Publication information

Title	Calibration of tactile pressure sensors for measuring stress in soils
Author(s)	Gao, Y.; Wang, Y.
Source	Geotechnical Testing Journal , v. 36, (4), July 2013, p. 1-7
Version	Published version
DOI	https://doi.org/10.1520/GTJ20120143
Publisher	ASTM International

Copyright information

Copyright ASTM International. All rights reserved, 2013. Downloaded via HKUST Institutional Repository, pursuant to Author/Copyright Owner Agreement. No further reproduction authorized.

Notice

This version is available at HKUST Institutional Repository via

<http://hdl.handle.net/1783.1/57271>

If it is the author's pre-published version, changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published version.

Y. Gao¹ and Y. H. Wang²

Calibration of Tactile Pressure Sensors for Measuring Stress in Soils

REFERENCE: Gao, Y. and Wang, Y. H., "Calibration of Tactile Pressure Sensors for Measuring Stress in Soils," *Geotechnical Testing Journal*, Vol. 36, No. 4, 2013, pp. 1–7, doi:10.1520/GTJ20120143. ISSN 0149-6115.

ABSTRACT: This paper provides a method of properly calibrating tactile pressure sensors for the measurement of stress in soils subjected to short-term and long-term static loading. Tailor-made cells were used for the sensor calibration and examination of the calibration accuracy. It was found that if the calibration results for each sensing element on the sensor (i.e., each sensel) are used, the precision of the measured stress in soil under short-term static loading can be greatly enhanced. The sensor creep has to be quantified and removed from the measurement when the soil is subjected to long-term static loading. Because the creep response of each sensel depends on the applied pressure, the associated calibration also has to be carried out under different levels of pressure. This is time consuming and not feasible in reality. A quick method that can significantly shorten the calibration time is therefore proposed in this work. The examination results prove the accuracy of the quick method for calibrating sensor creep.

KEYWORDS: tactile pressure sensor, calibration, sand, stress, sensor creep

Introduction

Measuring stress in a soil with the conventional load cell is always a challenge because the buried load cell unavoidably influences the stress field in the soil and creates an artificial boundary to promote soil arching. In this context, the soil stress measured with the load cell is significantly affected by the characteristics of the load cell, such as its stiffness, size, aspect ratio (i.e., the ratio of the thickness to the length), and many others (e.g., see Weiler and Kulhawy 1982; Selig 1989; Dave and Dasaka 2011). In addition, the default assumption that the stress distributions are uniform on the load cell can further bias the measurement (Paikowsky and Hajduk 1997). Tactile pressure sensors are ultra-thin and flexible and comprise numerous individual, tiny sensing elements, called sensels. These features resolve the problems associated with the conventional load cells and enable us to accurately measure stress in soils. Therefore, these sensors are useful for different geotechnical applications.

Paikowsky and coworkers were the first to use tactile pressure sensors for geotechnical applications. They used these sensors to measure the vertical stress under rigid footings (Paikowsky et al. 2000) and beneath a pile of sand (Paikowsky et al. 2006), and to measure the distribution of vertical stress on a trap door when soil arching was formed (Paikowsky et al. 2003, 2010). The tactile

sensor has also been used by other researchers for various applications, such as measuring the vertical stress transmitted from railroad tracks (Stith 2005) and sensing changes in the vertical stress of pipelines that are displaced laterally (Palmer et al. 2009). However, the focuses of previous studies have always been on stress measurement at the soil–structure interface, and not in soil. The calibration of tactile sensors has been known to be critical for measurement accuracy (see the detailed examination by Paikowsky and Hajduk [1997]). In addition, for long-term measurement, sensor creep must be calibrated (Paikowsky and Hajduk 1997; Palmer et al. 2009). Thus, the main objective of this study was to explore how to properly calibrate tactile sensors (including sensor creep) in order to accurately measure the stress in soil under short-term and long-term static loading conditions.

I-Scan System and Tactile Pressure Sensors

Figure 1 presents the pressure mapping system used in this study, the I-Scan system (Tekscan Inc., MA). This system consists of software, scanning electronics (called a handle), and a tactile pressure sensor. The handle connects to the sensor, obtains the data measured by the tactile sensor, and then processes the data and sends them to the computer. The tactile pressure sensor used in this study was a model 5076 (Tekscan Inc.), with a sensing range from 0 to 344.7 kPa and a sensing area of 83.8 mm × 83.8 mm. This sensor consists of 44 rows and 44 columns of ink traces whose intersecting area functions as a tiny load cell 1.9 mm × 1.9 mm in size, called a sensel. There are 1936 sensels in the sensor. The sensel is a force-sensitive resistor, and its impedance changes in response to different loadings. When a force is applied to the sensor, the analog-to-digital converter

Manuscript received July 25, 2012; accepted for publication March 7, 2013; published online May 16, 2013.

