Thermal pressuremeter- Novel tool for study the thermomechanical behaviour of soils

Pressiomètre thermique-Nouvel outil pour l'étude du comportement thermomécanique des sols

Ichrak Gaaloul[1,3#], *Wissem* Frikha[2,4], *Othman* Ben Mekki[1], *Sami* Montassar[1]

[1] *Laboratoire de Génie civil, Université de Tunis El Manar, Ecole Nationale D'Ingénieurs de Tunis, Tunis, Tunisia;*
[2] *Laboratoire de L'ingénierie Géotechnique, Université de Tunis El Manar, Ecole Nationale D'Ingénieurs de Tunis, Tunis, Tunisia;*
[3] *Institut Supérieur des Etudes Technologiques de Nabeul, Nabeul, Tunisia;*
[4] *Setec International, 42-52Quai de la Rapée, Central Seine Building, 75583, Paris cedex 12, France.*
[#]*Ichrak Gaaloul : email : ichrak.chihi@enit.utm.tn*

ABSTRACT

To analyze the thermo-mechanical behavior of soils, this paper proposes a device that introduces thermal effects into the pressuremeter apparatus, referred to as the thermal pressuremeter. The technique involves heating the liquid contained within the hydraulic system's reservoir, which is connected to the measuring cell. Glycol water is used as the liquid due to its favorable thermal properties. At various temperatures, the liquid is heated and then circulated through the tubing to the probe. As a result, the proposed device can measure the limit pressure of soil subjected to both internal pressure and temperature variations.

Before manufacturing the device, both analytical and numerical models are developed and discussed. Specifically, the pressuremeter test under thermal variations is numerically modeled by simulating the expansion of a cylindrical cavity, where the probe is represented as a cavity undergoing radial expansion. A finite difference analysis, accounting for large strains and thermal effects, is performed using FLAC V 7.00 (Itasca Consulting Group). The model assumes that the soil behaves as a homogeneous, elastic, perfectly plastic material following the Mohr-Coulomb yield criterion. The numerical simulation results, including stresses, displacements, and limit pressure, are compared with a published analytical solution. According to the numerical results, soil temperature has a significant impact on the limit pressure.

The major contribution of this work is the incorporation of thermal variations into a numerical 2D model of cylindrical cavity expansion, validating the effectiveness of the proposed device. These findings are particularly relevant for interpreting pressuremeter test results and designing geothermal piles.

RESUMÉ

Afin d'analyser le comportement thermo-mécanique des sols, cet article propose un dispositif qui introduit des effets thermiques dans l'appareil pressiométrique, appelé le pressiomètre thermique. La technique consiste à chauffer le liquide contenu dans le réservoir du système hydraulique, connecté à la cellule de mesure. Grace à ses propriétés thermiques, l'eau glycolée est le liquide utilisé. Le liquide est préalablement chauffé à différentes températures puis circulé à travers la tubulure jusqu'à la sonde.

Avant la fabrication du dispositif, des modèles analytiques et numériques ont été développés et discutés. En effet, l'essai pressiométrique sous variations thermiques a été modélisé numériquement en simulant l'expansion d'une cavité cylindrique, où la sonde pressiométrique est identifiée à une cavité soumise à une expansion radiale. Une analyse en différences finies, tenant compte des grandes déformations et des effets thermiques, a été effectuée à l'aide du code de calcul FLAC V 7.00 (Itasca Consulting Group). Le modèle suppose que le sol est homogène, élastoplastique selon le critère de plasticité de Mohr-Coulomb. Les résultats de la simulation numérique, y compris les contraintes, les déplacements et la pression limite, sont comparés à une solution analytique publiée. Selon les résultats numériques, la température du sol a un impact significatif sur la pression limite.

La contribution majeure de ce travail consiste à l'incorporation des variations thermiques dans un modèle numérique 2D d'expansion de cavité cylindrique, validant, ainsi, l'efficacité du dispositif proposé. Ces résultats sont particulièrement pertinents pour l'interprétation des résultats d'essais pressiométriques d'une part et le dimensionnement des pieux géothermiques d'autre part.

