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Laboratory validation of an innovative mono-cell pressuremeter probe: test procedures and first results

Validation en chambre d'étalonnage d'une sonde pressiométrique mono-cellulaire innovante : procédure et premiers résultats

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ABSTRACT: Membranes for pressuremeter probes have been considerably improved through recent technological innovation. The Mono-cell FC® probe takes advantage of these evolutions with a potential measuring range from small strain to complete soil failure. An experimental program was established to validate its measuring capabilities through both laboratory and *in-situ* tests. The present paper focuses on the description of the laboratory testing protocols, leading to the evaluation of soil's deformability properties at low strain level whilst using this probe. The obtained results were compared with those derived from laboratory tests in the same soil type as described in literature. A discussion is held regarding the first results and the required stress and strain level adjustment for the case of dry sands.

RÉSUMÉ : Des évolutions technologiques récentes ont apporté des améliorations considérables dans le domaine des membranes utilisées dans les sondes pressiométriques. La sonde Monochambre FC® bénéficie de ces avantages et permet potentiellement de couvrir un domaine de mesure allant des faibles déformations jusqu'à la rupture. Le programme de validation de ses capacités de mesure repose sur des essais de laboratoire et *in*-situ. Cette communication s'attache à décrire les protocoles d'essai en laboratoire permettant l'évaluation des paramètres de déformabilité des sols sous faibles taux de distorsion. Les résultats sont comparés à ceux obtenus à partir d'autres essais de laboratoire. Une discussion porte sur les premiers résultats obtenus.

Keywords: *In-situ* tests, pressuremeter test, dilatometer test, shear modulus, calibration chamber

1 INTRODUCTION

Pressuremeter tests are the most used *in-situ* test for underground investigation in French geotechnical engineering practice. Performed according to current standards, these tests make it possible to obtain the so called Ménard pressuremeter modulus and the pressuremeter creep and limit pressures. Deformation properties are determined under monotonic conditions or during a single unloading-reloading loop. Menard pressuremeter parameters are used in standard foundation design through well established and accepted empirical correlations. However, the design of a number of geotechnical structures (e.g. retaining walls, foundations under cyclic

loading) is more demanding. Establishing their response under low strain rates is required for design, however the necessary parameters cannot be obtained through standard testing protocols, nor using the most common testing equipment due to measurement limitations.

The Mono-cell FC® probe offers new possibilities in soils and soft rocks. It enables measurement of both relatively small strains, traditionally reserved for "dilatometer" probes, and large "pressuremeter" deformations, with direct measurement of the limit pressure.

A validation program for the probe's measuring capabilities has been undertaken using two approaches. The first regards tests conducted at reference sites with the soil layers well characterized by a large set of geotechnical and geophysical tests. The second approach, as described in this paper, consists of tests performed in a laboratory calibration chamber on soil specimens of reference Fontainebleau sand.

Section 2 discusses the technical characteristics of the Mono-cell FC probe, the laboratory testing set-up, the calibration procedures and the testing protocol enabling the evaluation of stiffness parameters at low strain rates. Section 3 describes the methods for interpreting test results. Section 4 presents the test results and discussion. Results are compared to those in literature for the same reference sand. The discussion emphasizes the adjustments required for comparing the stress-strain dependent stiffness assessed using cavity expansion tests, to that of other elementary soil tests.

2 MATERIALS AND METHODS

2.1 The probe

The main characteristics of the Mono-cell FC probe are related to recent technological innovations in the domain of inflatable bodies. The rubber impervious membrane, which makes up the measuring cell, is surrounded by a textile restraining sheath. This sheath (patented design) has the capacity to expand freely up to a limiting diametrical profile, at which point it will oppose any additional deformation. It is fabricated by cylindrical weaving of so-called hybrid cables (patented design), which are a combination of elastic yarns (elastomer) and very high strength yarns (kevlar, high density polyethylene or other). The restraining sheath imposes a beveled shape to the inflatable body (Figure 1). This shape gives the advantage of considerable stress reduction in the membrane ends and elimination of longitudinal stretches. It also enables probe dilatation of up to 60% of the at-rest diameter, even at high pressures (up to 20 MPa). Furthermore, an adjustment of the restraining sheath geometry has allowed assessment of the radial expansion of the probe precisely and directly from the measurement of its cell volume; more particularly, it yields a proportional relationship between diameter expansion and the injected volume. This relation can be assessed through a calibration procedure using different diameter steel tubes. More details on the probe's main characteristics and historical development are presented in Cour and Lopes (2018).

