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Executive summary

The use of tactile pressure sensing mats has been gaining popularity among geotechnical centrifuge modellers. Tactile sensing systems such as Tekscan allow experimenters to obtain profiles of soil-structure contact pressures and visualise the results. This report builds upon previous work on the calibration of such pressure mats and describes how they were used to measure slab-soil and wall-soil contact pressures on basements models subject to heave movements in clay, for the benefit of future researchers who want to use tactile pressure mats for static geotechnical centrifuge applications.

Each Tekscan sheet should be waterproofed by lamination and then calibrated. Known loads were applied onto Tekscan sheets using the Enerpac hydraulic frame in Schofield Centre. This produced individual calibration curves for each sensel. In contrast to previous work which fit a linear calibration relationship to measure cyclic load changes, large changes in pressure were expected in the basement heave centrifuge tests, with pressures sometimes dropping to near-zero values. Therefore, a quadratic fit with a forced zero intercept was applied to each sensel to capture the non-linearity of sensitivity.

The dead weight of the basement slab and heavy fluid during spin-up and in-flight reconsolidation provided an independent check of the calibration factors. This check also generates a calibration adjustment factor which may account for the influence of centrifuge gravity on the tactile sensors' sensitivity. The data was processed using Matlab with filtering in both time (averaging over 10 frames, typically) and space (taking special averages, typically over a 3×3 grid), and then presented as graphs and heat maps.

1 Introduction to tactile pressure sensing mats and Tekscan

Over the last few years, tactile pressure sensing mats have become a popular type of instrumentation among geotechnical centrifuge modellers. The advantages of using a tactile pressure sensing mat over other methods of measuring earth pressures are that the mat provides a spatial distribution of pressure over a broad area rather than single pressure readings at discrete locations, and that the mat is thin and flexible such that it poses minimal distortion to the soil pressures being measured.

One popular brand of pressure sensing mat among the geotechnical research community is Tekscan. The key component of the Tekscan system is the pressure sensing mat, or the Tekscan sheet. Each mat comprises two layers, each with parallel strips of pressure-sensitive, conductive ink. The ink strips on the two layers are perpendicular to each other, forming a grid of electrical contacts. The conductivity at each contact point increases with the contact pressure at that grid point, known as a "sensel" (Tekscan, 2003).

Each Tekscan sheet is installed into a Tekscan handle during operation. The handle injects electrical current into each combination of horizontal and vertical strips in turn, thereby measuring the electrical resistance at each sensel; this process is known as multiplexing. The handle converts the electrical response at each sensel into an eight-bit integer (0 to 255 in decimal), where higher numbers represent higher contact pressures. These raw readings from the Tekscan system are converted into estimates of soil-structure contact pressures in kPa.

This report describes uses the basement heave centrifuge test series (Chan et al, 2019) as a case study to explain how tactile pressure sensing mats like Tekscan can be prepared and calibrated for use in static geotechnical centrifuge applications. In this experimental project, a Tekscan tactile pressure sensing system was used to obtain profiles of soil-structure contact pressure along the bottom of the base slab and along the outside of the wall. This report records the process by which Tekscan was used in this research project for the benefit of future geotechnical centrifuge researchers who may like to use similar tactile pressure sensors.

2 Calibration methods in previous geotechnical research using tactile pressure sensing mats

Ideally, an instrument should provide an electrical response that is linearly proportional to the quantity to be measured, and this constant of proportionality should be constant throughout the instrument. However, this is not the case for tactile pressure sensing mats.

Tactile pressure mats were introduced to geotechnical physical modelling applications by Palikowsky and Hajduk (1997), who described the calibration of a Tekscan sheet to measure horizontal soil stresses.

El-Ganainy et al (2013) and El-Sekelly et al (2015) built upon the method of calibration and used the mats in centrifuge tests to measure horizontal soil stresses due to pre-shaking and over-consolidation respectively.

Palmer et al (2009) calibrated Tekscan sheets to measure contact stresses between a moving pipeline and surrounding soil, quantifying the influence of shear stress on normal stress measurements. Dashti et al (2012) adopted Tekscan sheets in dynamic centrifuge testing and calibrated the attenuation of the mat's response to high-frequency loading. Madabhushi & Haigh (2018) built on this and suggested methods to account for the differences in sensitivity between sensels and for adjustments using data recorded during centrifuge spin-up.

Pertinent issues in the calibration process of tactile sensing mats include:

- Inherent variation of sensitivity between different grid points on the same mat;
- Dependence of sensitivity on the granularity of the materials in contact with the mat;
- Non-linearity of calibration curve;
- Hysteresis under cyclic loads;
- Influence of shear stress on readings of normal stress;
- Time-dependent response of readings to changes of load, including both attenuation of harmonic responses and creep under long static loads; and
- Possible differences in sensitivity between normal gravity and centrifuge gravity.

The basement heave project extends the use of Tekscan sheets to the measurement of vertical soil stresses. Unlike many geotechnical problems where the vertical stresses are easily deduced from vertical equilibrium and self-weight, one of the main variables in the basement heave problem is the variation of vertical stresses with time due to consolidation.

This use of tactile sensing mats involved large changes of normal stresses (up to 100% loss of contact stresses upon excavation) over long periods of time (minutes to hours per load stage, as opposed to multiple cycles a second). Therefore, among the issues in the abovementioned lists, hysteresis and time-dependency would be relatively insignificant compared to previous geotechnical applications of Tekscan, while extra attention should be paid to the non-linearity of the calibration curve. The following sections will describe the calibration process used in this research project.

