Design and development of an innovative pressuremeter for improved soil characterization

Conception et développement d'un pressiomètre innovant pour une caractérisation améliorée des sols

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ABSTRACT

The analysis of the behaviour of soils in deformation, at the origin of many pathologies affecting structures subjected to static or dynamic loads, constitutes a major challenge for society. The maintenance of these infrastructures at a sufficient level of service is essential for strategic sectors such as the economy, energy production, industry and tourism in many countries and territories. However, the precise characterization of these phenomena remains a challenge, due to the lack of appropriate experimental tools to correctly define the evolution of the mechanical properties of soils, in particular the degradation of the shear modulus. In this context, this paper proposes a significant advance by presenting the development of a new pressuremeter device, designed to integrate major technological advances compared to existing equipment. This type of pressuremeter enables in-situ measurement of the shear modulus G at small strains. The design, development, and calibration of this device is the subject of the research work described in this paper.

RESUME

L'analyse du comportement des sols en déformation, à l'origine de nombreuses pathologies affectant les ouvrages soumis à des chargements statiques ou dynamiques, constitue un enjeu majeur pour la société. La maintenance de ces infrastructures à un niveau de service suffisant est essentielle pour des secteurs stratégiques tels que l'économie, la production d'énergie, l'industrie et le tourisme dans de nombreux pays et territoires. Cependant, la caractérisation précise de ces phénomènes demeure un défi, en raison de l'absence d'outils expérimentaux appropriés permettant de définir correctement l'évolution des propriétés mécaniques des sols, notamment la dégradation du module de cisaillement. Dans ce contexte, cet article propose une avancée significative en présentant le développement d'un nouvel appareil pressiométrique, conçu pour intégrer des avancées technologiques majeures par rapport aux équipements existants. Ce type de pressiomètre permet la mesure in situ du module de cisaillement G à faibles déformations. La conception, le développement, et l'étalonnage de cet appareil en fait l'objet des travaux de recherche décrit dans cet article.

Keywords: Development; Design; Pressuremeter; Calibration.

1. Introduction

The pressuremeter test occupies a very important place in the panoply of classical soil mechanics tests related to foundation studies. The pressuremeter test allows rapid in situ loading of soil. It consists of radially expanding a cylindrical probe in the soil in order to determine the relationship between the applied pressure and the resulting deformation. This relationship makes it possible to deduce the soil mechanical characteristics that are required for structural design calculations.

The first attempts to carry out in situ cylindrical cavity expansion tests in soils were realized by the German engineer Kögler in 1933 (Mair and Wood, 1987; Clarke, 2022). The apparatus used was a single-cell probe inflated with pressurized gas. Unfortunately, this ingenious device did not receive the consideration and attention it deserved and rapidly fell into oblivion (Briaud, 1992). A few years later, in January 1955, Louis Ménard who is a Civil Engineer for Bridges and Roads rethought the pressuremeter as Kögler had imagined it before. Since the invention of the pressuremeter, pressuremeter tests have developed considerably around the world.

Over the last few years, even more sophisticated data entry devices have appeared. This is the case of the Calculator-Assisted Pressuremeter (CAP), which is the last link in the chain of Ménard's pressuremeters. Its primary advantage lies in the electronic control of the progress of the pressuremeter test.

In addition to all the collateral inventions of Louis Ménard, other devices very similar to his pressuremeter, or supplementing it, were developed in France and around the world by several researchers like Wroth and Hughes (1972), Baguelin et al. (1974), Briaud and Shields (1979), Reid et al. (1982), Withers et al. (1986), Clarke and Allan (1989), Akbar (2001), Bello (2004), Reiffsteck et al. (2005), Thorel et al. (2007), Rehman (2010), Jacquard et al. (2013), Johnston et al. (2013), Shaban and Cosentino (2017), Karagiannopoulos (2020), Aissaoui et al. (2020). Table 1 gives a chronological summary of the development of the various devices, and the differences between them.

However, these latest developments in pressuremeter technology exhibit several limitations: they are costly and may not be suitable for the design of certain geotechnical structures subjected to cyclic loading. Establishing the response of such structures under low strain rates is essential for accurate design. Nevertheless, the necessary parameters cannot be obtained using conventional testing equipment due to inherent measurement limitations. This paper provides a detailed discussion on the development of a new generation of pressuremeters equipped with a measuring feeler, designed to determine the soil shear modulus at small strain levels and its degradation with increasing shear strain, thereby enhancing precision and versatility for geotechnical applications.