Keywords: thermal pressuremeter, numerical model, pressuremeter test, thermal effects, limit pressure, Cavity expansion.

1. Introduction

A pressuremeter test is an in-situ stress-strain test performed on the wall of a prebored hole using a cylindrical probe that expands radially (ASTM 2000). The test consists of placing an inflatable cylindrical probe in a predrilled hole and expanding it while measuring changes in volume and pressure. The pressuremeter test is widely used to determine the soil's mechanical parameters, including strength parameters (ultimate soil resistance) and stiffness parameters (modulus). These parameters help analyze the soil's mechanical behavior and aid in the design of various types of foundations (e.g., piles, footings) (AFNOR 2012).

The first pressuremeter prototype was designed by Louis Ménard in 1955. It featured a cylindrical expansion apparatus known as Type A, which included a hand pump for injecting constant increments of water and a large probe with a 140 mm diameter.

Since then, the pressuremeter has undergone continuous improvements in design. Over the years, several prototypes (Types B, C, D, E, F, G, etc.) have been developed, incorporating better materials for pressure application, minimizing approximations, and enhancing the sensor and recording system (Cassan 2005). The latest generation of pressuremeters follows electronic and automatic technological advancements. Known as the "auto-controlled pressuremeter," it was developed to address issues related to repeatability and the accumulation of inaccuracies in testing. According to the ISO 22476-4 (ISO 22476-4 2012) standard, this apparatus is fully automatic and autonomous, managing all test steps as preselected by the operator. The auto-controlled pressuremeter simplifies the operator's work, enhances result reliability, and reduces preparation time (Frikha and Varaksin 2018).

The manual Ménard pressuremeter (Type G) consists of three main components:

- A readout device or control unit (CU) that applies pressure and records volume changes.
- A measuring device, including a hydraulic probe composed of a measuring cell and two guard cells.
- Plastic tubing that connects the probe to the readout device.

These components enable in-situ testing in accordance with ISO 22476-4 (ISO 22476-4 2012) and ASTM D4719-07 standards (ASTM 2000). Figure 1 illustrates the schematic representation of the three main parts of the pressuremeter.

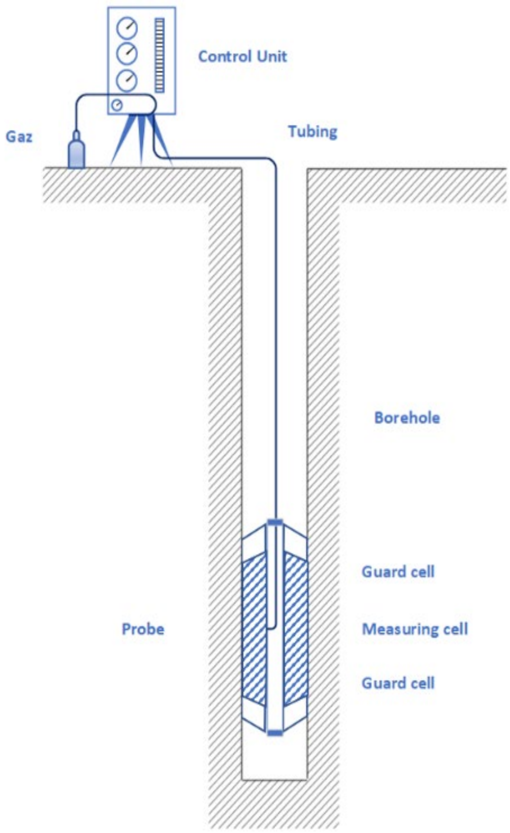


Figure 1. Menard Pressuremeter Apparatus.

The control unit (CU) consists of devices that regulate applied pressure and measure volume changes. It includes an 800 cm³ sight tube volumeter for reading volume variations in the measuring cell, regulators for both main and differential pressures, pressure gauges ranging from 0 to 25 bars and 0 to 60 bars for the guard and measuring cells, and several valves and connectors. The probe is fully protected by a rubber cover (with different types depending on soil stiffness), which is inflated by gas in the two guard cells and by water in the measuring cell (Frikha and Varaksin 2018).