3 Preparation of Tekscan sheets

In each centrifuge test involving Tekscan measurements, the Tekscan sheet would be in contact with the structural model on one side and with soil on the other side. Sheets that measured slab-soil contact pressures would fold around the slab-wall corner, so that the handle would sit above the top sand surface.

The formation level of the model basement would be under the water table of the centrifuge model, so the Tekscan sheets needed to be waterproofed. This is done by laminating the Tekscan sheet to create a waterproof pouch. Following the experience from experiments reported in Madabhushi (2018), an office laminating machine was first warmed up to target temperature, then allowed to cool down for 10 minutes before passing the Tekscan sheet and laminating pouch through the machine. The laminated Tekscan sheet was then reversed out of the laminating machine, because there is an internal pocket of air between the two sensing layers of a Tekscan sheet, which would cause damage if the laminating machine pushed all the air to one end of the Tekscan sheet.

Each sheet was calibrated after it was laminated, so that the calibration would account for influence of the laminate layer. The laminated Tekscan sheet was then attached to the desired position on the structural model using metallic tape (Figure 1).

Figure 1: Tekscan sheet attached onto structural model for centrifuge test DYC-04

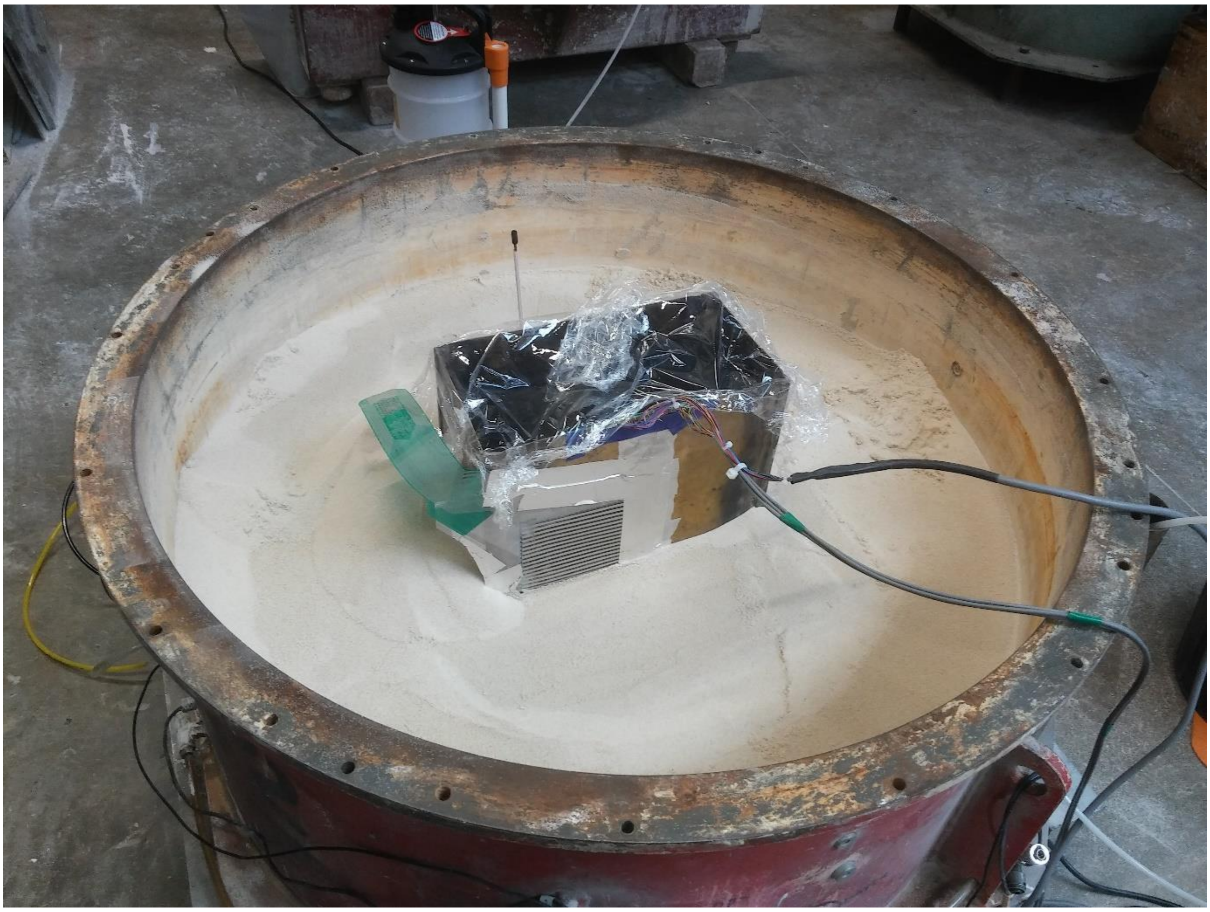

Figure 2: Basement model with Tekscan sheet installed into centrifuge package, during the preparation of centrifuge test DYC-03

4 Calibration methods

The strategy to calibrate the Tekscan sensors involved two stages. First, each Tekscan sheet was placed under a hydraulic piston and subjected to a range of known applied loads, giving independent calibration curves for each sensel. Second, the self-weight of the un-excavated basement box during the centrifuge test was used to adjust the calibration factors, to account for the effects of centrifugal gravity and contact granularity.

4.1 Physical loading with hydraulic piston

The Enerpac hydraulic piston was used to apply known forces to calibrate each Tekscan sheet. A stack of aluminium plates, underlain by a layer of soft polymer foam, was used to spread the load into a uniform pressure over the Tekscan sheet (Figure 3).