Examples of applications, accompanied by detailed interpretations of tests conducted on soils from the Tlemcen region in Algeria, are presented in a parallel communication (Aissaoui et al., 2025) at this same conference.

Table 1. Historical summary of the pressuremeter equipment

<table>
<tr><th>Years</th><th>Types of pressuremeter</th><th>Method of strain measurement</th></tr>
<tr><td>1933</td><td>Kögler's borehole side tester</td><td>--</td></tr>
<tr><td>1955</td><td>Menard's patent: a 3 cell pressuremeter: A type</td><td rowspan="8">Volume variation</td></tr>
<tr><td>1956</td><td>MPM B type</td></tr>
<tr><td>1957</td><td>MPM C type</td></tr>
<tr><td>1958-1959</td><td>MPM D types</td></tr>
<tr><td>1960</td><td>MPM E type</td></tr>
<tr><td>1963</td><td>MPM F type</td></tr>
<tr><td>1965</td><td>MPM G types</td></tr>
<tr><td>1970</td><td>LCPC self-boring pressuremeter for weak soils</td></tr>
<tr><td>1971</td><td>Oyo Elastmeter 100</td><td rowspan="2">3 diameter strain gauged springs</td></tr>
<tr><td>1972</td><td>Cambridge self-boring pressuremeter</td></tr>
<tr><td>1973-1976</td><td>MPM GB, GC, GA types</td><td rowspan="3">Volume variation</td></tr>
<tr><td>1976</td><td>LCPC self-boring pressuremeter for weak rocks</td></tr>
<tr><td>1979</td><td>LCPC Menard cone pressuremeter for offshore jobs</td></tr>
<tr><td>1980</td><td>Oyo Elastmeter 200 / Cambridge in-situ HPD</td><td>3 diameter strain gauged springs</td></tr>
<tr><td>1982</td><td>Push-In pressuremeter PIP</td><td rowspan="2">Volume variation</td></tr>
<tr><td>1985</td><td>Calculator Assisted Pressuremeter CAP</td></tr>
<tr><td>1986</td><td>Full displacement pressuremeter FDPM</td><td>3 diameter strain gauged springs</td></tr>
<tr><td>1989</td><td>Newcastle weak rocks self-boring pressuremeter (RSBP)</td><td>1 strain gauged</td></tr>
<tr><td>1992</td><td>pressuremeter with electronic data acquisition system SPAD</td><td>Volume variation</td></tr>
<tr><td>2001</td><td>Development of low cost in-situ testing devices</td><td rowspan="2">Hall Effect Transducer (HET)</td></tr>
<tr><td>2004</td><td>Developments of a full displacement pressuremeter</td></tr>
<tr><td>2005</td><td>A new generation of self-boring pressuremeter in France PAF2000</td><td>3/6 strain arms</td></tr>
<tr><td>2007</td><td>A cone pressuremeter for soil characterisation in the centrifuge</td><td>Volume variation</td></tr>
<tr><td>2010</td><td>Development of a Pressuremeter to Operate in Alluvial Soils of Punjab</td><td>Hall Effect Transducer (HET)</td></tr>
<tr><td>2013</td><td>A new probe for measuring the pressuremeter limit pressure of soils without extrapolation</td><td>Volume variation</td></tr>
<tr><td>2013</td><td>Development of a laboratory-scale pressuremeter</td><td>Two strains gauged</td></tr>
<tr><td>2017</td><td>Development of the Miniaturized Pressuremeter Test to Evaluate Unbound Pavement Layers</td><td>Volume variation</td></tr>
<tr><td>2020</td><td>Contribution of pore pressure measurement to pressuremeter testing.</td><td>Volume variation</td></tr>
<tr><td>2020</td><td>Contribution of modification of a pressuremeter for an effective prediction of soil deformability</td><td>Hall Effect Transducer (HET)</td></tr>
</table>

