Monitoring of stresses and deformations in soils by fiber optic sensors

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Abstract– This paper shows the application of LPG optical fiber sensors to the determination of the transmitted stress and deformation of a sample of confined soil subjected to surface loads. The transmitted stress was measured by a mechanical LPG pressure sensor and the curvature of the ground by permanent LPG sensors buried at depths of 0.1m; 0.2m; 0.4m and 0.6m. Clay-sandy soil characteristic of UNICAMP was deposited in a cylinder of 0.8m in length and 0.30m in diameter. The soil was lightly compacted in 0.2m layers and an LPG sensor was installed on each layer. Surface loads of up to 227 KPa were applied to the surface of the soil, measuring axial soil deformations of less than 3mm by our sensors with sensitivities of the order of 0.22 mm/dB. The values of the modulus of elasticity for this type of soil were determined from the fitting of the Boussinesq equations with the values measured by the buried LPG sensors. A Young's modulus of 5.40 MPa and a Poisson's coefficient v = 0.52 were determined for this type of soil.

Keywords-- Soil stress, elastic constants, fiber optic sensors, LPG gratings, geotechnical monitoring.

I. INTRODUCTION

Knowledge of stress transmission in soils subject to surface loading as well as its deformation at different depths is of vital importance in the performance of compaction works for buildings, in the design of pavements or in the determination of changes in soil properties induced by agricultural machinery [1-6].

One of the first models of transmission of stress in soils was developed by Boussinesq in the year 1885 [7], in this model it is considered that vertical stress transmission (σ_z) in the soil subjected to a surface load "q", uniformly distributed on a disk of radius "a" located on its surface is given by the expression:

$$\sigma_z = q\left[1 - \frac{z^3}{(a^2 + z^2)^{3/2}}\right] \qquad (1)$$

Determining, likewise, the deformation ξ (z) of the ground, on the vertical axis, from:

$$\xi[z\_] := \frac{(1+v)q}{\pi * a^2 * Y}\left[1 - 2v + \frac{2v * z}{(a^2 + z^2)^{\frac{1}{2}}} - \frac{z^3}{(a^2 + z^2)^{\frac{3}{2}}}\right] \qquad (2)$$

In this article we show the application of fiber optic sensors type LPG for the measurement of the transmitted effort (σ_z) and the deformation of the soil (ξ_z) clay-sandy, of the State University of Campinas (UNICAMP) in Sao Paulo-Brazil, at depths of up to 0.6m. Using the Boussinesq model, we determine the elastic constants of the soil (Young and Poisson modules) based on the adjustment of the theoretical model with the stress and strain values measured by the LPG sensors.

II. THE FIBER OPTIC SENSORS

To fabricate the LPG type fiber optic sensors, with the appropriate measurement range and resolution, we first calculate the strain distribution (σ_z) and deformations (ξ_z) expected for the clay-sandy soil of UNICAMP, subjected to loads surface up to 227 KPa. Young's modulus values Y = 4.6 MPa and Poisson's modulus v = 0.5 were used in this simulation for this type of soil in according to the values obtained using other techniques [8-13]. The results of the simulations showed, for a surface load of 227 kPa, a transmitted stress of less than 1% and a soil deformation of less than 2% of the maximum deformation at only a depth of 0,6 m.

A. Mechanical LPG sensors

Determined the range of variation of the transmitted effort, we decided to use mechanical LPG fiber optic sensors of 600μm of period and 15mm of length [14, 17] to measure this parameter.

Figure 1a shows the variation of the transmittance of this sensor subjected to loads up to 101 KPa. A sensitivity of 25,854 dBnm / KPa is determined for this sensor from the linear adjustment of the data.
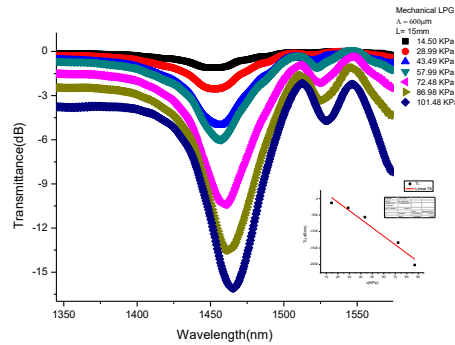
Fig. 1 Changes in amplitude and phase of the transmittance of the mechanical fiber optic LPG sensor subjected to loads up to 101 KPa. The inset show the linear response of the LPG sensor.

B. Sensors engraved on the fiber with CO_2 laser

The flexural sensitivity of the grating recorded in single mode fibers with CO_2 laser and the technique to determine their sensitivity to curvature changes are explained in the references [14, 17].