Pressuremeter tests directly apply the cylindrical cavity expansion problem, where the probe is modeled as a radially expanding cavity. Numerical analyses of cavity expansion problems were initially explored by Carter, et al. (1986), Huang et al. (2004), and Ladanyi and Foriero (1998). Recent numerical studies primarily rely on finite element simulations. For instance, Jang et al. (2003) used the finite element program ABAQUS to simulate a self-boring pressuremeter test, including the strain-holding stage. Huang et al. (2004) modeled the cone penetration process by simulating finite strain deformation in the soil and large-scale sliding at the interface between the penetrometer and the soil. Wang et al. (2010) developed a numerical model of cavity expansion to simulate the compaction grouting process.

Pressuremeter tests have been extensively analyzed in numerous studies using the cylindrical cavity expansion approach (Frikha and Bouassida 2013; Gaaloul, Montassar, and Frikha 2021; Gaaloul et al. 2024b; 2024a). Manandhar and Yasufuku (2013) applied cavity expansion theory to evaluate skin friction by incorporating a stress–dilatancy relationship and to determine the end-bearing capacity of tapered piles by introducing a tapering factor. Bouassida and Frikha (2007) focused on the theoretical determination of extreme net pressure in a cylindrical cavity and the prediction of soil strength characteristics from pressuremeter data.

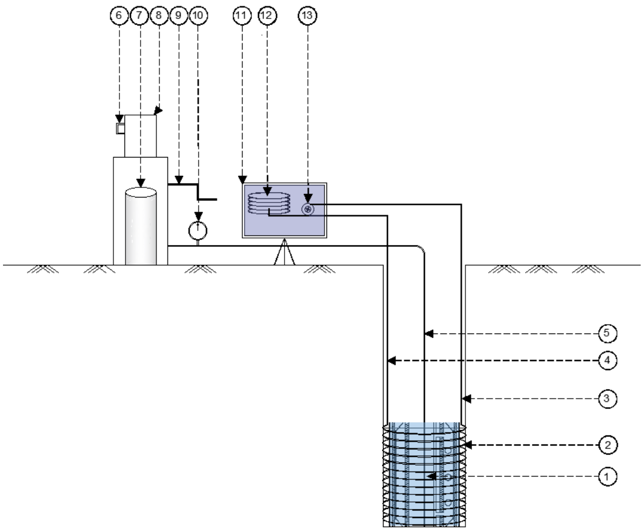
However, thermal effects in pressuremeter tests have not been extensively addressed. Thermal in-situ tests, such as the thermal response test (TRT) (ISO 17628:2015 2020), determine soil thermal characteristics, including thermal conductivity, but do not account for mechanical behavior. Only a few studies have investigated the impact of thermal variations on cylindrical cavity expansion. Zhou et al. (2018) proposed a semi-analytical solution for cavity expansion in thermoplastic soils, while Gaaloul et al. (2021) developed an analytical solution to assess the effects of temperature variations on soil limit pressure.

In this paper, an in-situ device called the thermal pressuremeter is introduced to analyze the thermo-mechanical behavior of soils. This device enables temperature variations to be applied to pressuremeter test equipment. Before manufacturing, analytical and numerical models are developed and discussed.

2. Proposed device of the thermal pressuremeter

In 1978, Briaud developed a simplified version of Ménard's pressuremeter, now known as TEXAM (Shidlovskaya, et al. 2019). This pressuremeter consists of a control unit, a monocellular probe, and tubing. The control unit contains pressure and volume sensors, connectors, a control valve, and a screw jack that pressurizes the fluid (water) in a cylinder via a piston mechanism. The monocellular probe is inflated by forcing water out of the cylinder through a crank-powered piston. The probe is inserted into a prebored borehole, prepared using wet rotary drilling with the injection of prepared drilling mud. It can be inflated using either equal pressure steps or equal volume steps. The tubing connects the control unit to the probe. This pressuremeter enables in-situ testing in accordance with ASTM D4719-07 standards (ASTM 2000).