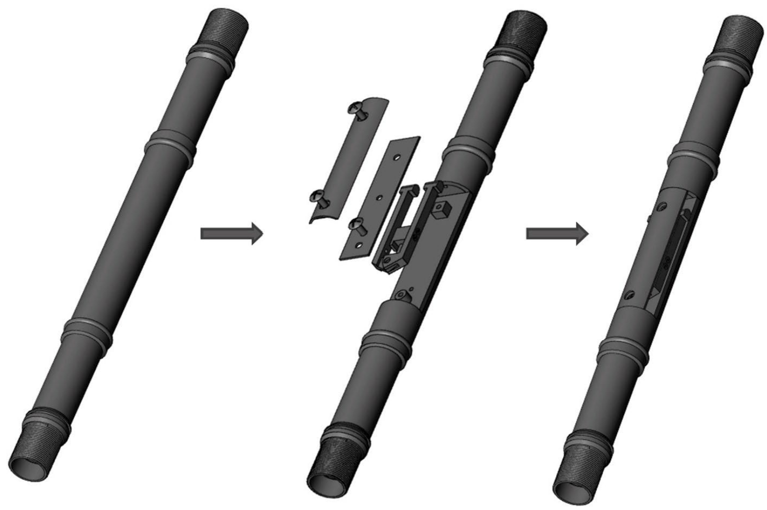


Figure 1. Principle of the proposed model.

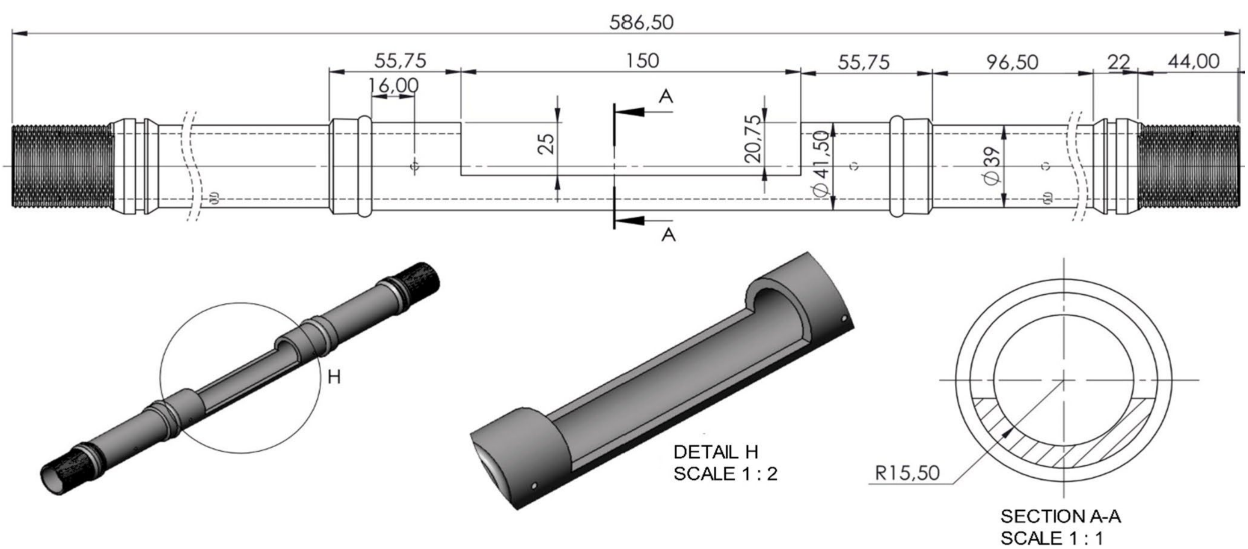


Figure 2. Illustration of the measurement area (the dimensions in mm).

2. Development and Design

2.1. The probe

Fig. 1 presents the schematic diagram of the conceptual design of the proposed prototype. A standard Menard probe, with a diameter of 60 mm, was utilized. This probe consists of three cylindrical cells with a circular cross-section, all sharing the same axis. A test plate was inserted into the central measuring cell. To accommodate the new measurement system, a portion of the standard probe was removed.

The modified section of the central measuring cell is illustrated in Fig. 2. This zone is waterproof, ensuring the containment of water and gas. A 150 mm long slot was created at the midpoint of the probe to facilitate measurements at the membrane's center. The inner diameter of the probe at the central cell level is 41.5 mm. The probe was cut to a depth of h = 25 mm, as shown in Fig. 2. This specific depth was selected to enable the straightforward and convenient installation of the measurement system.

Fig. 3 provides a schematic representation of the first prototype, detailing the configuration of the measurement zone within the central cell.