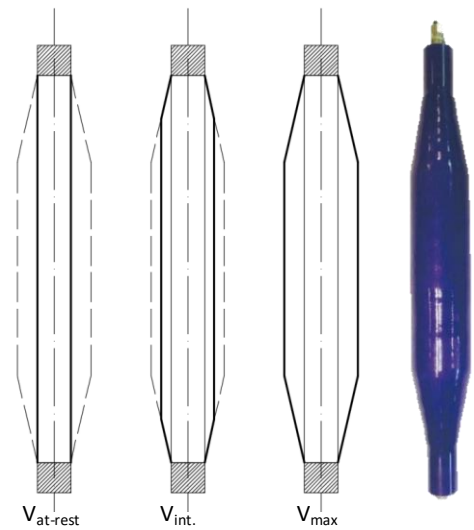

Figure 1 – Probe's inflation scheme and a photo at its maximum volume (Cour and Lopes, 2018)

2.2 Testing set

The testing set comprised the following elements: the probe itself, connection tubing, high precision volume-pressure controllers, the pressurized chamber, rigid discs for simulating *in-situ* boring conditions, and the soil specimen.

In the laboratory, the probe's inflation was controlled by an advanced pressure volume controller (GDS Instruments). This was connected to the probe via a tube of 2 m length and 4 mm internal diameter, with a very high stiffness (designed to support up to 74 MPa internal pressure), to minimize volume losses due to system dilatation.

The test was conducted within a calibration tank of dimension 550 mm internal diameter and 730 mm height (Figure 2). Soil compaction was manually performed around the pre-placed probed, in layers of 10 cm, to achieve a relative density index equal to 0.70. The boundary conditions in the calibration tank are: imposed vertical stress and imposed zero radial displacement at the cylinder walls (oedometric conditions). Pressure was applied via an internal disc-shaped flexible hydraulic jack, controlled by a parallel GDS device. Despite the impossibility to directly control the horizontal pressure as in a conventional calibration chamber, the oedometric calibration chamber was deemed a better fit for performing these particular tests. This is because the oedometric calibration chamber allows for better simulation of the *in-situ* pre-bored condition, modeled by leaving an empty annulus surrounding the probe extremities and ensuring no contact between the probe and the surrounding soil.

Preliminary tests indicated that the probe installation procedure should simulate the existence of a borehole within the soil specimen. This is due to this probe's special fuse geometry and its calibration procedure, which are well adapted for pre-bored tests.

This installation scheme would correspond to the realization of an "ideal borehole", in which the least possible disturbance is induced to the soil specimen. It is important to note that due to the probe's membrane compressibility, it is likely there will be some interaction between the soil specimen and the membrane during chamber pressurization. As a result, convergence of the cavity may occur even if the soil is in perfect contact with the probe. To minimize disturbance during the chamber pressurization, the probe has been pressurized simultaneously in an effort to keep the chamber radial stress homogeneous. Additional detail on this procedure is presented in Paragraph 2.4.

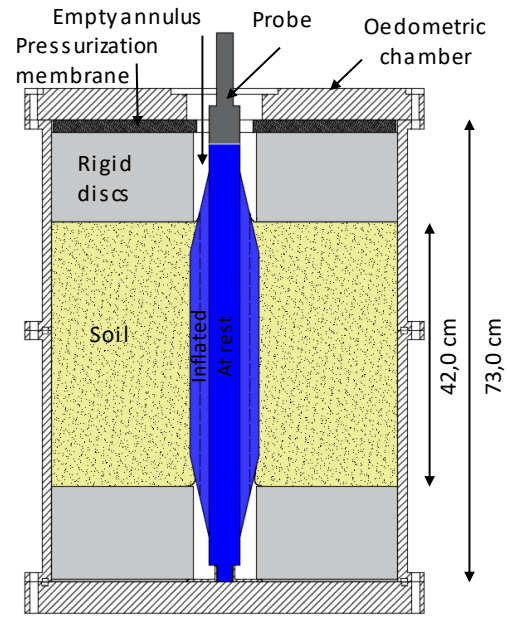

Figure 2 –Testing chamber scheme

2.3 Tested soil – Fontainebleau sand

Fontainebleau sand is a well-known reference silica sand used in France as a benchmark for soil mechanics laboratory tests. Its high grain regularity (quantified equal to 0.79) and beige colored grains have a sub-rounded geometry. The main granulometric properties are: e_{min} = 0.56; e_{max} = 0.88; U_c = 1.5; D_{50} = 0.21 mm; ρ_s = 2.65 g/cm^3.