The compressive load in the hydraulic piston was increased in steps of 3 – 10 kN until a significant proportion of sensels were saturated. The load was then decreased in similarly sized steps back to an unloaded state, followed by another load-unload cycle. A snapshot of raw Tekscan readings was recorded at each load increment. The same Tekscan sensitivity setting was used in the calibration process and the centrifuge flight.

In some tests, a layer of Hostun sand was added between the foam layer and the Tekscan sheet to create a granular contact on one side of the sheet (Figure 4), simulating the contact conditions in the centrifuge model. The advantage of using a sand layer is that this would capture the effect of granularity on sensitivity (Tekscan, 2003). However, preliminary results suggested that the presence of sand grains encourages local concentrations of stress, presumably due to arching effects in the sand. Calibrating with the foam layer in direct contact with the Tekscan sheet appeared to give a more uniform response between different sensels.

Since the sand grains would not fall into the exact same arrangement in the centrifuge model, the stress concentration effect means that calibrating with the sand layer would increase the inherent variability of the calibration process. Nevertheless, a comparison between calibration factors obtained with and without the sand layer may give an indication of the influence of granularity.

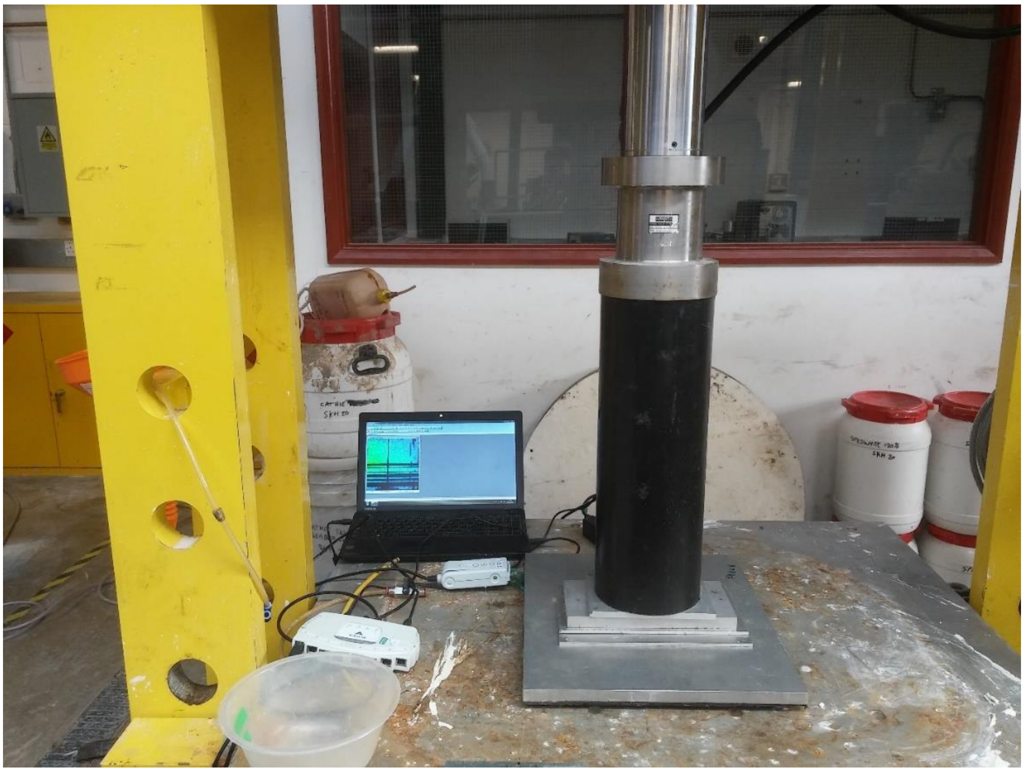

Figure 3: Calibrating a Tekscan sheet by applying a known load through a hydraulic piston

