

Use of Miniature Soil Stress Measuring Cells under Repeating Loads

Muhammad ARSHAD^{a,1} and Brendan C. O'KELLY^b

^a*PhD Student, Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland*

^b*Associate Professor, Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland*

Abstract. Different types of soil stress measuring cells have been successfully used in model tests under monotonic loading after following a strict calibration exercise to simulate field conditions. This paper explores the potential of one particular type of strain-gauged cell (type TML-PDA-200kPa) to determine the magnitudes of stresses generated at soil-structure interfaces and also within the soil medium for repeating load tests on models at 1 g. Difficulties associated with the use and calibration of these cells, including hysteresis, are discussed. In the present investigation, repeating load tests performed on dry sand prepared at different density states indicated that the cell response was strongly dependent on sand density, load amplitude, loading frequency and number of load cycles.

Keywords. Calibration, cyclic loading, miniature stress cells, soil stress

1. Introduction

Soil stress-measuring cells (SMMC) provide a valuable means of obtaining information to examine the validity of constitutive theories for soil behaviour and computational techniques for soil-structure interaction (SSI) problems [1]. The magnitude and distribution of *insitu* stresses can be determined using cells embedded within the soil mass; e.g. embankments or backfill material [2]. Contact pressures acting between the soil and a structural element (e.g. retaining wall, culvert, shallow foundation, pile [3, 4]) can be determined using interface cells [5]. For reliable interpretations of the sensor output, inclusion and placement effects, cell-soil interaction, environmental and dynamic response effects must be considered [1, 6, 7]. The device's size, geometry and flexibility relative to the soil grains have significant effects on response and reliability [2]. To minimise errors arising from inclusion effects, it is necessary to minimise the cell thickness, with a recommended ratio of overall cell diameter (D) to thickness of more than 5 [2, 6]. Interaction between the soil and sensing area of the cell is highly dependent on the rigidity of the sensing surface. The ratio between the sensitive cell diameter (D_c) and D typically used is in the range 0.5–0.7 [2, 6], with a ratio between D_c and the maximum deflection of the sensing surface ($\delta_{\max}$) in the range 2000–5000 [2, 6, 8]. Nevertheless, devices with larger D_c/D ratios have been also used; e.g. 0.86

¹ Corresponding Author: Muhammad Arshad, Department of Civil, Structural & Environmental Engineering, Trinity College Dublin, Dublin, Ireland; E-mail arshadm@tcd.ie

reported by Zhu *et al.* [7]. To reduce the effects of local heterogeneities of the soil and local fluctuations of contact forces acting between individual soil particles and the sensing surface, the ratio between D_c and the mean particle size (d_{50}) must be at least 10 [6, 9]. For SSI situations, the issue of hysteresis is a real effect and we want to see the difference between loading and unloading. For SMMC's working on the principal of 'null soil pressure system', hysteresis effects can be significantly reduced or eliminated although embedment of such bulky soil cells leads to an infinitely stiff inclusion relative to the soil mass. Such cells are described by Talesnick [5, 10].

The present study investigates the possible use and calibration procedure for a particular miniature SSMC device in dry sand prepared at different densities and subjected to repeating loads. The authors are interested in using these sensors to measure the boundary normal pressures on reduced-scale model piles and the stress changes within the surrounding sand under repeating lateral load testing at 1-g. In the authors' experience, the evaluation of normal stress using such devices based on the manufacturer's calibration factor values (which are usually produced for the monotonic loading condition only) may lead to misinterpretation, particularly under long-term repeating loads.