The proposed device integrates temperature control into the classic instrumentation of a monocellular pressuremeter to study the thermo-mechanical behavior of soils. A temperature control and heating unit is added to the control unit. A schematic representation of the proposed device is shown in Figure 2.



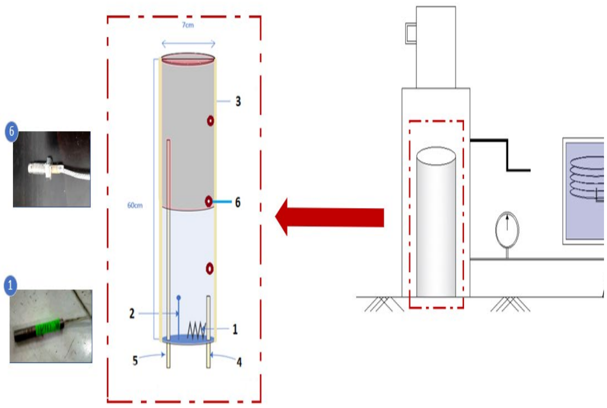
***1: monocellular probe, 2: spirally metal tube, 3, 4: thermocouples, 5: tubing, 6: Counter for volume, 7: glycol water reservoir, 8: Screw Jack, 9: Crank, 10: Pressure gage, 11: Heating bath, 12: Heater, 13: Pump*.**

Figure 2. Schematic description of the thermal pressuremeter.

The heating system consists of a heater (placed in a heating bath with the circulating fluid), a circulation device (pump), insulation, and a temperature control unit. The circulating fluid used in the thermal pressuremeter test is glycol water (20%) due to its favorable thermal properties: higher thermal conductivity, density, viscosity, and transport properties compared to water (Bohne et al. 1984).

The temperature is introduced into the pressuremeter instrumentation through the control unit, specifically into the water reservoir that supplies the measuring cell. Heating the glycol water in the reservoir allows the circulation of liquid at a specific temperature through tubing to the measuring cell. An immersion heater (1) is submerged at the bottom of the tank, heating the glycol water to a target temperature, which can reach up to 60°C. A control thermostat (2) continuously monitors and regulates the temperature as needed. To maintain the desired temperature, the reservoir is covered with insulating material (3).

The system uses two pipes (4 and 5): the first pipe allows water to enter for heating, while the second extracts the heated water. Two or three temperature sensors (6) are placed at different locations in the reservoir to ensure uniform heating. The system operates based on the principle of thermal stratification: as water is heated, it naturally rises to the top of the tank due to its lower density, while colder, denser water remains at the bottom (Figure 3).



1: Heater (electrical resistance), 2: Heat controller (thermostat), 3: isolating material, 4: Water supplier tube, 5: Water extractor tube, 6: Temperature sensors (thermocouples).

Figure 3. Reservoir of pressuremeter apparatus with temperature incorporation.

Characteristics of the immersion heater (1) and the thermostat (2) are resumed in the table 1.

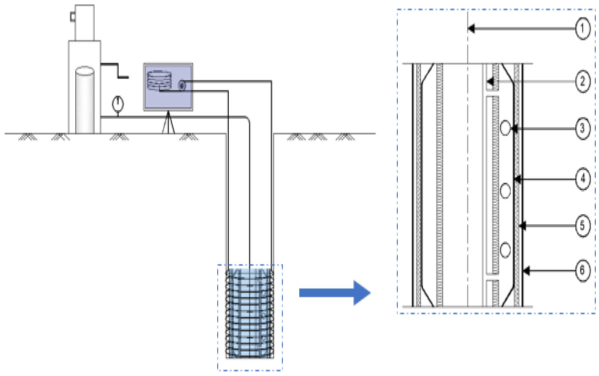
Table 1. Characteristics of the immersion heater and the thermostat.

