Chamber calibration of total stress cells in a fiber reinforced soil

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ABSTRACT: The main objective of this work is to present and evaluate the calibration of total stress cells embedded in a non-reinforced/reinforced soil. Calibration was initially made through air pressure application only, and, in a second stage, in a medium constituted by a compacted sandy soil, with and without the insertion of randomly distributed polypropylene fibers. The calibration tests were performed in a laboratory scale by using a cylindrical steel chamber with 50cm in diameter and 20cm high. The results showed that the calibration constants varied as a function of cell positioning but were not affected by the insertion of fibers. Finally, due to the great variability of calibration constants and the lack of a more general procedure, it was concluded that a reliable calibration of total stress cells in reinforced and non-reinforced soils can only be achieved through a detailed analysis and interpretation of appropriate calibration tests.

1 INTRODUCTION

Stress distribution within soil layers and at soil-structure interfaces has been widely studied in the past, generally through the utilization of total stress cells. These cells are built from materials with stiffnesses quite different from those of the media where they are usually embedded. As a consequence, the stresses being measured are redistributed and modified in the vicinity of the cell, thus justifying the intensive studies and detailed analyses found in the literature on this subject, mainly regarding the calibration of such stress cells (e.g. Weiler & Kulhawy 1982, Dunnicliff 1988; Clayton & Bica 1993; U.S. Army Corps of Engineers 1995; Clayton et al. 2002, Minkov et al. 1981).

To quantify the measurement errors in stresses, Taylor, in 1947, proposed a cell action factor (CAF), which, since then, has been used to calibrate stress cells. This factor is defined as the ratio between the stress reading provided by the cell and the stress existing in the absence of the cell.

In this context, the purpose of this work is to present and evaluate the calibration of total stress cells embedded in a sandy soil, with and without the insertion of randomly distributed polypropylene fibers.

2 EXPERIMENTAL PROGRAM

A comprehensive experimental program was carried out to investigate the response of total stress cells embedded in a reinforced/non-reinforced sandy soil subjected to vertical loadings following a K_o stress path.

The main aspects of the experimental program are described in the next sections, regarding the materials characteristics, the testing devices utilized, the experimental procedures adopted, and the analyses performed.

2.1 *Materials*

2.1.1 *Soil*

The soil used was obtained from an excavation pit located in the city of Osório/RS, in southern Brazil, and can be described as an uniform clean fine sand (see the grain size curve presented in Figure 1), with no traces of organic matter. The specific gravity is 2.63. Maximum and minimum void ratios are 0.88 and 0.59, respectively.

2.1.2 *Fibers*

The fibers used as soil reinforcement, in the contents of 0.25% and 0.50%, were corrugated polypropylene fibers, which are commercially available in the form of small filaments. These polymeric fibers were chosen because of their availability in large quantities and, also, their uniform and well defined features, being chemically inert as well.

The fibers were 50mm length with a title of 100dtex. The title is a quantity usually employed by the textile industry to represent the thickness of fiber filaments, whose proper units are the dtex (1dtex = 1g/10000m).

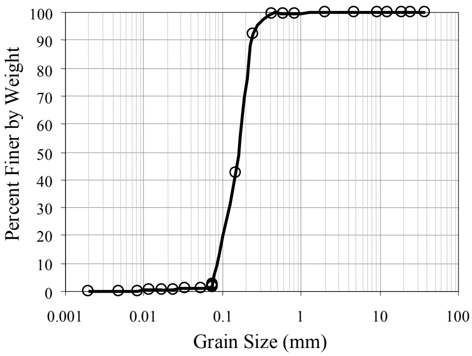


Figure 1 – Grain size curve of the soil

2.2 *Testing Devices*

2.2.1 *Calibration Chamber*

A cylindrical calibration chamber, 50cm in diameter and 40cm high, designed and built in steel as described by Gonçalves et al. (2003), was utilized in the present work. The chamber, shown schematically in Figure 2, was adapted to allow for the calibration of total stress cells embedded into the soil and at soil-structure interfaces as well.

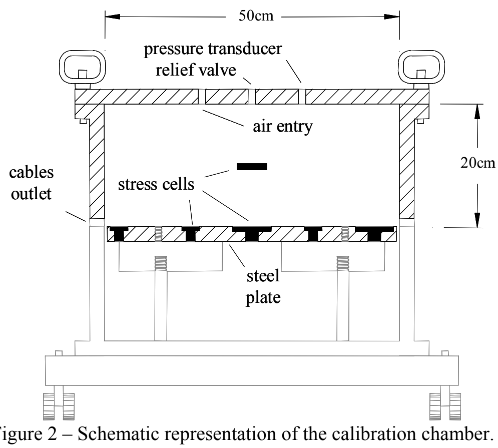


Figure 2 – Schematic representation of the calibration chamber.