2. Materials and Methods

Dry sub-angular to angular medium silica sand having a d_{50} of 0.27 mm, coefficient of uniformity of 1.85 and coefficient of curvature of 1.0 was used in the present investigation. This material had minimum and maximum void ratio values of 0.60 and 0.92, with corresponding dry densities of 1388 and 1662 kg/m³ respectively. The SSMC devices (type TML-PDA-200kPa manufactured by Tokyo Sokki Kenkyujo Co., Japan) incorporated a strain-gauged diaphragm (Figure 1) and had dimensions of $D = 6.5$ mm, $D_c = 5.6$ mm, with overall cell and diaphragm thicknesses of 1.0 and 0.14 mm respectively. For the test sand, the D_c/d_{50} ratio value of 20.7 was greater than the minimum recommended value [6, 9]. The cell's D_c/D ratio value of 0.86 was the same as that for similar SSMC devices used in investigations by Zhu *et al.* [7]. Such cells have also been used by in field studies by Gavin and O'Kelly [11] and Igoe *et al.* [12, 13] in determining the lateral earth pressures acting on model piles under repeating axial loads. The wire connection for the type TML-PDA devices used in the present investigation was in the plane of the instrument. A PDB version of this sensor with a top exit cable is also available from the manufacturer.

Test specimens were prepared by air pluviation into a steel cylinder, 92 mm outer diameter, 82 mm inner diameter and 200 mm long (Figure 2). The cylinder was internally lined using a double latex membrane, with a talcum powder coating between the membranes, in order to reduce the friction between the sand particles and the cylinder's inner wall. Similar sample preparation techniques were used by Zhu *et al.* [7]. The specimens were built up in 20 mm thick layers which were individually compacted, as necessary, to produce specimens having overall target density index values of 0.26 (loose), 0.55 (medium dense) and 0.85 (dense). When 120 mm depth of sand had been deposited in the cylinder, the first cell was placed horizontally on the levelled sand surface, with its sensing surface facing upwards. The second and third cells were similarly placed after pluviating 20 and 40 mm deep layers of the sand above the first device.

The overall height of the final sand specimens was ~ 180 mm, each incorporating 3 SSMCs at the different embedment depths. The wires from the embedded cells were run horizontally to the inner wall of the steel cylinder and then vertically, exiting via the top of the sand specimen. The cell's sensing surface should not be compressed before any external load is applied. In the present investigation, the test specimens were prepared to, lightly tapping the outer wall of the steel cylinder using a plastic hammer to achieve the necessary densification (without the loading platen in place), confirmed from specimen mass and volume measurements. A smooth loading platen incorporating a fourth cell was placed on the finished sand bed surface, with its sensing surface pointing downwards and contacting the sand bed. The cell in the loading platen is used to model the effect of these cells mounted in the sidewall of an instrumented model pile under repeating lateral load tests bearing in mind that, for a model pile with a circular cross section, the sidewall will be curved, while these pressure cells are flat (planar), which may affect the calibration.

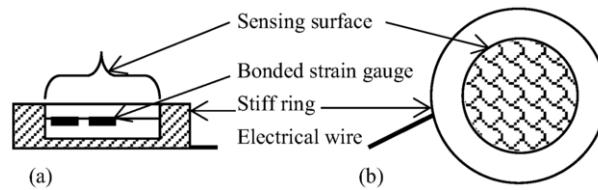


Figure 1. Schematic of SSMC: (a) in cross section; (b) in plan.

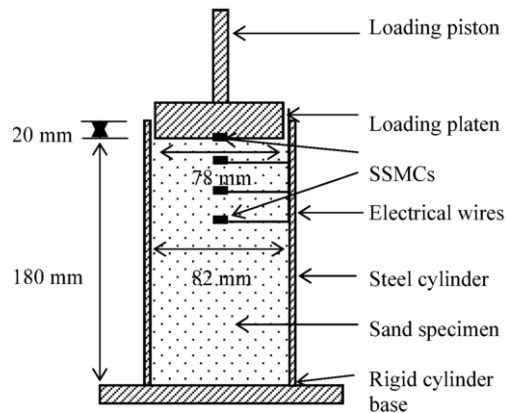


Figure 2. Schematic of experimental set up (not to scale).