¹Research Student, Dept. of Civil and Environmental Engineering, The Hong Kong Univ. of Science and Technology, Hong Kong 111, China, e-mail: gylyq@ust.hk

²Associate Professor, Dept. of Civil and Environmental Engineering, The Hong Kong Univ. of Science and Technology, Hong Kong 111, China (Corresponding author), e-mail: ceyhwang@ust.hk

FIG. 1—The I-Scan system.

assigns a digital output (DO) value between 0 and 255 (i.e., 8-bit resolution) to each sensel, depending on the corresponding impedance value. This DO can then be correlated to the pressure or other engineering units through calibration. In the following sections, the calibration of sensors under short-term static loading is presented first, followed by the calibration of sensors under long-term static loading, for which the influence of sensor creep is considered.

Calibration of Sensors Under Short-Term Static Loading

Conditioning and Equilibration of Tactile Sensors

Sensor conditioning and equilibration have to be carried out before calibration. In order to reduce sensor drift and hysteresis and improve repeatability during the experiment, sensor conditioning has to be conducted by loading the sensor several times to a value that is approximately 20 % greater than the target load used in the experiment. Sensor equilibration aims to eliminate the differences between the DOs of individual sensels subjected to the same pressure. During equilibration, uniform pressure is applied to the tactile sensor using an equilibrator. Then, a gain (i.e., a scale factor) is assigned to each sensel to level the DO. After equilibration, every sensel should be able to render the same DO for the same applied pressure. A model PB100H equilibrator (Tekscan Inc.) was used in this study; this model has a urethane bladder that fills with air for applying uniform pressure to each sensel on the tactile sensor.

Calibration Setup

According to the user manual, the calibration of sensors should be carried out under conditions similar to those of the experimental environment. That is, the material interface, the shape (or profile) of the interface, and the applied pressure in the calibration

FIG. 2—Calibration setup for the two methods suggested in the user manual (i.e., single-load calibration and two-load calibration).

should be similar to those in the experiment. Because we wanted to use the tactile sensor to measure the stress distribution in soils, a tailor-made cell with inner dimensions of 100 mm $\times$ 100 mm $\times$ 40 mm (shown in Fig. 2) was used for calibration to fulfill those requirements. In the calibration setup, the tactile pressure sensor was placed between the upper and lower boxes, which were filled with the testing soil, Leighton Buzzard sand (fraction E). The loading was applied to the sensor in the vertical direction. The grain size of Leighton Buzzard sand ranges from 0.425 mm to 0.063 mm. The associated mean grain size, D_{50} , is equal to 0.12 mm. The sand was first densified via vibration, and then several loading-unloading cycles were performed to ensure that the soil packing was stable enough for calibration. It was also assumed that an interface (or topography) was similar to that in the real experiment. A thin layer of vacuum grease was smeared on the wall of the box to minimize sidewall friction.

Calibration Methods and Results

The user manual recommends two calibration methods, single-load calibration and two-load calibration. When the single-load calibration was conducted, a linear line was drawn between the zero load and the known calibration load to establish the relationship between the applied pressure and the DO (i.e., the calibration function). For the two-load calibration, a power law equation was used by default to relate the applied pressure to the DO using three points: the zero load and the two calibration loads. Both calibration methods were applied in this study. Single-load calibration was performed at each loading stage to improve accuracy. That means a calibration function was established and used under the same loading. For instance, if the calibration function was obtained under an applied loading of 50 kPa, the function could be used to compute the stress in a soil sample measured with the tactile pressure sensor only when the sample was subjected to a pressure of 50 kPa. In the two-load calibration, the first calibration load should be two to three times lower than the second one, according to the user manual. For instance, when the two-load calibration was applied to the sensor under a loading of 50 kPa, the two known loads were selected as 20 kPa and 60 kPa. Similar to single-load calibration results, the calibration function obtained

FIG. 3—Examination of the accuracy of single-load and two-load calibration: (a) comparison of measured (by the tactile sensor) and applied pressure levels; (b) the associated percentage errors.

from the two-load calibration can be used to calculate the measured stress only when the experiment is conducted under the same loading as in the calibration. During the calibration, a waiting time of 120 s was required for each loading stage to ensure that the loading was stabilized, as suggested by [Palmer et al. \(2009\)](#).