We fabricated LPG gratings with different sensitivities so as not to exceed the linear region of response to curvature (Fig. 2). The most sensitive LPGs were placed at a greater depth, where the stress transmitted and the deformation of the soil presented the lowest values.
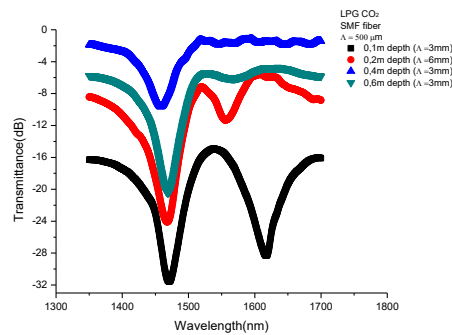

Fig. 2 LPG gratings recorded in single mode fiber using a CO_2 laser.

Figure 3 shows the sensitivity of the LPG sensor (F19) to changes in the curvature of the fiber. A sensitivity of 0.224 mm /dB was determined for this LPG.
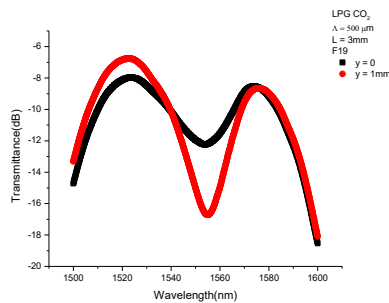

Fig. 3 Change in the transmittance of the LPG sensor (F19) subjected to curvature with 1 mm arrow.

III. MEASUREMENTS

A cylinder of 0.305m diameter and 0.8m length was filled with clay-sandy soil obtained from the diabasic residual soil of UNICAMP. A first layer of 0.2m thickness was compacted, placing on this surface the first optical fiber sensor LPG (F17). The fiber was packaged to prevent deterioration and direct contact when buried in the ground.

An additional layer of soil 0.2 m thick was added, this layer was also compacted and then a second LPG sensor (F13) was placed on its surface, repeating the same procedure for each floor layer of 0.2m.

The compaction energy applied was 0.24 KNm/ m^3. The sensors were finally installed at depths of 0.1m, 0.2m, 0.4m and 0.6m, on the vertical axis of the cylinder, as shown in Figure 4. The loads were applied on a circular aluminum plate of 0.1m diameter placed on the surface of the soil.
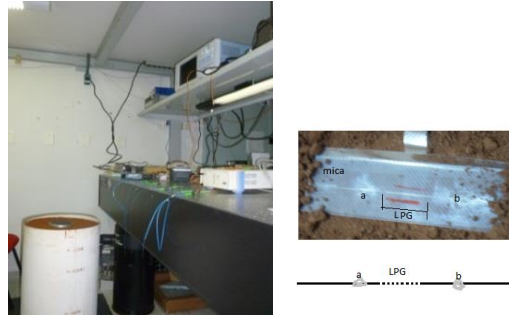

Fig. 4 This figure shows the experimental arrangement used for the determination of transmitted stresses and soil deformation.

A. Measurement of soil deformation

Figure 5 shows the variation of the transmittance of the fiber optic sensor LPG (F6) placed at the depth of 0.1 m, when the ground surface is subject to loads of up to 226.8 KPa. The inset shows the linear response of the sensor with sensitivity of 0.030 dB/KPa.
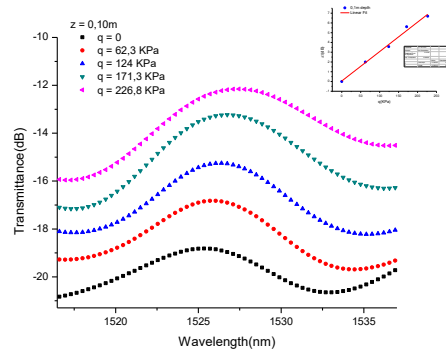

Fig. 5 The figure shows the variation of the transmittance in the LPG sensor (F6) placed at 0.1m depth, when the ground is subjected to loads of up to 226.8 KPa. The inset shows the linear response of the LPG sensor.

Table I shows the calibration constants of the LPG sensors used, recorded in optical fiber single mode with CO2 laser, and the corresponding equations to determine the values of unit strain (ξ) obtained when applying the loads σ on the ground surface. The loads applied on the ground surface were 62.3 KPa; 124 KPa; 171.3 KPa and 226.8 KPa.

TABLE I
STRESS AND STRAIN IN THE SOIL

LPG	Cte1 (dB/KPa)	Cte2 (mm/KPa)	ξ = cte2*σs /(L-z)
F6	0,030	0.00672	ξ = 0.00672*σs /700
F19	0,00903	0,002023	ξ = 0.002023*σs /600
F13	0,0049	0,001098	ξ = 0.001098*σs /400
F17	0,00428	0,0009587	ξ = 0.0009587*σs /200