Delfosse-Ribay et al. (2004) studied the stress and strain effects on Fontainebleau sand's deformability properties through resonant column

and cyclic triaxial tests. The authors showed that the power law in eq. (1) accurately represented the increase of this sand's shear modulus with the confining stress:

$$G_{max} = 200\frac{(2.17-e)^2}{1+e}\sigma_3'^{0.47} \quad (1)$$

where: e is the current void ratio; and σ_3' [MPa] is the confining stress. This expression is adopted henceforth for further calculations in this paper.

The same authors proposed an expression to evaluate shear stiffness decay with shear strain of Fontainebleau sand. Although it can satisfactorily represent shear modulus degradation for one given confinement stress, it cannot be generalized for varying confinements. Thus, on this work, the Oztoprak and Bolton (2013) shear modulus degradation model was considered (eq. 2):

$$\frac{G}{G_{max}} = \frac{1}{\left[1+\left(\frac{\gamma-\gamma_e}{\gamma_r}\right)^{a}\right]} \quad (2)$$

where γ is the shear strain, γ_r is the characteristic shear strain (calculated as a function of the confinement stress and sand's U_c, e and I_D), γ_e is the elastic threshold, and α is a curvature parameter.

2.4 Testing program

The testing procedure consists of: (1) assembling the controller devices and calibrating the probe; (2) placing the probe and the lower layer of rigid discs on the calibration tank; (3) manually compacting 10 cm thick layers of soil around the probe to achieve the desired density index of 0.70 (e = 0.656); (4) placing the upper rigid discs, the flexible jack and closing the tank; and (5) consolidating. Consolidation is performed in four steps in which vertical pressure and probe pressure are increased simultaneously to avoid cavity convergence due to membrane compressibility.

An initial high-pressure stress state was chosen to optimize probe performance. The imposed vertical stress was 750 kPa. The horizontal stress was calculated using a K_0 coefficient derived using Jaky's formula ($K_0 = 1 - \sin \phi'$), considering $\phi' = 37°$ as previously measured for Fontainebleau sand. Thus, $K_0 = 0.398$ and the horizontal stress at-rest is 300 kPa.

The test begins once the soil specimen is consolidated and the initial state is imposed. The test protocol comprises five unload-reload loops conducted at increasingly high stress levels, to assess shear moduli variation both with stress and with strain (Figure 3). Loading was performed at a constant rate of pressure increase, with a pressure-hold step performed before every load reversal. The pressure-hold was sufficiently long so as to limit superposition of creep outward strains with unloading inward strains. The amplitude of the loop was defined as a fixed ratio of 0.4 times the maximum radial pressure p'_c reached before unloading.

Figure 3 presents the performed testing protocol with five unload-reload loops of initial stress levels 811 kPa, 1208 kPa, 1408 kPa, 1605 kPa and 1698 kPa. These values are unrounded because gross pressures were controlled during the test. The probe is deflated at the tests conclusion. The final unloading curve is not interpreted.

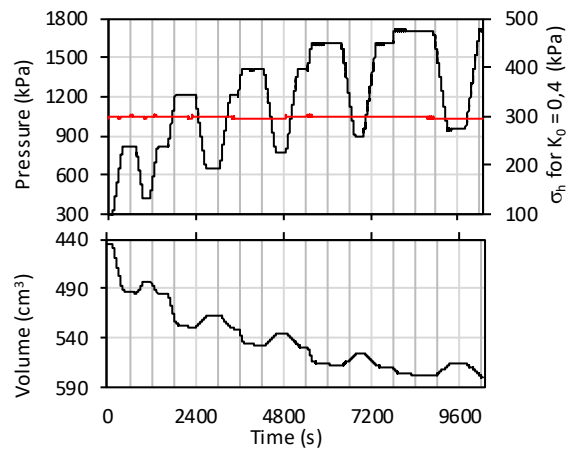

Figure 3 – Test loading protocol

3 INTERPRETATION

Test interpretation relies on two processes. The first consists of correcting gross data (pressure and volume) and transforming it to net values of pressure and radial strain. Calibration tests are used for this purpose. The second process consists of deriving soil's deformability properties from the cavity expansion curve obtained in the first step. In this paper, focus is given to the second process. Readers may refer to Cour and Lopes (2018) for a description of the calibration and interpretation procedure. Probe compliance was considered for calculating moduli using the method proposed by Fahey and Jewell (1990).