2.2 strain measurement system

Unlike conventional pressuremeter probes, this new probe uses a pneumatic system instead of the hydraulic system. In other words, the cell pressure is applied by means of an air-filled membrane and the radial deformation of soil can directly be estimated using a measuring feeler (Fig. 4), instead of deducing the displacements from the variations in the volume of the fluid (Aissaoui et al., 2018, 2021).

The measuring feeler consists of two arms and a support for the Hall Effect sensor.

Figure 3. The pressuremeter probe showing the key features.

The Hall Effect sensor was positioned on a suitable support placed between the two arm magnets. The dimensions of the sensor seat allow covering a measuring range of about 30 mm, which corresponds to the maximum limit that the device can reach, i.e. when the portion carrying the second magnet comes into contact with the support of the Hall Effect sensor.

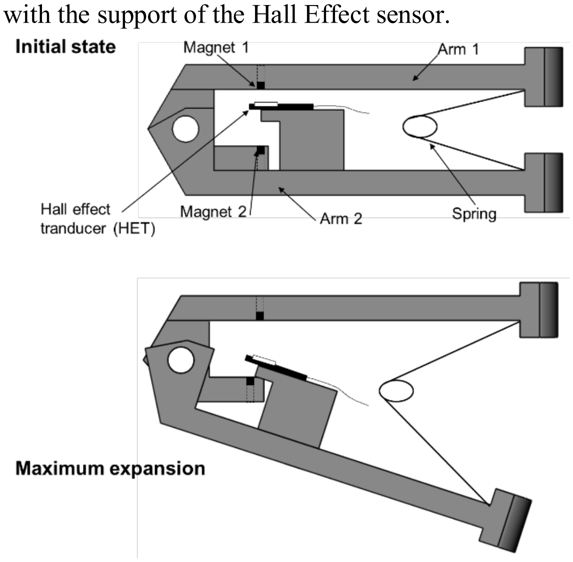


Figure 4. The measuring feeler.

A present limitation of Menard type pressuremeter test is due to the difficulty of reaching large expansion volumes and high pressures without exposing to significant risks of bursting. The expansion measurement system in the developed pressuremeter can record the cavity strain to about 72% of its original size, which is more than the minimum (50%) specified by Withers et al. (1986) and Clarke (2022). The new pressuremeter allowing the volume of the hole to be doubled, even under high pressures: the conventional limit pressure can then be directly measured.

Measurements of pressures and deformations during a pressuremeter test are taken electronically at the ground surface by connecting the probe to the control unit through electrical cables. The probe is connected to the analog-to-digital converter, where the soil deformation is often expressed as a radial strain εr that is equal to the change in membrane radius (*ΔR*) divided by its initial radius (R_0).

$$\varepsilon_R = \frac{\Delta R}{R_0} \quad (1)$$

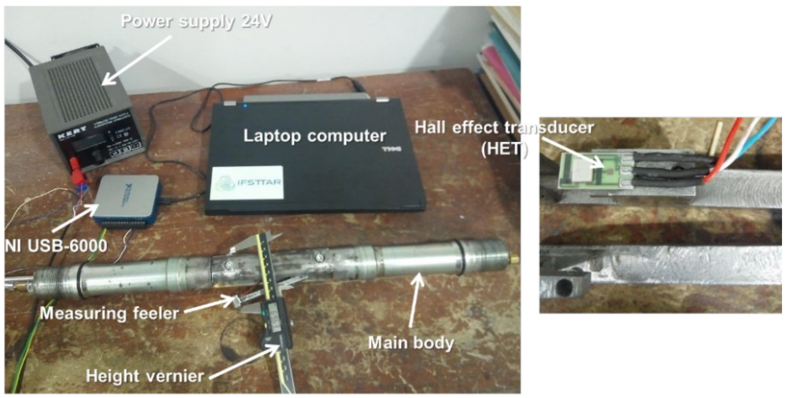
3. Measurement system calibration

Proper sensor calibration was performed to convert the analog output into pressure and radial expansion units during expansion tests. This calibration process is essential to ensure the accuracy and reliability of the measurements. Additionally, it guarantees the correct operation of the equipment, enhancing its reliability, productivity, and representativeness. The equipment setup includes a Hall Effect sensor, complete with its measurement circuit, and a pressure sensor, both of which were calibrated to meet precise measurement standards.