After calibration, a new loading cycle was applied to the soil sample using the same setup as shown in Fig. 2. This was aimed at assessing the accuracy of the single-load and two-load calibration methods, and Fig. 3 presents the results. As shown in Fig. 3, the pressure measured with the tactile pressure sensor was underestimated when the applied pressure was below 100 kPa, with an associated error of up to 20 %. Note that the measured pressure given is the average of the measurements obtained from all sensels. When the applied pressure was greater than 100 kPa, the pressure measured with the tactile sensor was overestimated by up to 10 %. These results are similar to those reported by [Paikowsky and Hajduk \(1997\)](#). They found that the percentage error might be as much as ~40 % when the applied pressure is around 50 kPa. In addition, the percentage error decreases with increasing applied pressure and is ultimately less than ~5 % when the applied pressure is greater than ~175 kPa. Soils are particulate media, and stress does not distribute uniformly through a soil sample. Thus, although the applied pressure might be, for instance, 50 kPa, the pressure measured by each sensel will not be 50 kPa and instead will vary widely, as demonstrated in Fig. 4. This feature certainly enlarges the extrapolation range of the calibration and therefore

FIG. 4—Distribution of the measured stress in each sensel under an applied loading of 50 kPa. The single-load calibration results were used to convert the digital output of each sensel to the corresponding pressure.

decreases the calibration accuracy, leading to measurement errors. As suggested in the user manual, for single-load calibration, accurate results can be obtained when the measured stress is within ± 20 % of the calibration load. Based on Fig. 3 and the above discussion, we concluded that the calibration methods suggested in the user manual were not suitable for soils. Therefore, we calibrated and established a calibration function for each sensel, called the sensel calibration method herein, in order to get more accurate results. This method is similar to the one used by [Palmer et al. \(2009\)](#).

The calibration for each sensel was carried out using the equilibrator to ensure that uniform pressure was applied to each sensel. Figure 5 presents the calibration result, or the relationship between the DO and the applied pressure for each sensel. Note that every sensel had the same response because equilibration was applied to the sensor. After this new calibration result was used to reprocess the same measured data (i.e., the DO) in Fig. 3, the measurement accuracy was greatly improved, as shown in Fig. 6. The measured pressure values were similar to the applied ones, and the percentage error was lower than 4 % when the applied pressure was greater than 40 kPa.

FIG. 5—The relationship between the digital output of the sensel and the applied pressure obtained using the sensel calibration method.

FIG. 6—Examination of the accuracy of the seneal calibration method: (a) comparison of measured (by the tactile sensor) and applied pressure levels; (b) the associated percentage errors.

Calibration of Sensors for Long-Term Measurement

Calibration Methods, Setups, and Results

The tactile pressure sensor exhibits drift or creep with elapsed time under a constant load (Tekscan Inc. 2009). Thus, sensor creep has to be calibrated in order for accurate results to be obtained for long-term measurement. The equilibrator is perfect for quantifying sensor creep. Figure 7 presents the calibration results for sensor creep in response to three days of constant loading. As revealed in the figure, the responses of sensor creep vary with the applied pressure. Such behavior was also observed by Paikowsky and Hajduk (1997) and Palmer et al. (2009). That is, the sensor creep response is a function of pressure, and this behavior complicates the calibration procedures. As the results show in Fig. 4 (obtained using the setup illustrated in Fig. 2), although the pressure applied to the soil sample was 50 kPa, each sensel detected different levels of pressure in the soil because the loading was not uniformly distributed throughout the soil. Because the sensor resolution was 8 bits, the DO values of the sensel ranged from 0 to 255, corresponding to 2^8 different pressure levels. That is, sensor creep has to be calibrated under 2^8 levels of pressure. The equilibrator can apply only one pressure level at a time. If three days of constant loading were required for

FIG. 7—Response of sensor creep as a function of the applied pressures (obtained using the equilibrator).

each creep calibration, it would take 768 days in total to complete all the calibrations. This is not feasible in reality.