The applied platen load was measured using a load cell (series LCM-703 manufactured by Omega Engineering Ltd., UK) having a range of ± 250 N. The outputs from the load cell and 4 SSMCs were recorded using a System-7000 data-acquisition system (Vishay Precision Group, USA). The system simultaneously scanned all sensors at 10 data points/s, with a measurement accuracy of $\pm 0.05\%$ of full scale.

Repeating load tests involving 1000 number of sinusoidal load cycles were applied to the loading platen in at constant temperature environment of $20 \pm 2^\circ\text{C}$, investigating an average bearing pressure range of 0 to 21 kPa applied across the platen contact area and loading frequencies of 0.13, 0.18 and 0.25 Hz. The stress amplitude covers the anticipated range of contact pressures mobilized against the sidewall of the model pile under repeated lateral loading, simulating conditions typically encountered for offshore wind-turbine foundation structures.

3. Experimental Results

Figure 3 shows the outputs (in mV/V) from the sensors at different numbers of load cycles plotted against average bearing pressure of 0 to 21 kPa applied, calculated as the measured platen load divided by its contact area. Data plots the 300th load cycle are presented for cells embedded at depths (d) of 20, 40 and 60 mm in medium dense sand under repeated loading at 0.13 Hz. Data plots are also presented for the interface cell and dense sand at the 10th, 500th and 1000th load cycle at 0.18 Hz. In Figure 4, the manufacturer's calibration factor values (which relate to monotonic loading) have been applied to the voltage data for the 3 embedded sensors to present their outputs in units of kilopascals.

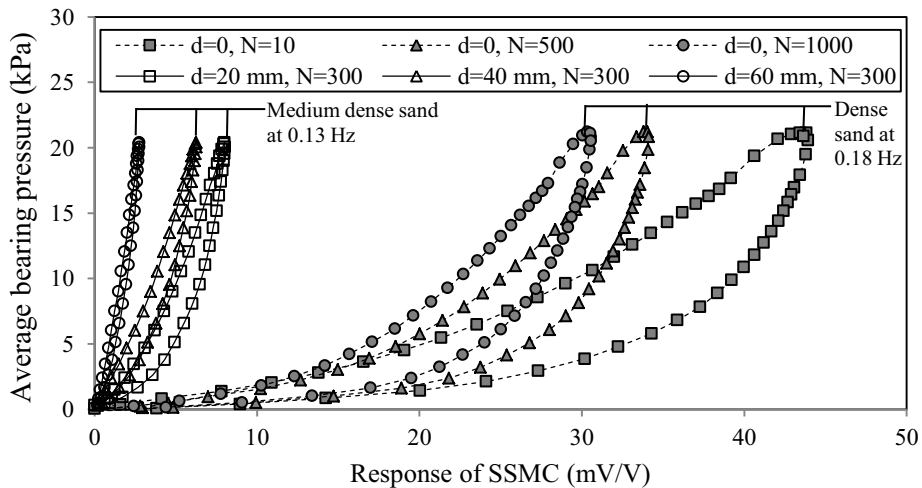


Figure 3. SSMC responses (in mV/V) for different numbers of load cycles (N) and embedment depth (d).

The interface and embedded cell responses were highly non-linear, with significant hysteresis induced by the repeated loading (response during loading was greater in magnitude than unloading), particularly for the interface cell, looser density states and during the early number of load cycles. Similar behaviour has been reported by Zhu *et al.* [7] and Talesnick [10]. Further, the cell responses were dependant on the load amplitude and frequency. For the interface cell and dense sand, the response appeared to be particularly sensitive to the number of load cycles (N), with the ratio of cell output to average bearing pressure applied by the platen decreasing with increasing N .

values (see data plots for dense sand presented in Figure 3). For the 3 cells embedded in medium dense sand, the responses appeared to be more sensitive to embedment depth (see data plots for $d = 20, 40$ and 60 mm presented in Figures 3 and 4) but not as sensitive to the number of loading cycles, compared with the interface cell. This general behaviour was observed for all of the loading frequencies and density states investigated. It was also found that the ratio of the cell response to average bearing pressure decreased with increasing embedment.