Deriving elementary, non-linear stress-strain response from cavity expansion tests in granular drained soils is a complex procedure because soil behavior varies with both stress and strain. The stress and strain levels within the soil mass vary as a function of the distance from the cavity wall. The maximum value is at the cavity wall and a decreased, at-rest value is attained far from the wall. As the soil modulus is dependent on these two variables, it will then also vary with the distance from the cavity wall and will evolve during the test as the cavity pressure increases and plasticity develops. As a result, pressuremeter tests with unload-reload loops in drained materials cannot lead to a direct evaluation of soil's shear moduli at at-rest conditions. Instead, it results in an averaged value for the soil mass around the cavity, associated to the specific stress-strain state when each loop is performed. Performing loops with different initial stress levels and with sufficiently large strain amplitudes allows deriving moduli stress and strain dependency. Thus, it becomes possible to transform measured moduli to elementary values, that can then be compared to other laboratory tests. Methods for adjusting stress and strain are required.

3.1 Evaluating G_{max}

Byrne et al. (1991) present a method for deriving soil's maximum shear modulus from one unload-reload loop. The method takes into account soil's non-linearity and stress state dependency through a hyperbolic model. The correction factors for converting the pressuremeter unload-reload modulus to *in-situ* G_{max} values were obtained using numerical models. The authors present a chart which may be used to determine the relationship between $G_{pressurmeter}/G_{max}$ provided: the stress amplitude of the loop, $\Delta p'_c$; the stress at the beginning of the loop, p'_c; and the initial horizontal stress, σ'_{h0}.

The results of maximum shear moduli obtained using this method were adjusted to the stress state around the cavity according to the methods described in the next paragraph.

3.2 Adjusting stress and strain

Bellotti et al. (1989) presented a method to correct moduli evaluated from self-bored pressuremeter tests in sands, performed both in a calibration chamber and *in-situ*. The proposed procedure requires evaluation of the average values of mean plane-strain effective stress, σ'_{av}, and the average shear strain amplitude, γ_{av}, within the plastic zone at the start of the unload-reload loop:

$$\sigma'_{av} = \sigma'_{h0} - \alpha(p'_c - \sigma'_{h0}) \quad (3)$$

$$\gamma_{av} = \beta \Delta\gamma_c \quad (4)$$

where: σ'_{av} is the average plane-strain effective stress; σ'_{h0} is the horizontal effective stress at rest; γ_{av} is the mean distortion in the plastic zone; $\Delta\gamma_c$ is the distortion at the cavity wall (equals twice the radial strain at this same point); p'_c is the radial pressure imposed by the probe before unloading; and α and β are reduction factors which are functions of σ'_{h0}, p'_c and the soil friction angle calculated according to cavity expansion theory in linear elastic-plastic soil.

Other methods for adjusting stress state are presented in literature. Whittle et al. (2017) proposed the following simplified eq. (5):

$$\sigma'_{av} = \frac{p'_c}{1+\sin\varphi} \quad (5)$$

The experimental observations on this work, presented in the next paragraph, shows that considering α equals 1 in eq. (3), or $\sigma'_{av} = p'_c$, leads to the best adjustment on the present case.

The degradation of the shear modulus with distortion of a given sand depends on the confining pressure. This last has an influence on sand's characteristic shear strain (which is the value of strain for which G has decreased to a reference value) and its threshold shear strain (which is the value of strain from which non-linearity begins to develop). Therefore, increasing the confining pressure results in an increase of the ratio G/G_{max} at a given shear strain. To account for this effect, normalized curves proposed by Oztoprak and Bolton (2013) were used. This model was applied and found to be well suited to model the shear stiffness decay of Fontainebleau sand. During the test, variations of void ratio and relative density due to cavity expansion were negligible (less than 1%) and so were neglected.

