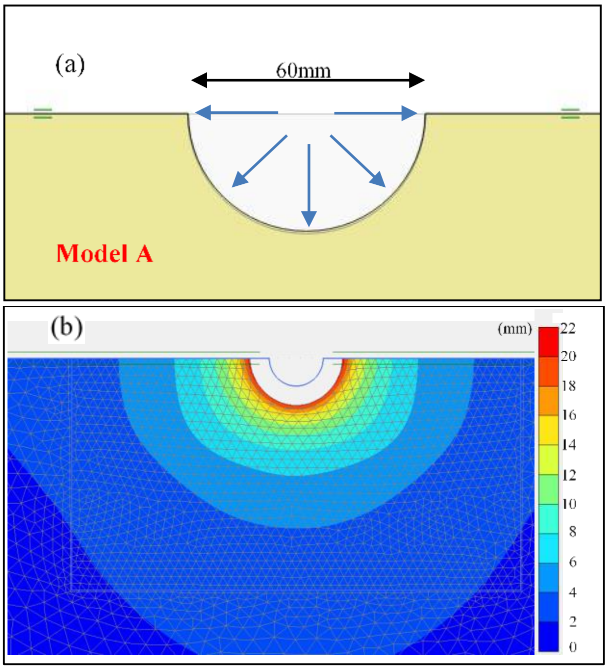

Figure 2. (a) Model A: model used for the pressuremeter test. It is a half-cylinder, infinite in the out-of-plane direction. (b) Deformed mesh with displacement field at the last step of the computation (P=300kPa).

The punches are modeled by plates assumed to be infinitely rigid on which a vertical load is applied (Fig. 3.). The first geometry, Model B, is a 60mm diameter half-cylinder. The Goodman or the Ettlinger borehole jacks can be approached by such geometry. An interface has been added at the plate to allow a relative displacement between the punch and the soil around. The second geometry, Model C, is a flat area. Vertical interfaces have been added at the edges of the structure to allow a discontinuity in the displacement instructions. The last geometry, Model D, is a half-sphere with a 60mm diameter.

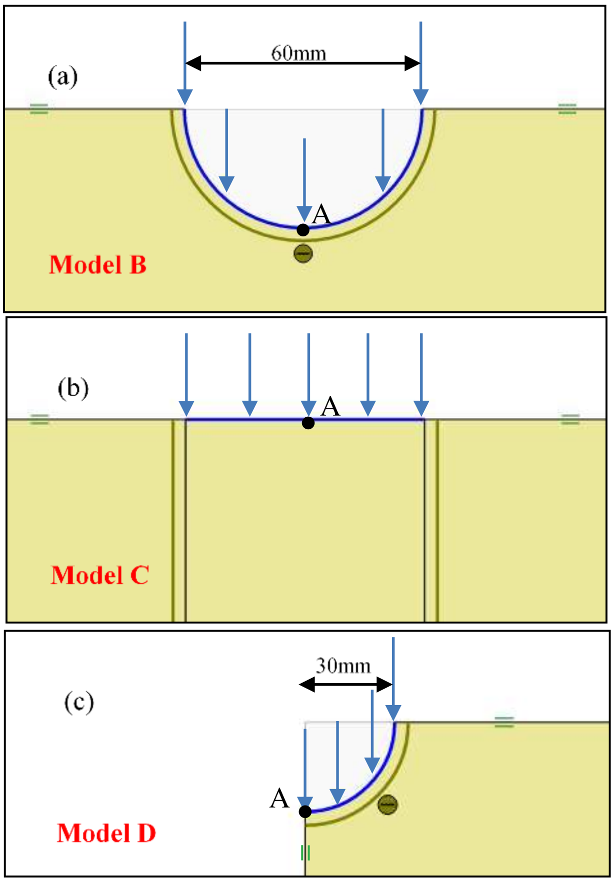

Figure 3. Geometries of the punches studied. (a) Model B: semi-infinite half-cylinder, (b) Model C: semi-infinite flat punch. (c) Model D: half-sphere with a diameter of 60mm (axisymmetric model).

Fig. 4. show the load-displacement curves at the point A. For the pressuremeter test, as the surface increases with the expansion of the cavity, the pressure applied is calculated thanks to the relation:

$$P = P_f \sum M_{stage} \frac{r_0}{r_0+\Delta r} \qquad (2)$$

Where P_f=300kPa is the maximum load applied, r_0=30mm is the initial radius of the cavity and Δr is the displacement of the cavity wall. Displacements above 15mm are not displayed as such values are never obtained with a pressuremeter test.