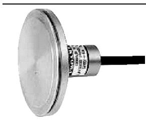
A perforated circular steel plate, 500mm in diameter and 25.4mm thick, was placed at the chamber mid-height to allow the stress cells to be inserted in different positions, so both, the cells and the plate, were perfectly leveled out. As a consequence, the effective height of the chamber was reduced to 20cm.

This chamber also allows the loading to be applied by air pressure transmitted to the soil surface by a rubber membrane, which ensures a very uniform stress distribution. The setting of the air pressure applied was made through a high precision regulating valve installed at the lid of the calibration chamber. Also, an electronic pressure transducer, with nominal capacity of 1MPa, was used for the reading of the applied pressure, along with a conventional manometer. For the sake of security, a relief valve was installed limiting the applied pressure to 700 kPa.

2.2.2 *Total Stress Cells*

Two different kinds of total stress cells were used in the present study: a contact cell and an internal cell, both manufactured by Kyowa, Inc. In Table 1, some basic characteristics of both cells are presented.

Table 1 – Basic characteristics of the total stress cells.

Image	Type	Diameter/ Thickness (mm)	Nominal Capacity (kPa)
	Contact	65/8	1000
	Internal	50/9	500

These hydraulic-type cells were chosen because they present, when compared to diaphragm-type cells, a lesser internal displacement of its smaller active face, what, according to Clayton & Bica (1993), results in a less intense redistribution of stresses in the vicinity of the cell, and consequently, in lower measurement errors.

2.3 *Calibration Tests*

2.3.1 *General Procedure*

The first stage of the calibration tests was the calibration by using air pressure only, which aimed to evaluate the linearity of the readings, to detect possible manufacturing flaws, and also to check the fluid calibration provided by the manufacturer.

At the second stage of the tests, calibration was performed in the dry non-reinforced soil only. At this stage, for comparison purposes, the positioning of the cells into the calibration chamber was intentionally varied, in the horizontal direction for the contact cell, and in the vertical direction for the internal one.

At the third and last stage of the tests, after defining the most suitable positioning for the internal and contact cells, calibrations were performed for both the non-reinforced and the reinforced soil with variable fiber contents.

For all the tests carried out, the application of the vertical pressure was made in increments of 50kPa, until the limit pressure of 400kPa was reached.

2.3.2 *Chamber Filling and Soil Compaction*

Prior to testing and after the installation of the bottom contact stress cells, the chamber was filled with soil, with or without fibers, by following two different methods, depending on the material initial moisture and relative density.

For the dry, loose, non-reinforced sand (0% moisture content and 0% relative density), the soil was simply poured into the chamber through a funnel, which was maintained at a constant distance of about 1cm from soil surface.

For the moist, medium dense, non-reinforced and fiber reinforced sand (10% moisture content and 50% relative density), the mixture (soil-water or soil-fiber-water) was properly prepared, placed into the chamber in several layers, each one being dynamically compacted by applying blows with a wooden socket until the specified relative density was reached, as can be seen in Figure 3.

The compaction parameters for both the non-reinforced and the fiber reinforced soil, for all conditions tested, are summarized in Table 2.

Table 2 – Compaction parameters for the calibration tests.

Fiber Content (%)	Moisture Content (%)	Relative Density (%)
0	0	0
0	10	50
0.25	10	50
0.50	10	50

2.3.3 *Stress Cells Installation*

Differently from the contact stress cells, whose installation at the bottom perforated steel plate (see Fig. 2) was straightforward, the insertion of the internal stress cells at the mid-height of the calibration chamber was tricky and made during the filling process by carefully carving and inserting the cell into the poured/compacted layer and manually replacing the soil above it, before resuming the filling process. Also, additional care was taken in positioning the electric cables as the pouring/compaction process proceeded.

2.4 *Numerical Analysis*

The numerical analysis was performed in order to predict the vertical distribution of stresses inside the calibration chamber, through a finite element method (FEM) approach, using the commercial software Ansys, version 5.4.

The constitutive model used to reproduce soil behavior was the elastic perfectly plastic model with the Drucker-Prager failure criterion and a non-associated flow law. The model input parameters (c', ϕ', E, ν, ψ) were obtained from triaxial tests performed by Vendruscolo (2003) and are summarized in Table 3.

Table 3 - Values of the model input parameters used in the numerical analysis.

Parameter	Value
Effective Cohesion Intercept (c')	0 kPa
Effective Friction Angle (ϕ')	36°
Elasticity Modulus (E)	34 MPa
Poisson Coefficient (ν)	0.25
Dilatancy Angle (ψ)	0°


Figure 3 – Soil compaction inside the calibration chamber.