A quick method for calibrating sensor creep is therefore proposed. Figure 8 presents the calibration setup. A thin layer of sand of about 1 mm thick was placed on top of the tactile pressure sensor. The sensor and this sand layer were sandwiched between two steel plates. Under constant loading, the stress in a soil packing can be redistributed after some time (Gao et al. accepted). Thus, the sand layer on top of the sensor has to be thin to minimize the influence from the stress redistribution in this sand layer on the sensel output. That is, we have to ensure that changes in the output of each sensel are the result of sensor creep itself and not of the stress redistribution in the sand layer. When loading is applied to the sensor using the setup illustrated in Fig. 8, the pressure acting on each sensel can vary in a wide range because the thin layer of sand distributes the loading unevenly. Hence, different sensel outputs, which can cover the whole range of DO (0–255), are rendered. In light of this response, calibrations of

FIG. 8—Setup used in the quick method to calibrate sensor creep.

FIG. 9—The creep responses of different sensors subjected to the same pressure: (a) 55 kPa; (b) 110 kPa (using the proposed quick method).

sensor creep under 2^8 different pressure levels can be performed in one test. For example, if the constant loading applied in the experiment is 50.34 kPa for three days, the same loading amount and time are also applied to the calibration of sensor creep using the setup in Fig. 8. During the three-day calibration period, the creep response of each sensor is continuously recorded. Figure 9 presents the recorded results for some sensors, indicated by different sensor numbers, subjected to the same pressure. In the figure, creep responses of sensors are given by the percentage changes. Using the results in Fig. 9, the creep responses of all sensors, which were subjected to different pressure levels, can be quantified and therefore removed from the sensor output in long-term measurement. The results in Fig. 9 also suggest that the sensors exhibit similar creep responses as long as they are subjected to the same pressure. This lends support to the validity of the proposed quick method.

Comparisons and Discussion

One might still wonder whether the proposed quick method and measurement using the equilibrator can deliver the same response of sensor creep. The comparisons in Fig. 10 and Table 1 resolve this concern and demonstrate that similar sensor creep responses can be obtained no matter which calibration method is used or

FIG. 10—Comparison of the sensor creep results obtained using the equilibrator and those obtained using the proposed quick method under different levels of pressure: (a) 55 kPa; (b) 110 kPa; and (c) 152 kPa.

what pressure a sensor is subjected to. Nevertheless, there is still a need to examine whether the influence of sensor creep can be effectively removed using the calibration result obtained with the quick method. The setup shown in Fig. 2 was used again for the examination. Two constant levels of stress, 50.34 kPa and 197.21 kPa, were applied to the soil sample for three days. The tactile pressure sensor located in the middle of the sample continuously monitored the changes in stress of the soil at different elapsed times. The calibration result of each sensor (e.g., the result shown in Fig. 5) was used to convert the DO of each sensor to the corresponding pressure. Figure 11 presents the examination results for the evolution of the pressure measured by the tactile sensor during three days of constant loading. It can be seen that when the influence from sensor creep is not eliminated (i.e., the case before correction), the pressure measured by the tactile pressure sensor increases continuously with elapsed time. Such a

TABLE 1—Parameters of the equations used for the best-fit line in Fig. 10.

Loading	Calibration Method	Parameters			R^2
		a	b	c	
$\sigma_v = 55$ kPa	Quick method	8.624	8.463	0.950	0.989
	Using an equilibrator	8.570	8.883	0.949	0.988
$\sigma_v = 110$ kPa	Quick method	8.254	8.130	0.929	0.995
	Using an equilibrator	8.237	8.022	0.928	0.997
$\sigma_v = 152$ kPa	Quick method	8.776	8.718	0.940	0.997
	Using an equilibrator	8.914	8.474	0.945	0.991

Note: The equation used in the best fit is $y = a - b \cdot c^x$.

measurement is not correct, as the applied stress was kept constant. After the influence of creep in each sensel is removed from the measurement (i.e., the case after correction) using the quick method, the measured stress becomes fairly constant. As also shown in Fig. 11, the percentage errors are less than 1.3 % and 0.8 % for the cases under constant loading of 50.34 kPa and

FIG. 11—Comparison of the pressure measured using the tactile pressure sensor before and after correction of sensel creep under constant loading for three days: (a) under 50.34 kPa; (b) under 197.21 kPa. The percentage error describes the difference between the true value and the results after correction.

197.21 kPa, respectively. This finding confirms the effectiveness and accuracy of the quick method for calibrating sensor creep.