The effect of stress anisotropy on the values of G_{max} for Fontainebleau sand were investigated using the method proposed by Payan et al. (2016). Due to the pronounced regularity of Fontainebleau sand grains (0.79), stress anisotropy has only a minor influence on G_{max}, increasing it to no more than 3% of its isotropic value. Stress anisotropy effects were therefore neglected.

4 RESULTS AND DISCUSSION

The pressuremeter test results are presented in Figure 4, in terms of cavity stress and cavity strain.

The values of unload and reload shear modulus were calculated for each loop by taking the slope between the two extremities of the loop and dividing it by two. It was observed that the unload moduli were systematically higher than the reloading moduli. For this reason, it was decided to investigate them separately rather than calculate an average "unload-reload" modulus. The calculated values of shear modulus and cavity strains were then corrected for probe compliance. The results are summarised in Table 1 on which the influence of the stress state before unloading can be clearly seen.

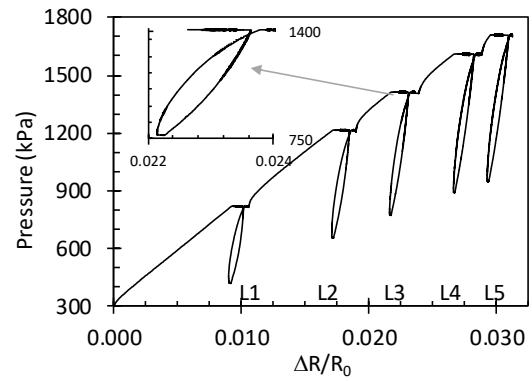

Figure 4 – Results of the pressuremeter tests performed in the oedometric chamber

Table 1 – Evaluated values of G for each loop

L	Dir	p'_c (kPa)	$\Delta p'_c$ (kPa)	$\Delta\varepsilon_r$	$G(\Delta\varepsilon_r)$ (MPa)
1	U	811	391	1.6E-03	126
	R	811	396	1.8E-03	112
2	U	1208	555	1.6E-03	173
	R	1208	559	1.9E-03	149
3	U	1408	636	1.6E-03	199
	R	1408	638	1.9E-03	170
4	U	1605	713	1.7E-03	215
	R	1605	709	1.8E-03	192
5	U	1698	749	1.6E-03	228
	R	1698	750	1.8E-03	206

4.1 Stress adjustment

Each unloading loop was interpreted using Byrne et al. (1991) method. Obtained values of G_{max} were compared to the elementary values of G_{max} (σ'_{av}) given by eq. (1). For comparison intent, they were plotted against σ'_{av} calculated by Bellotti et al. (1989), Whittle et al. (2017) methods and using the previous approach $\sigma'_{av} = p'_c$. The scatter is represented by the grey clouds in

Figure 5. Plotting the obtained G_{max} against p'_c results in better agreement with the elementary values calculated according to literature.

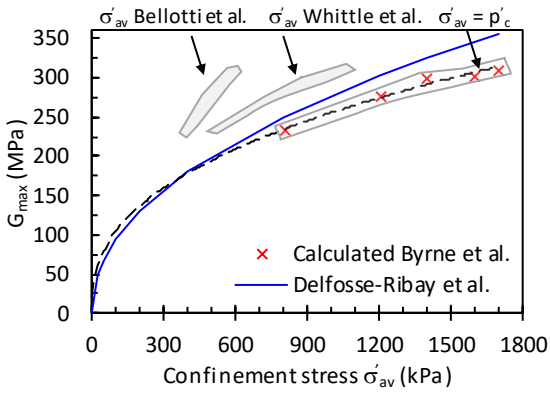

Figure 5 – G_{max} values obtained by Byrne et al. method compared to values for Fontainebleau sand as proposed by Delfosse-Ribay et al.

This result differs from that of other methods presented in the literature, and more research is required to understand why. It is possible that the finite dimensions of the physical model have some influence on the stress distribution on the soil specimen. This could be further investigated via finite element modeling.