Immersion heater	Performance	1000 W
	Temperature	30 to 70 °C
	dimensions	8×200 mm
	Voltage	230 V
Thermostat	Voltage	230 V
	Temperature	-10 to 110 °C
	dimensions	150 mm

The tubes in the thermal pressuremeter remain unchanged; they are Rislan-type tubes, resistant to temperatures ranging from -60°C to +130°C. To maintain the required temperature during testing and minimize heat loss, an insulation material may be incorporated into the coaxial tubing.

Pressure loss in a pressuremeter test depends on the tubing dimensions and the flow rate of the liquid circuit. Since the tubes remain the same for thermal pressuremeter testing, adjustments to pressure measurements depend on the pressure increment between steps. The pressure must be increased to the next increment within an optimal time frame, not exceeding 20 seconds, while maintaining the appropriate pressure level. To mitigate intense oscillations in tests with long tubing or creep effects at certain levels, the first approach for compensating pressure loss involved identifying the tubing characteristics through laboratory tests and determining the pressure loss coefficients per unit length (Arsonnet et al. 2013). The inclusion of a pump in the heating system can further reduce pressure loss by ensuring a sufficient flow rate of heated glycol water.

The probe consists of a single measuring cell, meaning it is supplied with hot water at specific temperatures. It is equipped with a series of thermocouples to monitor and ensure the target temperature is reached. If the required temperature is not achieved due to pressure or temperature loss, the thermocouple provides a feedback signal to the heater. In such cases, the cell is indirectly heated by circulating water through a metal tube spirally wrapped around the probe (Figure 4).



1: Axis of probe, 2: liquid injection tube, 3: sensors (thermocouples), 4: cover, 5: diaphragm, 6: metallic reinforced sleeve

Figure 4. Probe measuring cell of thermal pressuremeter.

The first step in the test procedure involves heating the glycol water to the required isothermal temperature. Before starting the test, it is important to wait a few minutes to achieve thermal stability (1 minute to reach 20°C, 2 minutes to reach 40°C, and 3 minutes to reach 60°C). For each set temperature, the test is conducted in successive pressure increments with a step size of Δp = 25 kPa. During each pressure level, the time required to reach the target pressure (δt) is measured. The pressure application time (Δt) for each step is 1 minute. Multiple volume measurements are taken during each step at time intervals of Δt = 0s, 10s, 20s, 30s, 40s, 50s, and 60s. The test is considered complete when a minimum of eight steps or an injected volume of 600 cm^3 is reached. The first test is conducted at 20°C and then repeated at 30°C, 40°C, 50°C, and 60°C.

The test concludes with the plotting of pressure curves at different temperatures, and the determination of the limit pressure, creep pressure, and pressure modulus, in order to study the thermo-mechanical behavior of soils.

3. Numerical Model

The finite difference code FLAC V7.00 (Itasca Consulting Group) was used to perform the numerical model of the cylindrical cavity expansion to simulate pressuremeter tests.

3.1. Geometry and Boundary Conditions

The analysis of the cylindrical cavity expansion was treated as an axisymmetric two-dimensional problem with plane strain boundary conditions. An initial cavity radius of a_0 = 3 cm was used in the simulation (ASTM 2000). The outer radial boundary of the numerical model is set to 150 times the cavity radius, resulting in a value of 4.5 m, and the height is 45 cm. This choice of dimensions is supported by recommendations from existing research. According to Nahra and Frank (1986), an extent of the field R = 50a₀ is sufficient for good accuracy, while Bahar (1992) suggests a value of R = 133a₀.

Initially, the cavity's boundary is fixed, in-situ stresses are applied, and a uniform pressure boundary condition is imposed. The axisymmetric and thermal configurations are selected, and the no-flow and large-strain options are specified. Additionally, the y-displacement is fixed at both the top and bottom boundaries, and the x-displacement is fixed at the far x-boundary (Figure 5).

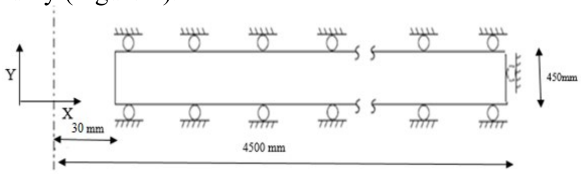


Figure 5. Geometry and bouandary conditions.