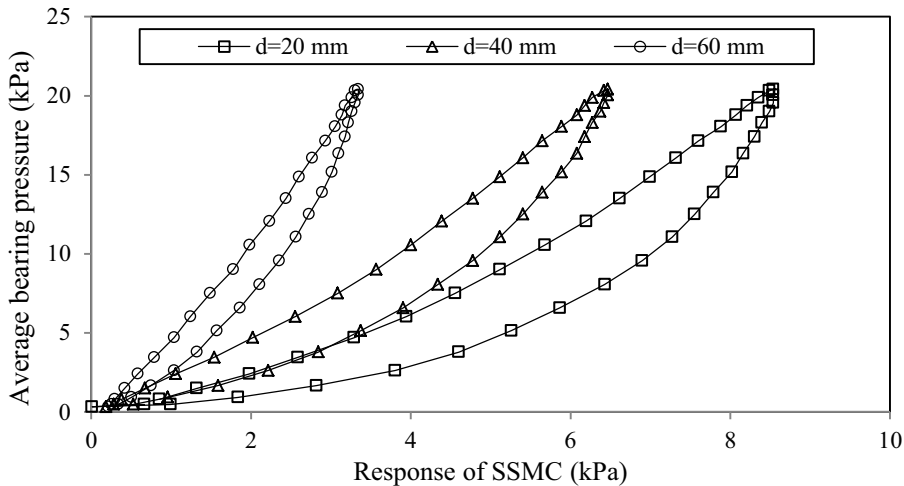


Figure 4. Cell responses at 300th load cycle for different embedment depths in medium dense sand under repeated loading at 0.13 Hz.

4. Discussion

The experimental setup is one of load control of a rigid plate (not a boundary condition of pressure) and hence the distribution of contact stress between the loading platen and specimen surface is non-uniform. In other words, the bearing pressure mobilised at the centre of the platen is unlikely to be equal to the applied load divided by its cross sectional area. Non-uniformity of the distribution of contact stress between the cell devices and surrounding soil is also an issue (Selvaduri *et al.* [14]; Wachman and Labuz [15]). The fact that the “pressure” monitored decreased as the number of cycles increased is more than likely to be an effect of change in soil arrangement patterns rather than anything to do with the sensor response. Calibration of embedded cells using such a narrow pressure vessel is also not ideal. The most significant reason for the reduction in response as a function of depth is likely to be due to friction along the cylinder sidewall and arching effects around the stress-sensitive surface [8, 16, 17] and unrelated to the cell calibration/response. Use of the TML-PDB version of the device, which has a sensing diaphragm the same as the outer diameter ($D_c = D = 6.5$ mm), may prove to be a better option to avoid the discontinuity between the diaphragm.

Since it appears that hysteresis cannot be avoided for these particular devices, it should be calibrated (as done by Zhu *et al.* [7]). Empirical rules/correlations are not a solution to this difficult problem. An averaging curve (i.e. splitting the difference between loading and unloading) does not sufficiently capture the hysteresis and

therefore will not correctly predict the stresses on either the load or unload part of the cycle. For instance, an uncertainty of 8 kPa (± 4 kPa) on a full scale reading of 21 kPa occurs in the example presented. The situation is worse at lower pressures.

5. Summary

The response of stress-measuring cells is dependent on soil type (its physical characteristics including particle size, water content), condition (density state/stress history) and the loading characteristics (amplitude, frequency, number of load cycles). Compared with null-pressure type devices, the inclusion effects for the miniature TML-PDA cell considered in this investigation are minor although significant hysteresis can arise under repeating loads. For the particular application, these cells must be carefully calibrated using pressure boundary condition, especially when performing repeating load tests.