A rigidity has been calculated in the linear part of the curves delimited by the few first points corresponding approximatively to a displacement of 0 to 0,1mm. The results are presented in Table 2. Stress parameters are not addressed here. Significant discrepancies can be observed in terms of curves shape and initial rigidities. Particularly, initial rigidity of Model B (the Goodman or the Ettlinger borehole jacks) is quite far from the rigidity calculated for Model A (the expansion test). Thus, two additional models were created (Fig. 5.) allowing to study the influence of the punch's width. They are based on the half-cylinder in Model B but with a smaller horizontal length (45mm for Model E and 30mm for Model F). The load-displacement curves are represented in Fig. 6. Initial rigidities have also been calculated for these models (Table 3.). Unsurprisingly, the modulus increases when the length of the punch decreases. The model that has the smallest punch, Model F, is the model that has the closest rigidity to the one measured in the cavity expansion test, Model A.

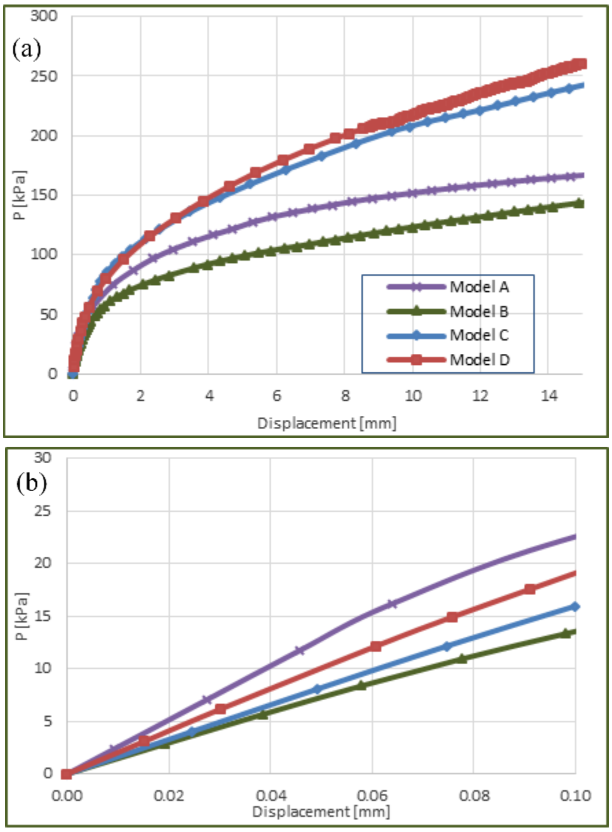

Figure 4. (a) Load-displacement curves associated to the models introduced Fig. 3. in point A (b) zoom-in the linear zone where rigidities were calculated.

Table 2. Rigidities calculated in the initial part of the load-displacement curves.

Model	A	B	C	D
Rigidity [kPa/mm]	253	132	160	189

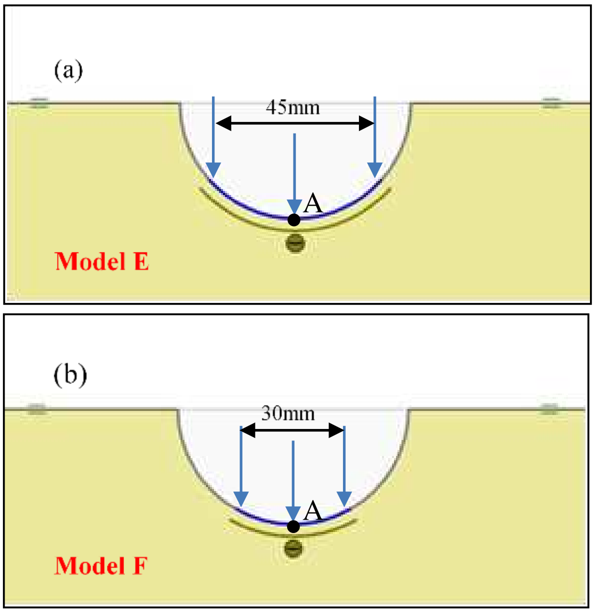

Figure 5. Geometries of the semi-infinite curvy punches studied with a length of (a) 45mm, Model E, and (b) 30mm, Model F.