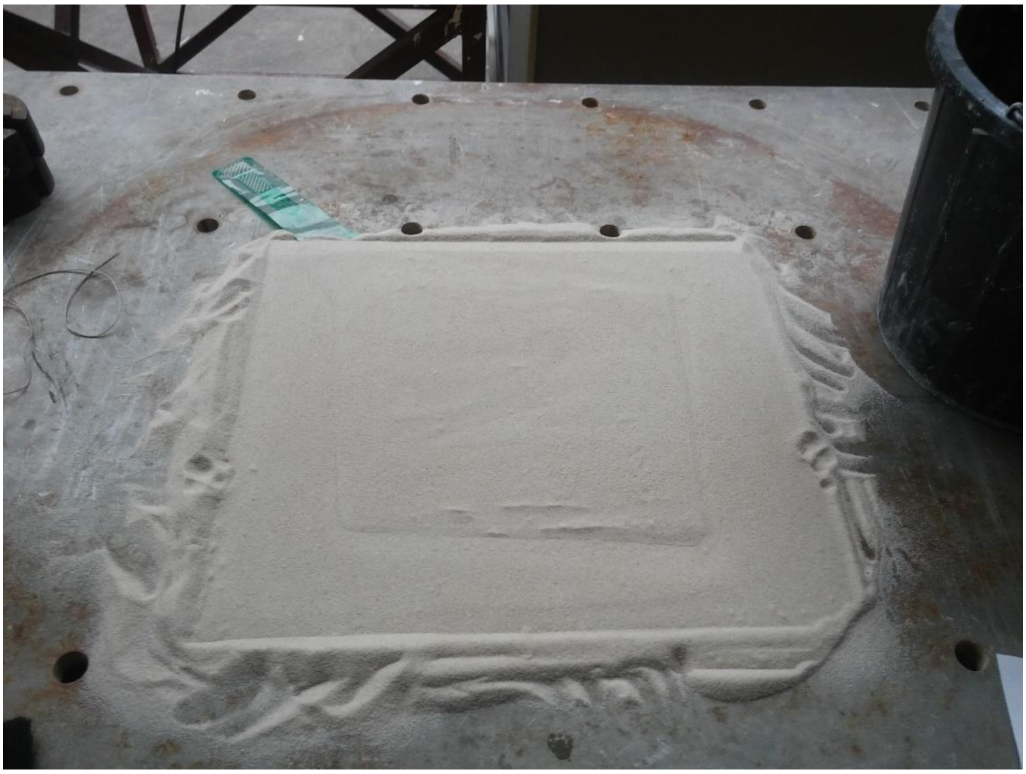

Figure 4: Tekscan sheet buried between hydraulic jack platform and Hostun sand layer

4.2 In-flight calibration

Madabhushi & Haigh (2018) used Tekscan data recorded during centrifuge spin-up to adjust their Tekscan calibrations. A similar approach was used in this project, as the slab-soil contact pressure before excavation could be estimated by equilibrium using the known self-weight of the basement and the heavy fluid that was inside it. The contact pressure near the toes of the walls might see significant stress concentration due to the weight and vertical stiffness of the walls, but the contact pressure away from the walls should simply be the total weight of the heavy fluid and the slab per unit area.

After some experimentation, it was decided that the Tekscan sheets should be calibrated under the piston with foam contact on one side and metal contact on the other side, without using sand. The measurements were used to obtain a calibration curve for each sensel. Then, the self-weight of the unexcavated basement box during the centrifuge test was used to obtain a “calibration shift” scaling factor to be multiplied onto all calibration curves, to account for the effect of contact granularity and the difference in sensitivity inside and outside the centrifuge.

5 Processing of results

5.1 Conversion of physical loading results to calibration factors

For each known load on the hydraulic press, the load was converted to a contact pressure by adding the self-weight of the plates (about 10 kg; varies between calibration runs due to different shim plates being used), subtracting the zero-offset of the load cell (in the range of 0 – 1.5 kN), and dividing by the contact area of the foam plate (0.459 m × 0.405 m).

The relationship between applied pressure and Tekscan raw readings was plotted for a random selection of sensels. The results showed a largely monotonous response with some non-linearity and some hysteresis (Figure 5).

Previous research typically fitted a straight line with a non-zero intercept to the response of each sensel (Dashti et al 2012; Madabhushi & Haigh 2018). However, those experiments used tactile sensing mats to measure oscillations of pressure around an average value. In contrast, the experiments in this project involved large changes in pressure. For example, the slab-soil contact pressure at the centre of the flexible basement would drop from about 250 kPa before excavation to nearly zero upon excavation. Therefore, it would be preferable to fit a quadratic curve with a forced zero intercept. These best-fit lines are shown on Figure 5.

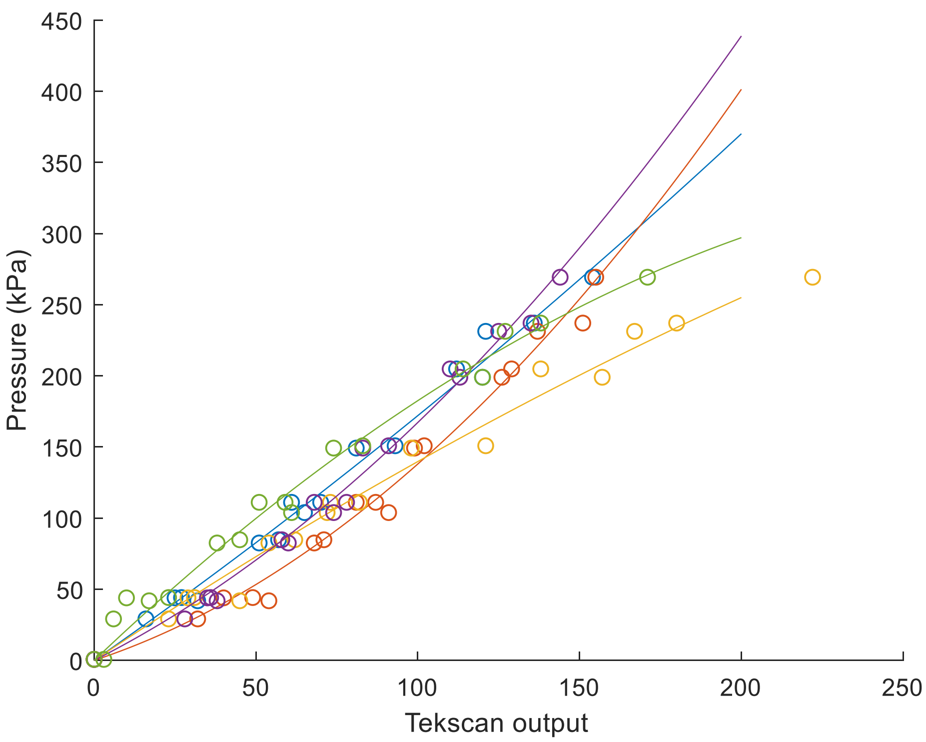

Figure 5: Plot of the responses of five randomly selected sensels from the calibration used in centrifuge test DYC-06. Curved lines are quadratic best-fits.