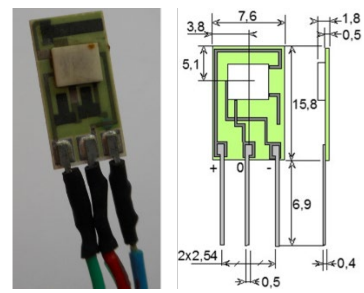
3.1 The Hall Effect Transducer (HET)

The primary purpose of using this type of Hall Effect sensor is to enable non-contact measurement of radial displacements. According to Clayton et al. (1989), the Hall Effect has been utilized in devices developed for measuring local axial strains on triaxial specimens. These authors explain that "when a metallic or semiconductor plate carrying an electric current is placed in a magnetic field with flux lines perpendicular to both the plate and the current flow, the charge carriers (e.g., electrons) are deflected, generating a voltage across the plate in a direction orthogonal to the current flow. This voltage, known as the Hall voltage, serves as the basis for the sensor's operation."

The sensor was powered by a DC voltage source supplying 15 V to the terminal marked +.



(a)



(b)

Figure 5. a) Assembly carried out for calibration, b) Ratiometric Hall Effect sensor.

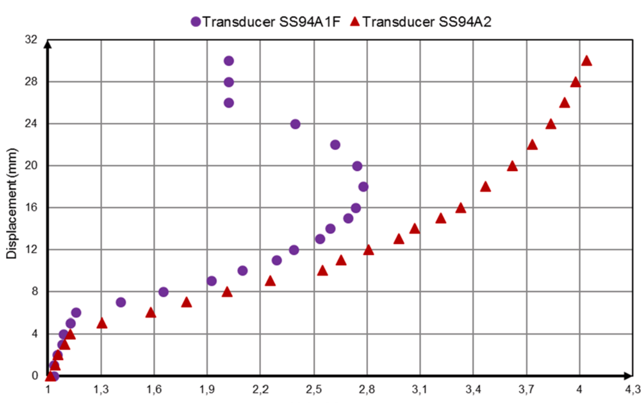


Figure 6. Effect of the SS94A1F and SS94A2 sensors on the measurement.

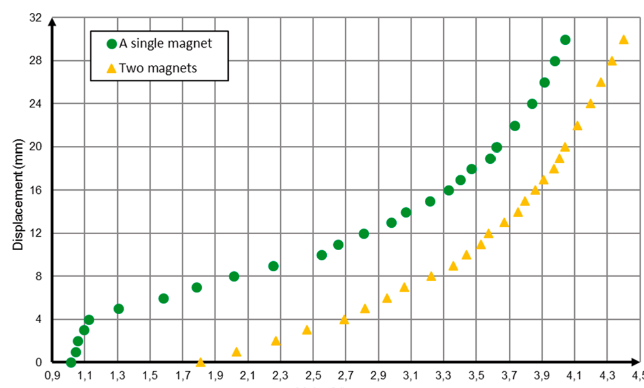


Figure 7. Influence of the magnetic polarization on the response of the sensor.

The terminal marked - was connected to the ground, while the terminal labeled 0, which uses the ground as a reference, was employed for signal acquisition (Fig. 5). This configuration ensures accurate and reliable measurements of radial displacements during testing.

Calibration of the radial movement of the measuring feeler arms against the sensor's output voltage was performed before membrane installation. This established a relationship between the voltage (recorded via a National Instruments data acquisition system) and the radial displacement. The probe was fixed horizontally, and a digital Vernier caliper measured arm displacement at 1 mm intervals up to 30 mm. Calibration focused on one arm, while the other remained fixed.

Two sensors, SS94A1F and SS94A2, were tested to assess their performance. The SS94A1F sensor, with a range of [-100, +100] Gauss, proved inadequate, as it could not detect the magnetic field beyond ~18 mm, leading to non-unique voltage-displacement relationships. In contrast, the SS94A2 sensor, with a range of [-500, +500] Gauss (Fig. 6), covered the full displacement range (up to 30 mm) with consistent and accurate measurements. Consequently, the SS94A2 sensor was selected for future use.

Following sensor calibration, the pressuremeter test results were found to be inconsistent with the standard Menard curve, suggesting a calibration issue. As shown in Fig. 6, the relationship between displacement and output voltage is approximately linear within the range of 1–1.2 V, where the magnetic field generated by the magnet on the measuring feeler arm is strongest. However, beyond a displacement of 4 mm, the Hall Effect sensor's response becomes non-linear due to the weakening magnetic field around the sensor.