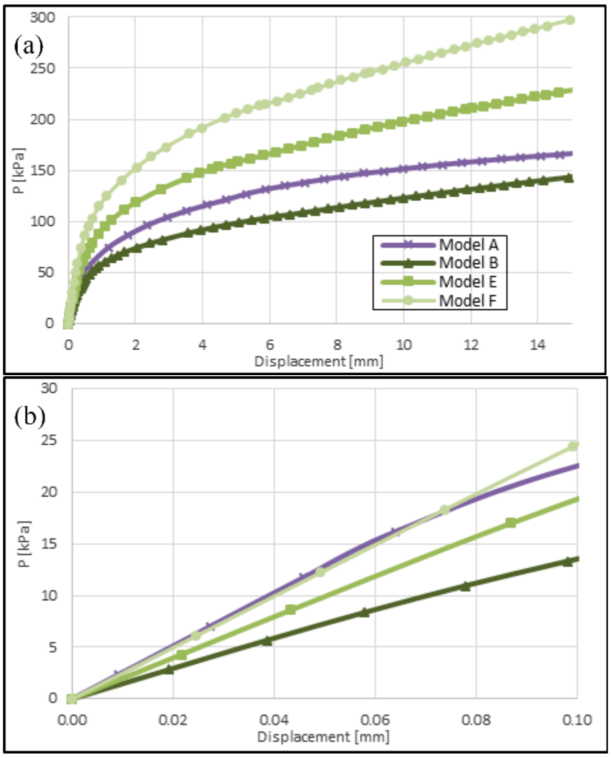

Figure 6. (a) Load-displacement curves associated to the models introduced Fig. 5. (b) zoom-in the linear zone where rigidities were calculated.

Table 3. Rigidities calculated in the initial part of the load-displacement curves.

Model	A	B	E	F
Rigidity [kPa/mm]	253	132	196	248

4. Analytical study of the punch's shape

A bibliographic study has been done in order to find the elastic theory that better describes the penetration of the new probe's bodies. To compare the numerical analyses with the elastic theories, we had to remove the zero-displacement condition applied at the surface of the models. Indeed, in the elastic theories introduced in this section, the surface is free. The models concerned are Model C and D.

It appeared that the penetration of a curvy punch has not been studied very much to the best of our knowledge. The derivation of a lateral modulus of piles from a Ménard modulus is not addressed here. The only relevant publication found is from Dahan [6] who studied the penetration of axisymmetric punches with various shapes according to the elastic theory. Equation (3) gives the penetration u_z of a half-sphere of radius R in a semi-infinite soil depending on the pressure P (Fig. 5. (a)):

$$u_z = \mathrm{R}\left(\frac{3\pi(1-\upsilon^2)P}{2\mathrm{E}}\right)^{\frac{2}{3}} \tag{3}$$

The load-displacement curve is introduced Fig. 6. (b) assuming R=30mm and E=10MPa.

The rigidity in the initial part of the curve is equal to 10 kPa/mm which is quite smaller than the rigidity calculated with Model D without the zero-displacement condition at the surface: 117kPa/mm. The general shapes of the curves are also quite different which could be explained by the fact that the punch progressively penetrates the soil and thus the surface of the soil in contact with the punch increases with the deformation. Conversely, in the Plaxis simulation, the soil is already all around the punch when the penetration begins.

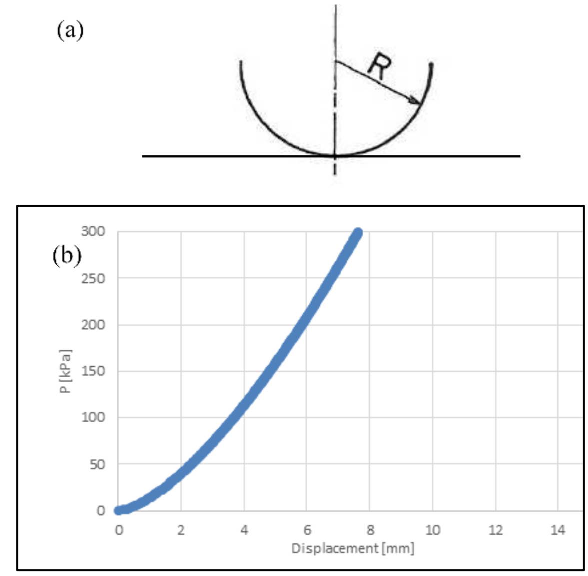

Figure 7. (a) Geometry of the punch in contact with the soil. (b) Load-displacement curve.

Penetration of flat areas has been extensively studied (Poulos and Davis [11]). Gray [9] provides the strain field of a semi-infinite elastic body on which a semi-infinite flat surface load is applied (Fig. 8.)

Strain in z-axis (oriented toward increasing depth) is given by:

$$\delta_z = \frac{P}{\pi E} \cdot \frac{(m+1)}{m^2}\left[(m-2)\alpha + m sin\alpha \cdot cos2\beta'\right] \tag{4}$$

where m= $1/\upsilon$. Assuming υ=0,3, E=10MPa, b=30mm and looking at a point located just beneath the middle of the slip, we obtain an apparent modulus $\frac{\Delta P}{\Delta\delta_z}$ =14,2 MPa. In comparison, the modulus computed in Model C, with a flexible load and without the zero-displacement condition at the surface, is 14,3 MPa.