References

- [1] Dave, T. N., and Dasaka, S. M., 2011, "A review on pressure measurement using earth pressure cell." *Int. J. Earth Sci. Eng.*, Vol. 4, No. 6, pp. 1031–1034.
- [2] Dunncliff, J., and Green, G. E., 1988, "Geotechnical Instrumentation for Monitoring Field Performance." Wiley, New York.
- [3] Lehane, B. M., and White, D. J., 2005, "Lateral stress changes and shaft friction for model displacement piles in sand." *Can. Geotech. J.*, Vol. 42, pp. 1039–1052.
- [4] Rao, S. N., and Kumar, N. D., 2007, "Earth pressure on caissons in marine clay under cyclic loading." *Marine Georesources and Geotechnology*, Vol. 25, No. 1, pp. 15–35.
- [5] Talesnick, M., 2005, "Measuring soil contact pressure on a solid boundary and quantifying soil arching." *Geotech. Test. J.*, Vol. 28, No. 2, pp. 1–9.
- [6] Weiler, W. A., and Kulhawy, F. H., 1982, "Factors affecting stress cell measurements in soil." *J. Geotech. Eng.*, ASCE, Vol. 108, No. 12, pp. 1529–1548.
- [7] Zhu, B. T., Jardine, R. J., and Foray, P., 2009, "The use of miniature soil stress measuring cells in laboratory applications involving stress reversals." *Soils and Found.*, Vol. 49, No. 5, pp. 675–688.
- [8] Trollope, H., and Lee, I. K., 1961, "The measurement of soil pressure." *Proc. 5th Int. Conf. Soil Mech. and Found. Eng.*, Paris, France, pp. 493–499.
- [9] Rusinek, R., Molenda, M., and Horabik, J., 2009, "Performance of membrane pressure transducers in granular materials of various particle sizes." *Powder Technology*, Vol. 190, No. 3, pp. 410–414.
- [10] Talesnick, M., 2013, "Measuring soil pressure within a soil mass," *Can. Geotech. J.*, Vol. 50, pp. 716–722.
- [11] Gavin K. G., and O'Kelly, B. C., 2007, "Effect of friction fatigue on pile capacity in dense sand." *Geotech. and Geoenviron. Eng.*, Vol. 133, No. 1, pp. 63–71.
- [12] Igoe, D., Gavin, K., and O'Kelly, B. C., 2013, "An investigation into the use of push-in pile foundations by the offshore wind sector." *Int. J. Environ. Studies*, Special Issue: Renewable Energies and Smart Grid — The Solution for Tomorrow's Energy, Vol. 70, No. 5, pp. 777–791.
- [13] Igoe, D. J. P., Gavin, K. G., and O'Kelly, B. C., 2011, "Shaft capacity of open-ended piles in sand." *Geotech. and Geoenviron. Eng.*, Vol. 137, No. 10, pp. 903–913.
- [14] Selvadurai, A. P. S., Labanich, S., and Boulonnet, M. J., 2007, "On the mechanics of contact between a flexible transducer diaphragm located at a rigid boundary and an elastic material." *Int. J. Numer. Anal. Meth. Geomech.* Vol. 31, No. 7, pp. 933–952.
- [15] Wachman, G. S., and Labuz, J. F., 2011, "Soil-structure interaction of an earth pressure cell." *Geotech. and Geoenviron. Eng.*, Vol. 137, No. 9, pp. 843–845.
- [16] Clayton, C. R. I., and Bica, A. V. D., 1993, "The design of diaphragm-type boundary total stress cells." *Geotechnique*, Vol. 43, No. 4, pp. 523–536.
- [17] Frydman, S., and Keissar, I., 1987, "Earth pressure on retaining walls near rock faces." *J. Geotech. Eng.*, ASCE, Vol. 113, No. 6, pp. 586–599.