3.2. Mesh sensitivity

The mesh of the model was graded in both the radial and vertical directions. It consists of 124 linear axisymmetric quadrilateral elements across the entire domain. To more accurately reflect the behavior of the soil adjacent to the cavity, the mesh is refined by increasing the mesh density near the cavity. This refinement is graded by a factor of 1.1, specifically where the pressure gradient is expected to be the highest (Figure 6).

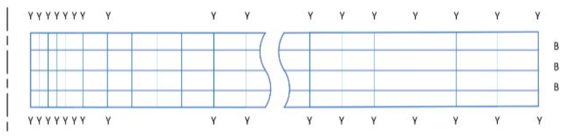


Figure 6. Finite difference axial-symmetric mesh modelled in Flac Software.

A variation in mesh dimensions was performed to verify the validity of the obtained results:

- The first mesh consists of 63 quadrilateral elements (20,2) with a grading factor of 1.1.
- The second mesh consists of 124 quadrilateral elements (30,3) with a grading factor of 1.1.
- The third mesh consists of 427 quadrilateral elements (60,6) with a grading factor of 1.1.

The three mesh configurations provided similar results in terms of the pressure-volume response. Therefore, the second mesh (30,3) was selected for further analysis.

3.3. Soil Model and Parameters

The soil was assumed to be isotropic and homogeneous. An isotropic elasto-plastic model using the Mohr-Coulomb failure criterion was adopted. The properties of the clayey soil used in the finite difference model are summarized in Table 2. In this model, the user is required to provide the values for Young's modulus, Poisson's ratio, cohesion, and the friction angle.

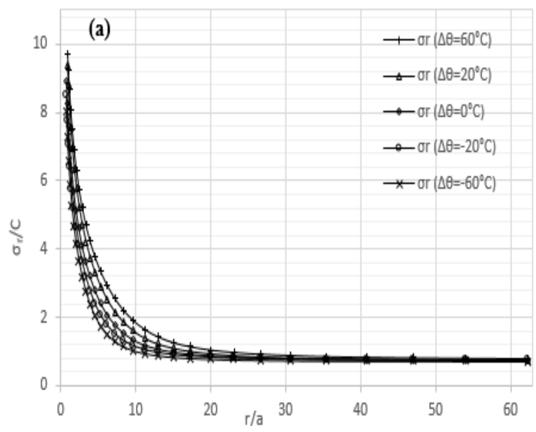
Table 2. Properties of a clayey soil.

	Value
density	1550 kg/m^3
Young's Modulus	18 MPa
Poisson's Ratio	0.33
Cohesion	10 kPa
Friction angle	12 °
thermal expansion coefficient	10^{-5} °C^{-1}

4. Results

4.1. Distribution of stresses around the cylindrical cavity

The distribution of stresses σ_r, σ_θ, and σ_z for temperature variations $\Delta\theta$ = -60°C, $\Delta\theta$ = -20°C, $\Delta\theta$ = 0°C, $\Delta\theta$ = 20°C, and $\Delta\theta$ = 60°C is illustrated in Figure 7: (a) σ_r, (b) σ_θ, and (c) σ_z. Higher temperatures result in larger radius values in the plastic zone, which then attenuate to an asymptotic value that characterizes the thermoelastic zone. However, the radius of the plastic zone is not significantly affected by temperature changes. The σ_r curves show a sharp decrease followed by a gentler slope as the radial stress approaches a constant value when (r/a) = 30. Radial stress increases significantly with temperature. Indeed, by heating the soil, it expands, and the radial stress increases (since the strain is constrained). This increase in stress can reach up to 94% when heating to 60°C. Conversely, when cooling the soil, the radial stress decreases, with the decline reaching up to 40% at -60°C.