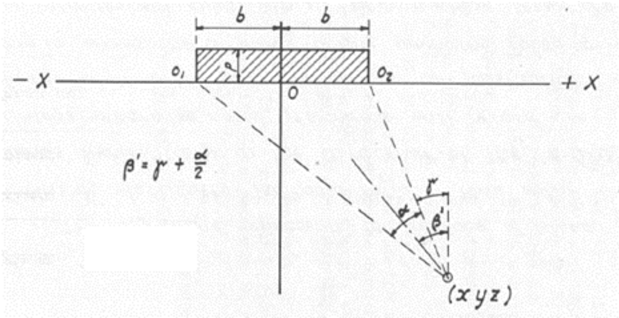

Figure 8. Uniformly loaded strip of width 2b and infinite length (from Gray [9]), z-axis is oriented toward increasing depth.

Whitman and Richart [13] provide the rigidity of a rigid rectangular loaded area of length L and width B. The settlement can then be expressed as:

$$u_z = \frac{(1-\upsilon^2)\sqrt{BL}}{\beta_z E}P \tag{5}$$

where β_z is an influence factor that depends on the L/B ratio (Fig. 9). Assuming a 60mm width rectangle, Fig. 10. shows the influence of the rectangle's length on the rigidity. This shows the limits of models using plane strain assumptions, the real geometry of the punch cannot be forgotten.

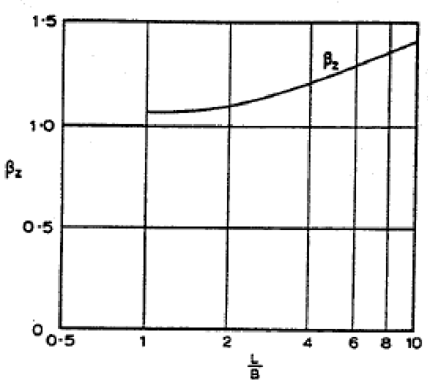

Figure 9. Coefficient β_z for a rigid rectangle of length L and width B (Whitman and Richart [13]).

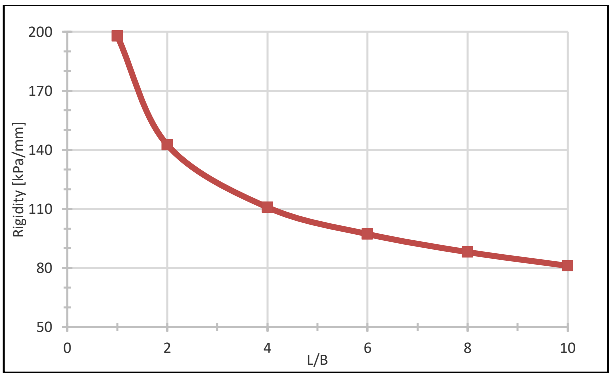

Figure 10. Influence of the length of a 60mm width rectangle on a soil's rigidity.

5. Conclusion

A state-of-the-art of the expansion test has enlightened the interest of rigid dilatometers such as the Goodman or the Ettlinger borehole jacks. However, a full review of their conception appeared to be necessary to enable their use in soft soils (problems of sealing) and in a smaller borehole.

The numerical comparison of the penetration of a punch with the Menard expansion test shows similarities in their initial rigidity. Especially, a curvy punch with a 30mm horizontal length gives a very similar initial rigidity than an infinite inflating cylinder with a 60mm diameter.

This numerical analysis has enabled the development of a new apparatus that consists of two cylindrical, rigid and semi-cylindrical boxes which are spread in the soil.

By analogy with the elastic theory, we aim to define a resistance and deformation parameters that could agree with the measurements of the new probe and that could be compared with those measured with the Ménard pressuremeter. In this study we gathered several elastic theories that may be relevant for our purpose. When compared with the proper models, the theories show good agreements with them. However, the main issue that remains is the fact that in these theories the surface is totally free whereas in the Plaxis simulations, the vertical displacement of the surface is prohibited to obtain real in-situ conditions in a borehole. This has resulted in lower initial rigidities predicted by the theories. Also, the semi-infinite numerical models should be questioned considering the real geometry of the probe parts and a 3D model.

Comparisons should now be made with measures obtained with the new probe. We aim to realize comparison tests in a sandy artificial soil with the Ménard expansion test. This artificial soil will be reconstituted by eluviation in a test chamber which consists of a concrete cylindrical pipe of 1m internal diameter and 1,50m height. Then, tests will be carried out on experimental sites.

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