Conclusions

This study has explored how to properly calibrate a tactile sensor in order to precisely measure the stress in soils under short-term and long-term static loading. Under short-term static loading, the calibration methods suggested in the user manual are not applicable, and therefore calibration has to be carried out for each sensing element (or sensel). When the results of calibration for each sensel measured by an equilibrator are used, the accuracy of the stress measured in the soil sample by the tactile pressure sensor is greatly improved. For long-term static loading, sensor creep has to be calibrated and removed from the measurement. The response of sensor creep was found to be a function of the applied pressure. In addition, stress is not uniformly distributed in soil even when the soil sample is subjected to one particular level of pressure. As a result, the creep response of each sensel under different applied pressures has to be quantified in order for the calibration of the sensor creep to be completed. Such a calibration requirement is time consuming and is not feasible in reality. A quick method that can greatly shorten the time spent on calibration has therefore been proposed in this study. The examination results confirm the effectiveness and accuracy of the quick method for calibrating sensor creep.

Acknowledgments

This research was supported by the Hong Kong Research Grants Council (Grant No. GRF 620310). The writers are grateful to the reviewers for valuable comments and to MEMS Technology Corp., Taiwan, for technical support.

References

- Dave, S. M. and Dasaka, S. M., 2011, "A Review on Pressure Measurement Using Earth Pressure Cell," *International Journal of Earth Sciences and Engineering*, Vol. 4, No. 6, pp. 1031–1034.
- Gao, Y., Wang, Y. H., and Su, J. C. P., 2013, "Mechanisms of Aging-Induced Modulus Changes in Sand under Isotropic and Anisotropic Loading," *J. Geotech. Geoenviron. Eng., ASCE*, Vol. 139, No. 3, pp. 470–482.
- Paikowsky, S. G. and Hajduk, E. L., 1997, "Calibration and Use of Grid-Based Tactile Pressure Sensors in Granular Material," *Geotech. Test. J.*, Vol. 20, No. 2, pp. 218–241.
- Paikowsky, S. G., Palmer, C. J., and Dimillio, A. F., 2000, "Visual Observation and Measurement of Aerial Stress Distribution under a Rigid Strip Footing," *Geotech. Spec. Publ.*, Vol. GSP 94, pp. 148–169.
- Paikowsky, S. G., Palmer, C. J., and Rolwes, L. E., 2006, "The Use of Tactile Sensor Technology for Measuring Soil Stress Distribution," *Proceedings of the GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*, Atlanta, GA, February 26–March 1, ASCE, Reston, VA, pp. 1–6.

- Paikowsky, S. G., Rolwes, L. E., and Tien, H. S., 2003, "Visualization Measurements of Stress around a Trap Door," *Proceedings of the 12th Pan-American Conference on Soil Mechanics and Geotechnical Engineering and 39th Rock Mechanics Symposium*, Cambridge, MA, June 22–26, P. J. Culligan, H. H. Einstein and A. J. Whittle, Eds., VGE Publications, Essen, Germany, pp. 1171–1177.
- Paikowsky, S. G., Tien, H. S., and Rolwes, L. E., 2010, "Observing and Measuring Arching in Ideal and Natural Granular Materials," *Physical Modelling in Geotechnics: Proceedings of the 7th International Conference on Physical Modelling in Geotechnics (ICPMG 2010)*, Zurich, Switzerland, June 28–July 1, S. Springman, J. Laue, and L. Seward, Eds., Taylor and Francis Group, London, England, pp. 373–378.
- Palmer, M. C., O'Rourke, T. D., and Olson, N. A., 2009, "Tactile Pressure Sensors for Soil-Structure Interaction Assessment," *J. Geotech. Geoenviron. Eng.*, Vol. 135, No. 11, pp. 1638–1645.
- Selig, E. T., 1989, "In-Situ Stress Measurements," *Proceedings: Symposium on the State-of-the-Art of Pavement Response Monitoring Systems for Roads and Airfields*, West Lebanon, NH, March 6–9, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, pp. 162–168.
- Stith, J. C., 2005, "Railroad Track Pressure Measurements at the Rail/Tie Interface Using Tekscan Sensors," M.S. thesis, University of Kentucky, Lexington, KY.
- Tekscan 2009, "I-Scan & High Speed I-Scan User Manual (v. 6.0x)," Tekscan Inc., Boston, MA.
- Weiler, W. A. and Kulhawy, F. H., 1982, "Factors Affecting Stress Cell Measurements in Soil," *J. Geotech. Geoenviron. Eng.*, Vol. 108, pp. 1529–1548.