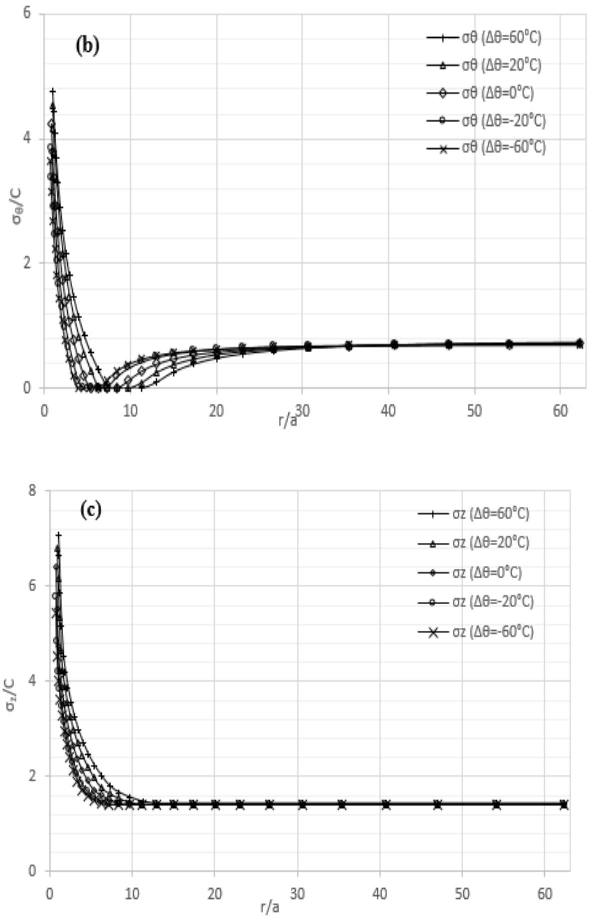


Figure 7. Radial (a), orthoradial (b) and vertical (c) stresses around the expanding cavity at different temperature variations.

4.2. Radial displacement

Figure 8 shows the dimensionless radial displacements ξ_r/a_0 around the cavity immediately after expansion for different temperature variations. The radial location r is normalized with respect to the cavity radius a, where a = $2a_0$. The radial displacement ξ_r decreases as the ratio (r/a) increases, until it reaches zero. Radial displacement increases significantly with heating, showing an increase of about 40% at 20°C and 70% at 60°C.

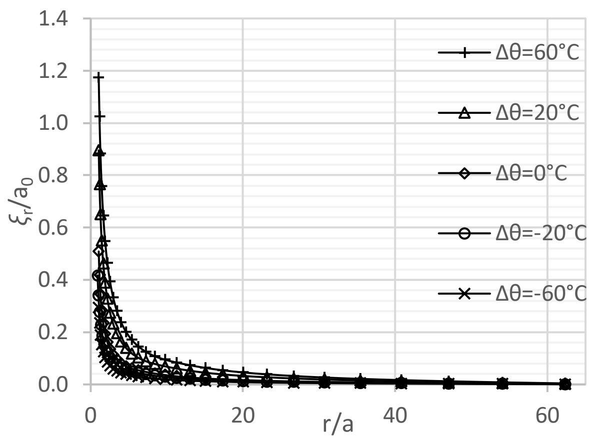


Figure 8. Variation of dimensionless radial displacement with regards to dimensionless radius for different temperature variation values.

4.3. Evolution of pressure as a function of volume

The variation of the dimensionless pressure at the cavity wall as the cavity expands is illustrated in Figure 9 for different temperature variation values. These curves show a sharp rise followed by a gentler slope as the pressure approaches a limit value. As the pressure increases, the rate of radial strain in the cavity accelerates. The pressure reaches a constant value immediately after expansion. The curves reveal a pseudo-elastic zone, delimited by the creep pressure P_i, indicating the onset of plastic deformations near the probe. The second zone, the large deformation zone, is defined between P_r and the horizontal asymptote, representing the failure of the soil, known as the limit pressure P_L. Moreover, the greater the temperature variation, the higher the ratio P/C for any value of the normalized injected volume. Therefore, cavity wall pressure is highly sensitive to soil temperature.