The calibration factors were then plotted on histograms to identify outliers and faulty sensels. Using the calibration of the Tekscan sheet used on the slab in centrifuge test DYC-06 as an example, the histogram of linear calibration factors shows a Gaussian peak at 1.3 kPa (per unit raw reading) and a spike at 0 kPa representing completely unresponsive sensels. The histogram of quadratic calibration factors shows a Gaussian peak centred slightly to the positive side of zero. Cut-off values were picked by eye ([0.5, 3] kPa for linear factor; [-0.01, +0.02] kPa for quadratic factor in this case) to exclude outliers. Any sensel deemed an outlier was marked as such, and readings from the same sensels would be replaced with NaN ("not a number", special value in Matlab) in further analysis.

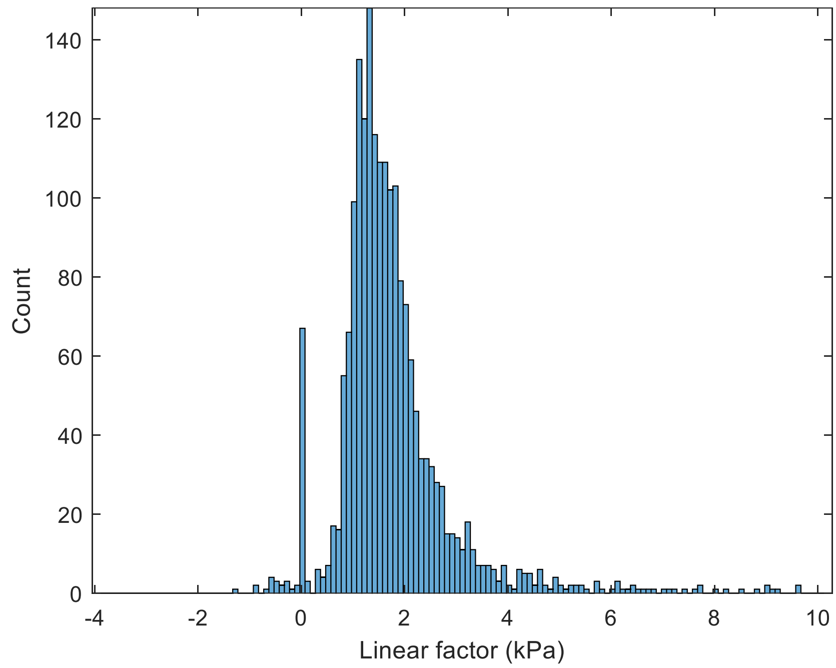

Figure 6: Histogram of linear factors, from slab Tekscan sheet in test DYC-06

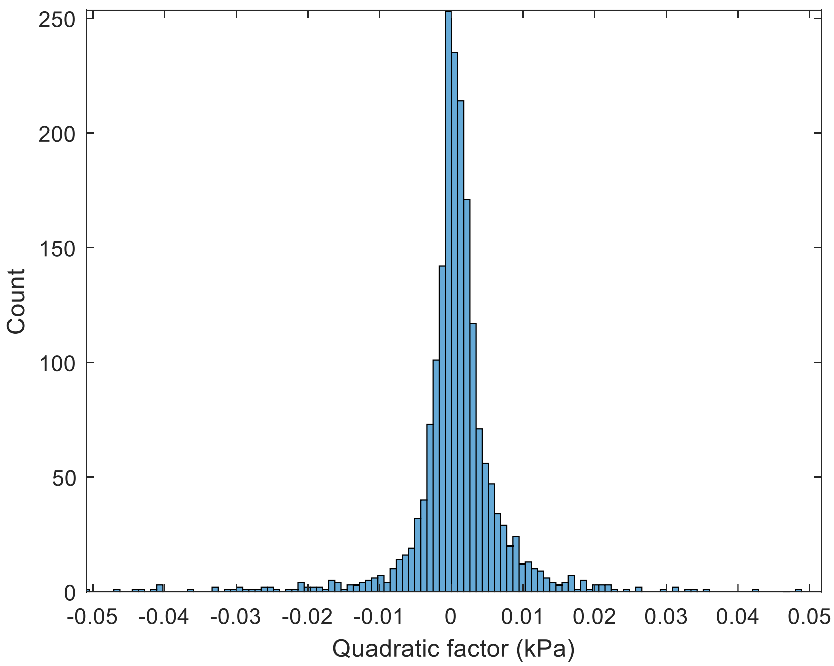

Figure 7: Histogram of quadratic factors, from slab Tekscan sheet in test DYC-06

At the end of this calibration process, three parameters were assigned to each sensel: a Boolean "calibration valid" flag to mark whether a sensel had been rejected as an outlier; and two calibration parameters b_1 and b_2, representing the linear and quadratic scaling factors respectively.

5.2 Calibration of Tekscan movies

During continuous data-logging in a centrifuge test, the Tekscan data acquisition system produces "movies" of measurements. Each movie can be divided into individual frames, with pressure readings (in raw units from 0 to 255) for each sensel, a timestamp for each frame, and other metadata such as the sensitivity setting of the data acquisition system. These movies were exported via a comma-separated values (CSV) document to Matlab, where the raw sensel readings and the timestamps of each frame were extracted for further processing. The raw sensel readings form a three-dimensional array (two spatial coordinates and one time coordinate); the timestamps form a one-dimensional array.

For each sensel and each frame, the raw measurements were converted to pressure readings in kPa:

- For all sensels marked as outliers ("calibration valid" is false), replace the reading with NaN;
- Then calculate the calibrated pressure readings using the calibration factors specific to each sensel: $\sigma = b_1 x + b_2\, x^2$, where x is the raw Tekscan reading.