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The continuous curves in figure 6 are the best fit using equation 2 and the normalized strain data ξ (points) obtained using the relationships shown in table 1.
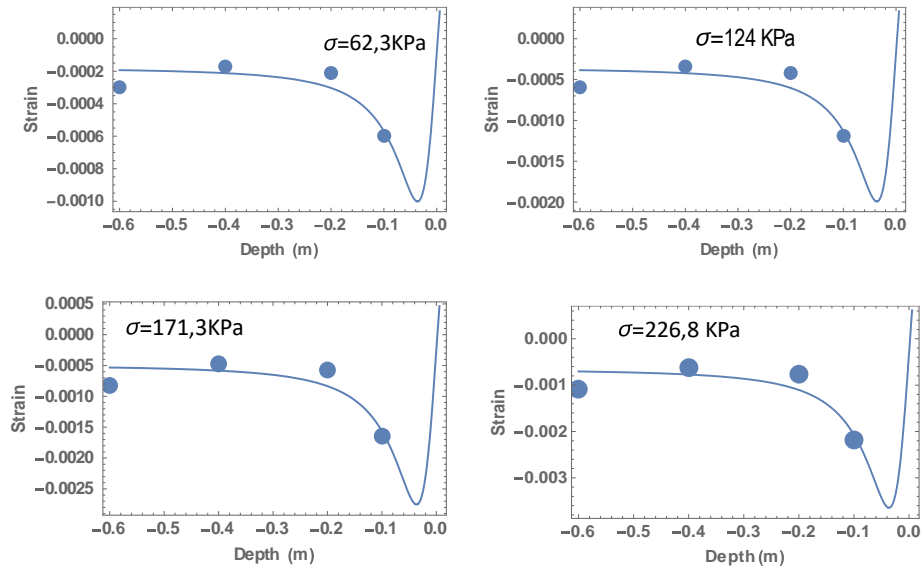

Fig 6 The points in the graphs show the values of soil deformation versus depth, as measured by the LPG sensors, when this is subjected to different surface loads. The continuous line curves are the parameter adjustment curves (Y and v) using the Bousinessq equation (Eq. 2).

B. Transmission of vertical soil stress

A mechanical LPG grating 600 μm of period and 20.5mm of length was buried at the depth of 0.2m to determine the value of the transmitted load.

Figure 7 shows the variation of the transmittance of the mechanical LPG fiber optic sensor placed at this depth while the ground was subjected to loads of up to 81.11 KPa on its surface. Figure inset shows the slope of the linear response of the sensor when subjected to surface loads (m_0 = 25,854 dBnm / KPa) and the slope of its linear response due to the loads transmitted at 0.2m depth ($m_{0,2}$ = 22,638 dBnm/KPa).

The quotient of these slopes $m_{0,2}$ / m_0 is 0.876. According to equation (1) of Boussinesq at this depth, the quotient of the transmitted load / expected surface charge must be $\sigma_{0.2}$ / σ_0 = 0.87.
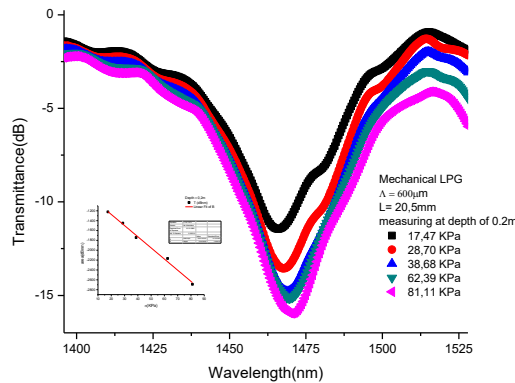

Fig 7 (a) Variation of the transmittance of the mechanical LPG sensor placed at the depth of 0.2m while the ground is subjected to loads of up to 81,11 KPa on its surface. (b) The response of the sensor is linear and its sensitivity is 22.64 dBnm / KPa.

C. Determination of soil elasticity parameters

Table II shows the values of Young's modulus and Poisson's coefficient determined by the non-linear fitting curves shown in Figure 6.

TABLE II
PARAMETERS OF SOIL ELASTICITY

Load on the surface (KPa)	Young module (MPa)	Poisson's coefficient ν
62,3	5,39	0,52
124	5,40	0,52
171,3	5,40	0,52
226,8	5,39	0,52

D. Conclusions

The LPG type fiber optic sensors recorded with CO2 laser were used to measure the curvature of the soil caused by surface loads of 62.3 to 227 KPa. The mean value, measured using this technique, for Young's module = 5.40 MPa was found in the range of values corresponding to the type of soil used (semi-compacted sandy clay) and measured by Paulo Rocha [8] using triaxial equipment.

The value found for the Poisson's coefficient ν = 0.52 contrasts with the expected value for this type of soil ν ≈ 0.4, the cause probably originates from the effect of confinement of the sample (metallic cylinder of r = 0.15m).

A mechanical LPG network was used to measure the load transmitted by the soil to a depth of 0.2m. The values of the loads transmitted to the depth of 0.2m measured by this sensor showed good agreement with the expected values from the Boussinesq equation (Eq.1).

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