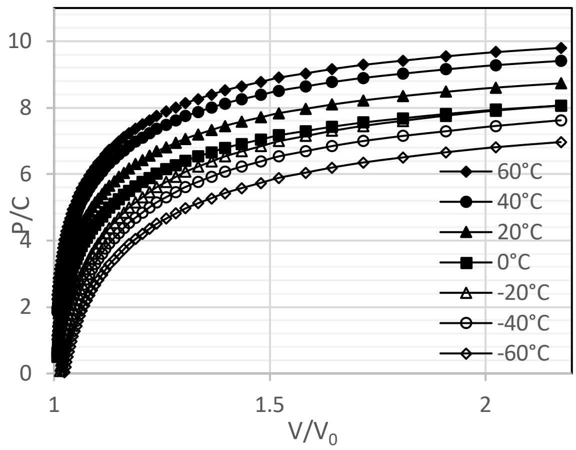


Figure 9. Evolution of pressure as a function of volume for different temperature variation values.

4.4. Limit Pressure

Limit pressure is defined as the pressure at which the cavity volume reaches twice the initial volume of the cavity. Using numerical curves that describe the evolution of pressure as a function of volume (Figure 9), the limit pressure is determined for different values of Δθ and presented in Figure 10. P_L is normalized with respect to P_{Lo}, the limit pressure at Δθ = 0°C. The results of numerical simulations show an increase in the limit pressure with heating due to the expansion of soil particles and an increase in radial stress. This increase reaches 18% for Δθ = 40°C. Conversely, cooling the soil causes a decrease in P_L, with a reduction of 14% at Δθ= -40°C.

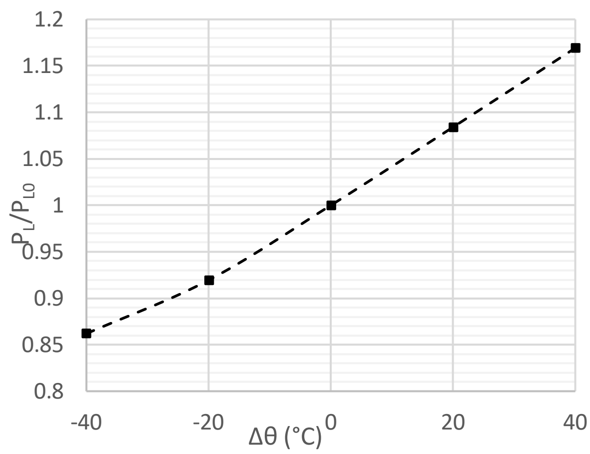


Figure 10. Thermal effects on limit pressure: numerical results.

5. Conclusions

In order to study the thermal effects on the mechanical behavior of soils, a device is proposed to introduce temperature into the pressuremeter apparatus. The thermal pressuremeter is equipped with devices that heat glycol water in the reservoir of the pressuremeter's control unit and measure and maintain the required temperature in both the reservoir and the probe.

Before manufacturing the device and analyzing its effectiveness, a numerical design of a pressuremeter test under temperature variations was carried out. The probe of the pressuremeter was modeled as an expanded cylindrical cavity. Numerical simulations of soil behavior during cavity expansion were conducted using finite difference analyses. A thermo-elastoplastic soil, governed by the Mohr-Coulomb criterion, was adopted. The numerical results of the expanded cylindrical cavity illustrate that temperature has a significant effect on the cavity expansion response. The influence of temperature is notable on stresses, displacements, and the limit pressure in the soil surrounding the cavity. The limit pressure of the soil increases quasi-linearly with rising temperature variation.

Considering the variation of pressuremeter test parameters with temperature is essential, particularly when estimating the bearing capacity of geothermal piles in temperature-sensitive soils. Indeed, using the numerical results of limit pressure provided by the proposed thermal pressuremeter device, the bearing capacity of geothermal piles can be easily determined.

Further work is needed to investigate thermal effects on soil behavior by analyzing experimental data from the thermal pressuremeter and comparing it with analytical and numerical solutions based on cavity expansion theory.

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