3 RESULTS

In the following sections, the results obtained from the numerical analysis and the chamber calibration tests performed in air, as well as in the no-reinforced/reinforced soils, are presented and discussed.

3.1 *FEM Simulation*

The proper interpretation of the results obtained from the laboratory calibration tests required the use of simulation tools based on the finite element method (FEM), for the prediction of the stress distribution inside the calibration chamber.

Regarding the boundary conditions, it was assumed a full restriction to the vertical soil displacement along the side walls of the calibration chamber. Otherwise, the vertical stresses at any point inside the calibration chamber would be exactly equal to the vertical pressure applied at the soil surface. The actual distribution of stresses is obviously a function of the boundary conditions and can be properly estimated through a FEM approach.

The FEM simulation performed, based on the assumption of zero vertical displacement along the side walls of the calibration chamber, is shown in Figure 4, in which, since the vertical loading is axis-simetric, only half of the chamber diameter is represented.

One can easily verify that the predicted distribution of vertical stresses inside the calibration chamber is not uniform, since there is a clear reduction in stresses from the top to the bottom and from the center to the edges of the chamber. Thus, the positioning of the stress cells inside the calibration chamber constitutes an important issue to be accounted for when calculating the value of the CAF factor.

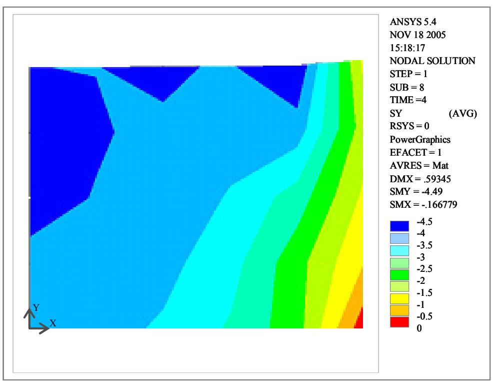


Figure 4 - Distribution of vertical stresses inside the calibration chamber.

3.2 *Calibration Tests*

3.2.1 *Calibration in Air*

Figure 5 shows the results of two cells calibrations performed in air pressure. Linear regression lines were used to depict the linearity of the cells responses, which presented coefficients of determination (R^2) close to unity.

In Table 4, the calibration constants obtained from the laboratory calibration tests, as well as the constants provided by the manufacturer are presented.

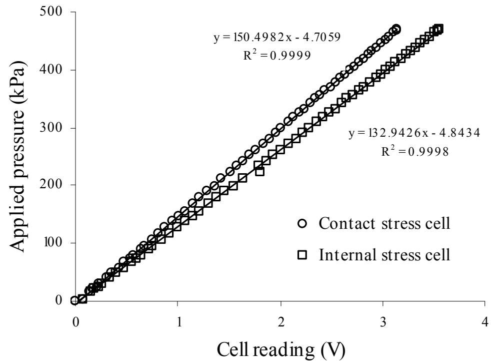


Figure 5 - Calibration in air of the contact total stress cells.

As stated earlier, the calibration in air was necessary to test the cells against possible defects and also for checking the calibration provided by the manufacturer, which differed from the calibration performed in this study.

Table 4 – Calibration constants for the total stress cells.

Stress Cell	Calibration constant obtained (kPa/volt)	Calibration constant provided by the manufacturer (kPa/volt)
Contact	150.49	133.55
Internal	132.94	122.73

3.2.2 *Calibration in Soil*

The first calibration tests were conducted in dry sand compacted at its loosest possible state with a void ratio of 0.88 (relative density of 0%), in order to investigate the stress distribution in vertical and horizontal directions inside the calibration chamber. For comparison, the outcomes of numerical simulations are presented in Figure 6 along with the calibration tests results.

In all the tests performed, it was observed an excellent repeatability of the measured stresses and, also, a quite linear correlation between the cell readings and the increasing applied pressure measured by the pressure transducer. This feature allowed the normalization of the measured stresses by the applied ones, as presented in Figure 6.

Figure 6 also shows the stresses measured by the cells in different positions inside the chamber along with the stresses estimated from the numerical analysis. Figure 6a shows the variation of vertical stress with depth at the center of the chamber, while Figure

6b shows the stress at the bottom of the chamber and its variation in the horizontal/radial direction.

From a preliminary analysis, it is readily noticed the good agreement between the stresses measured by the cells and those estimated from the numerical analysis, for both the internal cell (Fig. 6a) and the contact cell (Fig. 6b). The difference observed between the measured and the estimated values is the cell action factor (CAF), which quantifies the stress measurement error.