The next step was to adjust these calibration factors using the known self-weight of the basement model before excavation. First, a region representing the area on the basement most unaffected by local stress concentrations was identified ("bottom area" in Figure 8). Considering only the chosen region, a graph of the spatial average of contact pressure versus time was plotted (Figure 9).

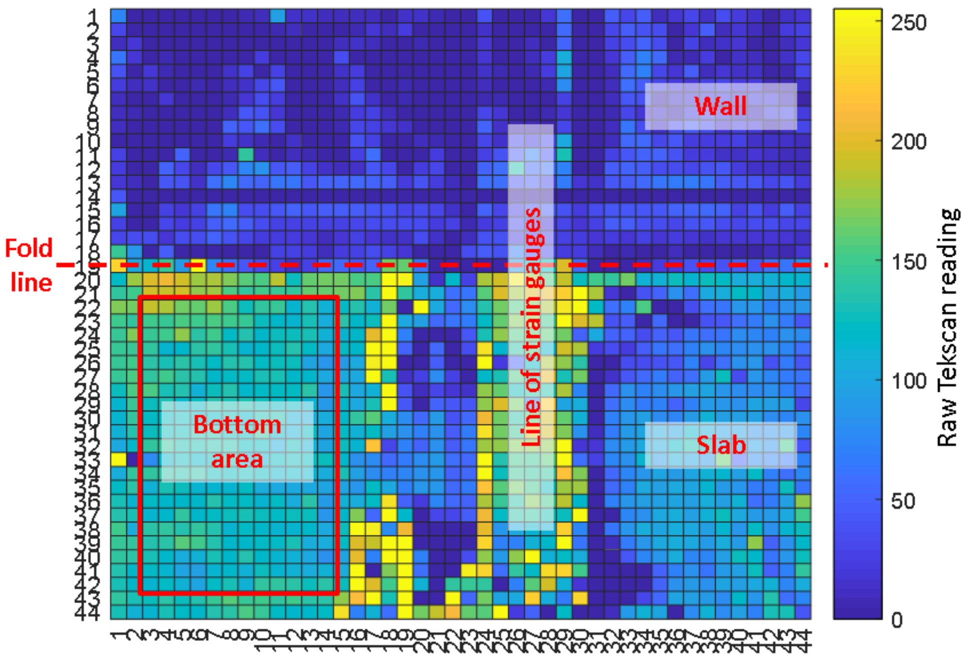

Figure 8: Illustration of the different regions measured by the tactile sensing mat, using the "slab" mat from centrifuge test DYC-06 as an example

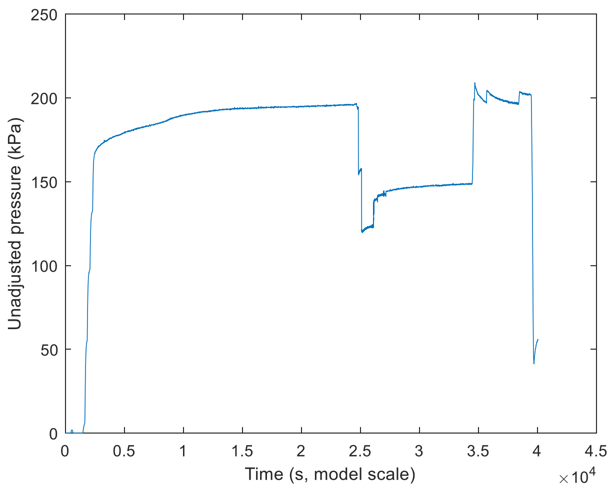

Figure 9: Variation with time of unadjusted pressure readings of slab-soil contact pressure on the non-edge regions, from centrifuge test DYC-06

As shown on Figure 9, there is a long plateau of approximately constant estimated pressure of 195 kPa. At the same time, static equilibrium should imply a contact pressure of 270 kPa (240 kPa of heavy fluid load and 30 kPa of base slab weight). This leads to a "calibration shift" adjustment factor of 1.39, which was multiplied onto all values of pressure obtained by this Tekscan sheet in this centrifuge test (Figure

10). This factor accounts for the differences in behaviour caused by centrifugal gravity and the effects of soil contact on one side of the tactile sensing mat.

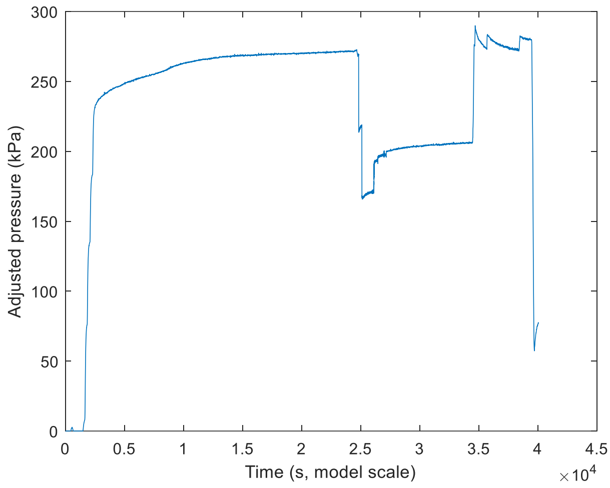

Figure 10: Adjusted average slab-soil contact pressure, centrifuge test DYC-06

The same method of adjustment was applied to all Tekscan sheets used to measure slab-soil contact pressure and the calibration shift factors are tabulated in Table 1. The good agreement between the calibration shift factors of tests DYC-04 and DYC-05, which used the same Tekscan sheet at the same settings on two different metal slab–sand interfaces, gave confidence to the reliability of this approach.