4.2 Strain adjustment

Bellotti et al. (1989) proposition to correct for the average strain level in the plastic zone around the cavity was applied. The ratio between the average shear strain amplitude in the plastic zone, γ_{av}, and the measured strain at the cavity wall, $\Delta\varepsilon_r$, ranged between 1.07 and 0.57. Those values are resumed on Table 2.

4.3 Comparison to Fontainebleau sand

Fontainebleau sand maximum shear modulus, G_{max} (σ'_{av}), was calculated using eq. (1) and assuming $\sigma'_3 = \sigma'_{av} = p'_c$. This theoretical value of maximum shear modulus was then degraded to correspond to the average shear strain (or distortion) imposed on each loop G_{max} (γ_{av}, σ'_{av}), using Oztoprak and Bolton (2013) proposition (eq. 2). Results are presented on Table 2.

Shear moduli obtained with the pressuremeter for each loop, G ($\Delta\varepsilon_r$) (Table 1), were compared to the expected values of G_{max} (γ_{av}, σ'_{av}) for Fontainebleau sand. The results are presented in Table 2 in terms of relative difference (column "Diff") and plotted on Figure 6.

Table 2 – Adjusted values of stress for α = 1 and strain according to Bellotti et al (1989)

L		σ'_{av}	$\gamma_{av}/\Delta\varepsilon_r$	$G_{max}(\sigma'_{av})$	$G(\gamma_{av},\sigma'_{av})$	Diff
1	U	811	1.07	251	101	25%
	R	811	1.07	251	93	20%
2	U	1208	0.74	303	167	4%
	R	1208	0.74	303	155	4%
3	U	1408	0.66	325	198	1%
	R	1408	0.66	325	185	8%
4	U	1605	0.60	346	223	4%
	R	1605	0.60	346	215	11%
5	U	1698	0.57	355	237	4%
	R	1698	0.57	355	229	10%

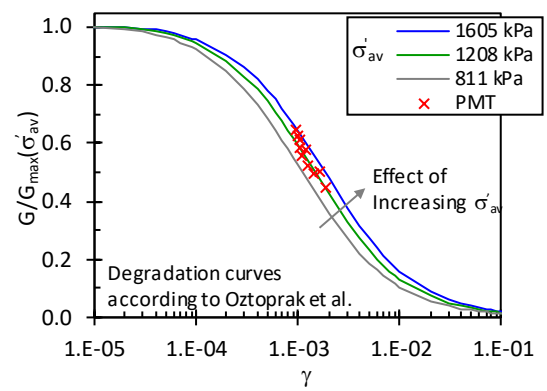

Figure 6 – Measured values of pressuremeter shear modulus normalized to maximum shear modulus adjusted for $\sigma'_{av} = p'_c$ for each loop

The evaluated values of shear moduli using the pressuremeter were in good agreement with Fontainebleau sand elementary values. In general, less than 10% relative difference between measurements and theoretical values were found using the proposed stress and strain adjustment procedure. The biggest relative difference takes place for the first loop (25%). The unloading

modulus tends to be a slightly better match than the reloading modulus.

5 CONCLUSION

A pressuremeter test was performed in a soil specimen constituted by Fontainebleau sand, in a laboratory calibration chamber using the Mono-cell FC probe. Five unload-reload loops were performed at different stress levels to assess soil's stress-strain dependent behavior.

Each loop was interpreted, yielding unload and reload values of shear modulus and associated cavity strains. Different methods were employed to adjust cavity stress and strain levels to representative values within the soil specimen. By comparing the obtained values of moduli to those expected for Fontainebleau sand, the following conclusions can be drawn.

- The maximum shear modulus evaluated by each unload-reload loop in the experiment was found to be a function of the maximum cavity stress before unloading (p'_c).
- It was found that the representative soil volume around the cavity was subjected to a shear strain rate equivalent to an average of the shear strain imposed between the cavity wall and the limit of the plastic zone induced by p'_c. The ratio between the averaged value of shear strain and the strain at the cavity wall varies as a function of the radius of the plastic zone developed around the cavity. The Bellotti et al. formulation resulted in good agreement with the tested degradation model.

Shear moduli obtained using the pressuremeter were in good agreement in comparison to the expected values for Fontainebleau sand.

Those results are encouraging and highlight the real potential of using the Mono-cell FC probe to measure soil properties at small strain rates. The laboratory validation program is to be continued by performing similar testing protocols in soil specimens of different relative densities.

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