To address this, a series of tests were conducted by increasing the magnet diameter and adding a second magnet to the lower part of the arm. Initial attempts with a single magnet yielded unsatisfactory results. However, using two magnets (with opposite polarities, N-S and S-N) significantly improved the linearity of the sensor's response, as illustrated in Fig. 7. This dual-magnet configuration provided greater accuracy and a more realistic representation of the displacement-voltage relationship, aligning with the study's objectives.

Ultimately, the setup with two magnets—one at the top and one at the bottom of the arm—was adopted to enhance measurement precision and linearity.

3.2 Calibration procedures for pressure measurement systems

The search for good precision in measurements is absolutely necessary. This operation focused mainly on measuring the pressure applied on the probe. For this, it was decided to replace the conventionally used reed manometers by a KELLER brand sensor whose function was to measure the pressure, and then to transmit the information to an EV-06 recorder, as shown in Fig. 8.

This series of pressure sensors shows good characteristics of precision, stability and reliability. It is worth mentioning that the applied pneumatic pressure is controlled by means of servo control software which allows varying the pressure with high precision and at a precise rate.

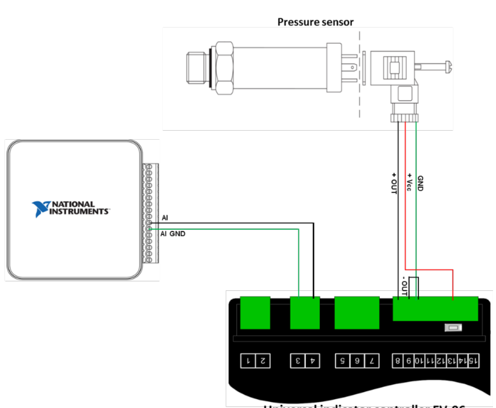


Figure 8. Schematic Diagram of the Pressure Sensor Setup.

The calibration results are summarized in Fig. 9, which includes the linear regression equation derived from the data. The results indicate a rapid and nearly linear variation in voltage as a function of the applied pressure. The test was repeated three times, and the results demonstrated strong consistency. As shown in the calibration curve, the abscissa at the origin (i.e., the voltage reading at zero pressure) is 0.08 V, corresponding to atmospheric pressure.

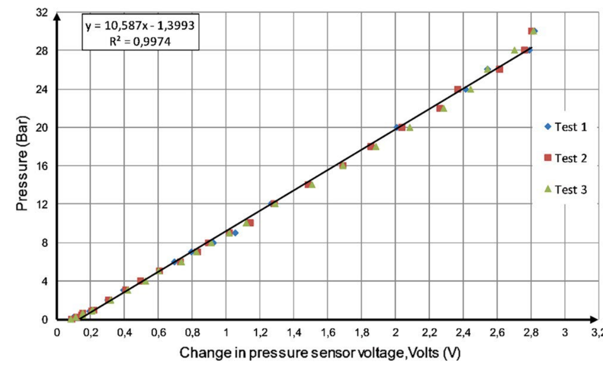


Figure 9. Calibration curve of the pressure sensor.

4. Overall instrumented pressuremeter system

Figure 10 (a) clearly illustrates the setup diagram to be realized in order to install the workstation. This is the functional diagram of the pneumatic and electrical network to be used in performing the different tasks of the test. To do this, one end of the nitrogen pressure supply tubing is connected to the head of the pressuremeter probe, where the wires of the measuring feeler are welded to the wires of the electric cable. Note that the power cable and the pressure supply tubing are attached to the rods of the pressuremeter probe through plastic ties to avoid any problem of friction of the cable and tubing with the borehole wall. The second end of the power cable is plugged into the NI USB-6000 data acquisition hardware. Likewise, the second end of the tubing is connected to the pressure sensor through a male - female adapter. Moreover, the pressure sensor is attached to the solenoid valve through a male-female connection adapter. As for the three wires of the pressure sensor, they are connected to the Digital Indicator and Controller EV-06 which is directly connected to the NI USB-6000 module in order to record all the output pressure values. After connecting the two sensors to the recording and measuring system, the solenoid valve is then connected to the Geomatech G100 volume pressure controller (VPC) through the female connection of the air outlet. In addition, the nitrogen bottle is attached to the female quick connector for the purpose of supplying the volume pressure controller with nitrogen. As for the NI DAQPad-6015 module, it is connected to the solenoid valve for the piloting and controlling tasks during the test. Both NI acquisition modules are connected to the laptop computer through USB ports. It is worth specifying that the solenoid valve is powered by a stabilized 24V integrated switching power supply. The microcomputer and the EV-06 indicator are powered by a 220V electrical source available on site, while the measuring feeler is powered by a stable 9V supply.