Table 1: Calibration shift values and sensitivity settings

Experiment and sheet	Contact conditions	Sensitivity setting	Calibration shift factor	Comments
DYC-03	Slab-sand	S-40	3.414	Old Tekscan sheet, different sensitivity settings
DYC-04	Slab-sand	S-36	1.597	
DYC-05	Slab-sand	S-36	1.556	S-29 also attempted but results were not used
DYC-06 “Clayton”	Slab-clay	S-36	1.387	
DYC-06 “Sandy”	Wall-sand	S-36	(1.576)	
DYC-07	Wall-sand	S-36	(1.576)	

In two cases, the calibration of the Tekscan sheets could not have been adjusted using in-flight data, because those sheets only measured horizontal stresses behind walls. Nevertheless, given the agreement between the calibration shift factors from centrifuge tests DYC-04 and DYC-05 where the Tekscan sheet also had metal on one side and sand on the other side, it would be reasonable to use the average of those two calibration shift factors for the wall Tekscan sheets.

The process of converting raw Tekscan readings into pressure estimates can be summarised in the following equation:

$$\sigma = c(b_1 x + b_2\, x^2)$$

Where c is a calibration shift constant that is assumed to be uniform over a Tekscan sheet, b_1 and b_2 are sensel-specific calibration factors, and x is the raw Tekscan reading.

5.3 Data visualisation

The final step of the calibration process is to apply suitable smoothing to the data and report the results. Smoothing is needed because of inherent variabilities in the calibration process and in the effect of granular contact. Tekscan (2003) recommended that readings from individual sensels should not be reported in isolation, but rather be reported as averages of 2×2 or larger grids. The data can also be filtered along the time axis by taking the average of multiple frames to ameliorate any electrical noise.

To obtain a plot of contact pressure variation along a section at a certain point in time, a representative strip of M sensels wide ($M \geq 3$) would be chosen (Figure 11). A three-dimensional average is taken, such that each point in the reported data is an average over an M × 3 grid of sensels over 10 frames. Sensels with rejected calibration values would have their data rejected, and the data point reported at that location would be the average of measurements from valid sensels within the averaging area. (Figure 12)

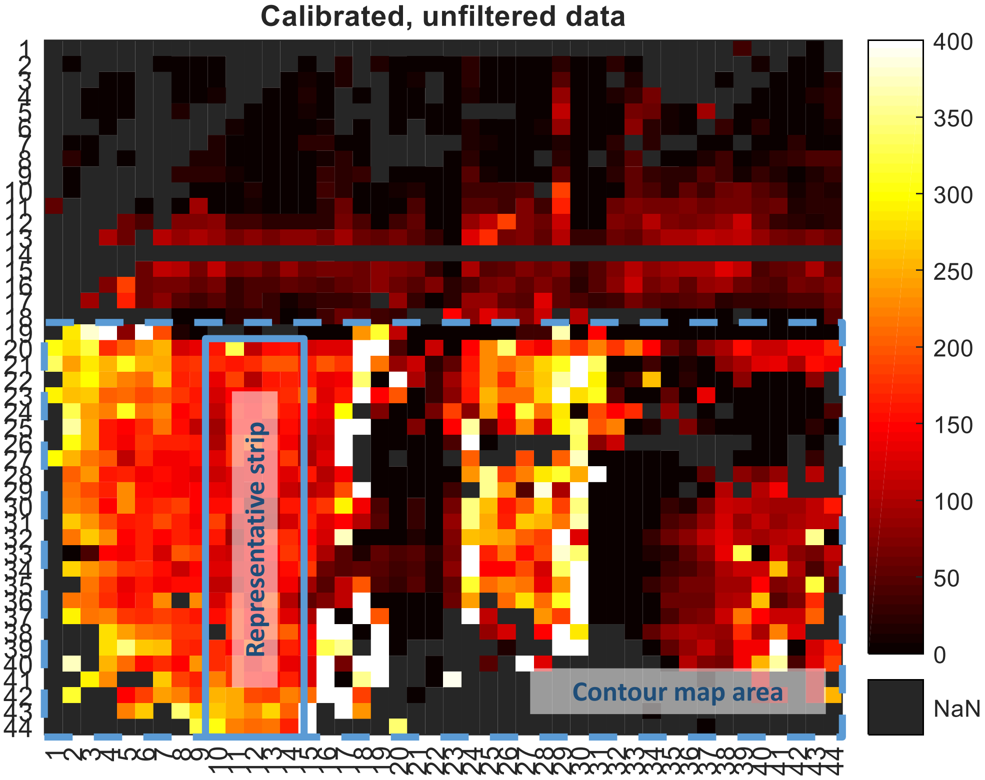

Figure 11: Calibrated, unfiltered heat map plot of data from equilibrium slab-soil contact pressure in centrifuge test DYC-06, to illustrate the process of filtering and contouring

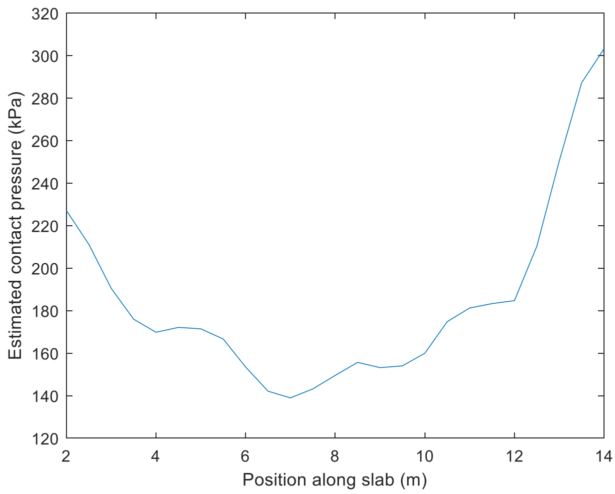

Figure 12: Plot of filtered pressure data along a representative strip

To obtain a contour map of pressure, an area on a Tekscan sheet is chosen (Figure 11). Within the chosen area, sensel readings are averaged locally in a 3 × 3 grid and in time over 10 frames (Figure 13). The Matlab functions `fillgaps` and `contourf` are then used to generate a smoothened contour map (Figure 14).