The distribution of vertical stresses tended to be more uniform than the distribution of horizontal stresses, in which case there was a clear reduction in stresses towards the edges of the calibration chamber. Therefore, in the absence of a numerical analysis, the positioning of the stress cells should be as close as possible to the center of the calibration chamber, where the estimated stresses are closer to the applied ones.

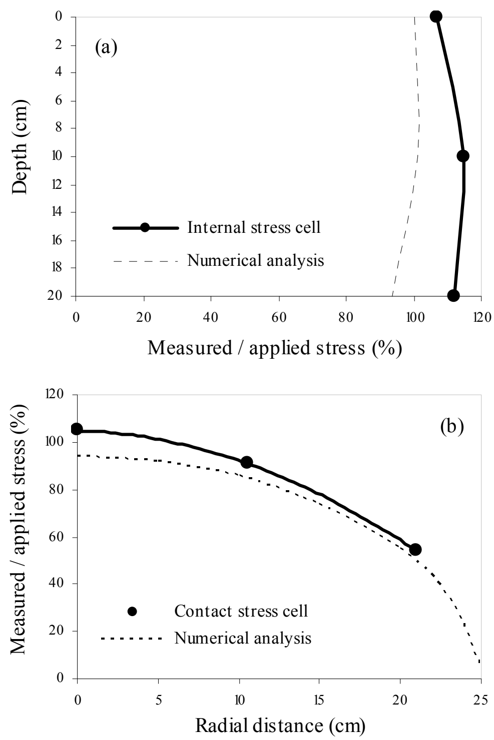


Figure 6 – Stress distribution: (a) vertical; (b) horizontal.

For the calculation of the CAF factor, it is common practice to relate the stress applied to the cell to the pressure applied on the surface of the chamber. This simplification results in significant errors if the cell is not installed at the center of the chamber. Also, according to Donato et al. (2006), the shape of the calibration chamber has also a significant effect on the stress distribution and, consequently, on the calibration constants.

Figure 7 and Table 5 present the results of the calibration tests for both the contact and the internal stress cell, performed in non-reinforced sand, dry and moist, and in moist reinforced sand, with fiber contents of 0.25% and 0.5%.

The analysis of Figure 7 and the summary of the results presented in Table 5 clearly show that the calibration constants for both stress cells were not influenced neither by the insertion of fibers nor by the moisture content increase. This is due to improvements in the robustness of such cells, which are designed and manufactured for use with various types of soils, with large variations in elasticity modulus, including strongly cemented materials. The small variations observed in Table 4 might be attributed to the natural dispersion inherent to calibration tests.

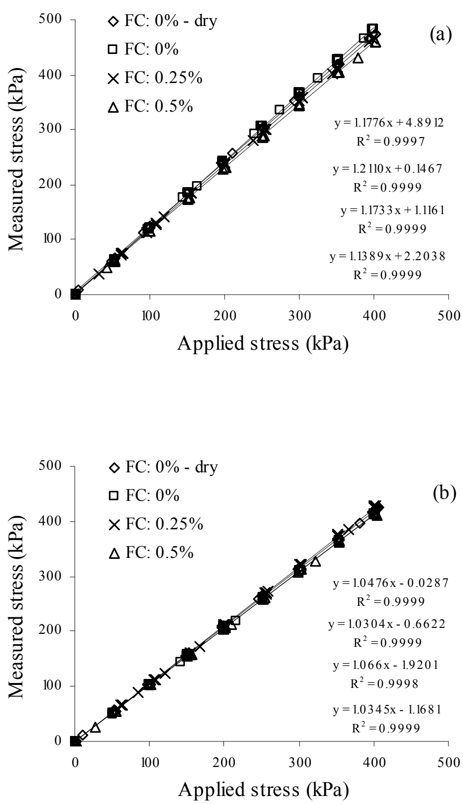


Figure 7 – Applied stress versus measured stress in the cells: (a) internal; (b) contact.

Table 5 – Calibration constants and CAF values for the total stress cells.

Fiber Content (%)	Internal		Contact	
	Constant	CAF	Constant	CAF
0 (dry)	1.1776	1.163	1.0476	1.114
0	1.2110	1.196	1.0304	1.096
0.25	1.1733	1.159	1.0660	1.134
0.50	1.1389	1.125	1.0345	1.101

4 CONCLUDING REMARKS

From the results and analyses presented in this paper, the following conclusions were established:

- The total stress cells have shown a good repeatability and a highly linear correlation between stress readings and applied pressures;
- The FEM approach has proved to be of great value in interpreting the stress distribution inside the calibration chamber;
- Errors in calculating the cell action factor (CAF) might occur if the position of the stress cell into the calibration chamber is not accounted for properly;
- The soil reinforcement by adding randomly distributed polypropylene fibers does not seem to significantly affect the calibration of the total stress cells.

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