Figure 10 (b) depicts the equipment used for the tests at the experimental site; all the components are shown schematically in the photo.

Examples of applications, accompanied by detailed interpretations of tests conducted on soils from the Tlemcen region in Algeria, are presented in a parallel communication (Aissaoui et al., 2025) at this same conference.

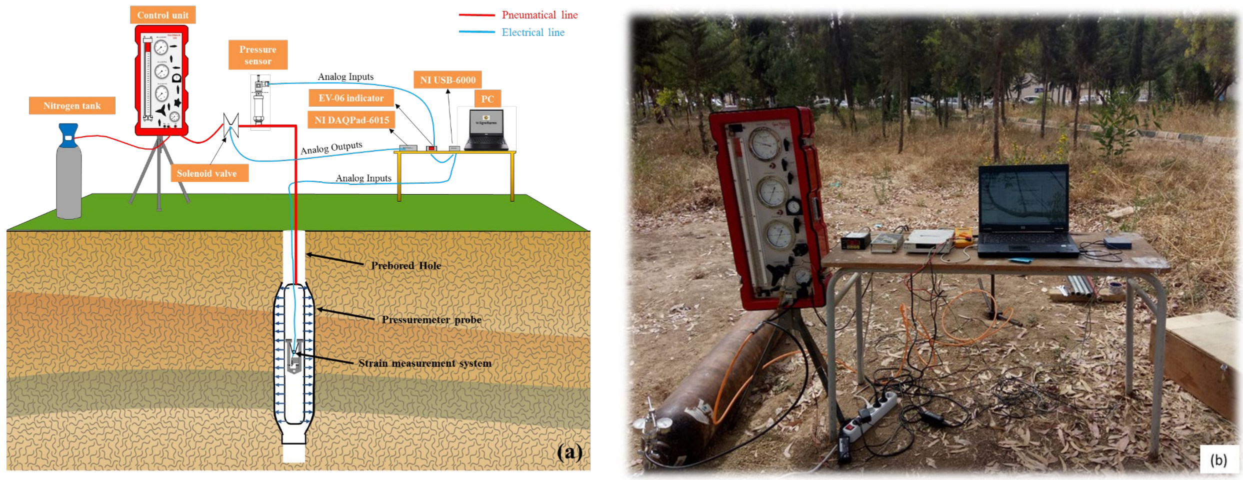


Figure 10. (a) Schematic sketch of the pressuremeter equipment on site assembly; (b) Assembly and overview on site.

5. Conclusions

This paper provides details on the design and manufacturing of a new pressuremeter that contributes to a better understanding of soils, particularly in the domain of small strains and the characterization of soil response under cyclic loading. This innovative pressuremeter stands out from conventional pressuremeters, such as the Ménard pressuremeter, due to its system for measuring radial deformations using a Hall Effect sensor, rather than inferring displacements from fluid volume changes. This approach enables more precise and direct measurements, thereby improving the quality of the collected data.

The paper briefly discusses the calibration procedure for the two key sensors integrated into the new pressuremeter: a pressure sensor and a Hall Effect sensor. Mathematical relationships were developed to convert the raw voltage outputs from these sensors into practical engineering units. This calibration process is crucial, as it ensures the reliability, accuracy, and consistency of the measurements obtained with the pressuremeter.

Future research is expected to confirm the significant role of this equipment in the identification and characterization of soils, particularly in seismic contexts. By providing more precise data on the mechanical properties of soils, this pressuremeter could contribute to a better assessment of soil stability and a more reliable prediction of their behavior under dynamic loading, such as that induced by earthquakes. This would enable the design of safer and more resilient infrastructure.

In conclusion, this new pressuremeter represents a significant advancement in the field of geotechnical instrumentation. It offers notable improvements in the precision and reliability of soil analysis, particularly for small deformations and cyclic loading. These advancements are essential for practical applications in civil engineering, as well as for research in soil mechanics, paving the way for a better understanding of the complex behaviors of soils under varied conditions.

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