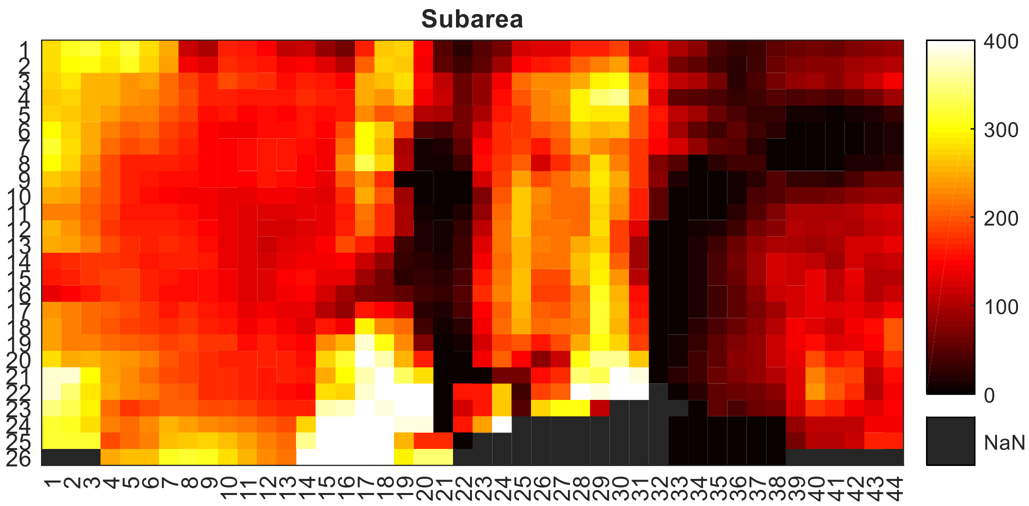

Figure 13: Filtered data for slab-soil contact pressure, extracted by filtering the data in Figure 11

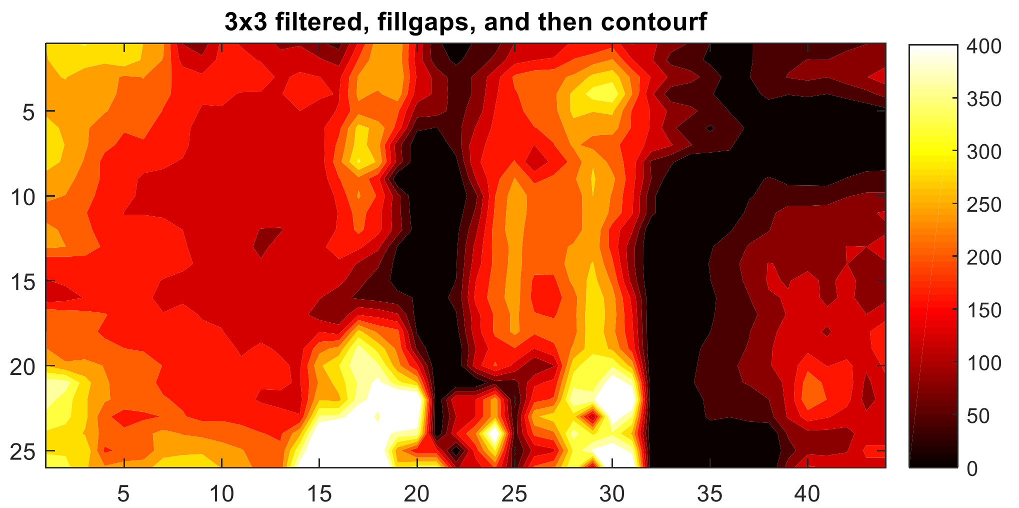

Figure 14: Contour plot of slab-soil contact pressure

6 Summary

According to previous research, the use of Tekscan tactile pressure mats in geotechnical centrifuge testing should require two stages of sensor calibration. First, each sensor should be subject to a range of known loads outside the centrifuge to obtain calibration factors for each sensel. Second, the in-flight readings should be cross-checked with another in-flight measurement of pressure.

The Tekscan sensors in the basement heave research project were waterproofed using an office lamination machine. Each sensor was then calibrated using the Enerpac hydraulic piston in Schofield Centre. A quadratic calibration curve was obtained for each sensel, giving independent calibration factors for each sensel. Outliers sensels were ignored in subsequent data processing.

The self-weight of the basement slab and heavy fluid during the in-flight consolidation stage of the centrifuge test was used as a cross-check for the calibration of each sensel. This generated a calibration shift factor per Tekscan mat per centrifuge test, which was used to adjust the estimates of pressure. This accounts for the effect of granular contact and centrifuge gravity on the sensitivity of the sensors.

The calibrated Tekscan data was filtered by taking local averages in both space and time. The results were visualised in graphs of pressure versus position, pressure versus time, and heat maps of pressure.

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