TACTILE PRESSURE SENSOR CALIBRATION METHODS AND DATA ANALYSIS FOR GEOTECHNICAL CENTRIFUGE MODELING

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Tactile Pressure Sensor Calibration Methods and Data Analysis for Geotechnical Centrifuge Modeling

Thesis directed by Assistant Professor Shideh Dashti

ABSTRACT

When investigating the seismic response of buried structures in geotechnical experiments, a reliable measure of dynamic earth pressure is necessary. Tactile pressure sensors are flexible, thin sheets containing a matrix of sensels (sensors), allowing them to measure pressure distributions with minimal intrusion and avoid soil arching effects. Each of the sensor's sensels can record pressure at high sampling rates (e.g., up to 20,000 samples/second).

Calibrating tactile pressure sensors for use in dynamic centrifuge modeling with granular materials has been challenging in the past. In particular, they have been unable to capture the full amplitude content of a dynamic signal at high frequencies. This is due to the low sampling rate of older sensor models (leading to signal aliasing) and the sensor's own frequency response. In this thesis, a dynamic calibration procedure is proposed and evaluated to correct for the tactile sensor's frequency response. Further, different static calibration procedures are compared and evaluated in this study.

The dynamic response of tactile pressure sensors was characterized by loading them with sine-waves of different frequencies using a controlled loading machine at the University of Colorado, Boulder. A transfer function was calculated to relate the pressure sensor's signal to the reference load cell recording as a function of frequency. A digital filter was developed based on this transfer function and applied to pressure sensor recordings to recover the original, high frequency signal. The reliability of the proposed dynamic calibration procedure was then tested through a series of blind dynamic tests with the loading machine and dynamic centrifuge tests with water.

Two methods of static calibration were explored and compared in this study: (1) loading of the sensor with a controlled loading machine; and (2) placing the sensor at the bottom of a centrifuge container covered with the test sand and spun to different g-levels. Calibration results from each method were applied to sensor recordings of static lateral earth pressure on a tunnel wall during a centrifuge model test. For the particular tactile sensor tested here, static calibration with the loading machine yielded better comparisons with theoretical estimates of lateral earth pressure.

To my mom, Betsy.

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When I left New Orleans after rebuilding houses destroyed by Hurricane Katrica, I left with a desire to develop a skill that would help prevent such disasters. Looking back over the last couple years, I feel that my Master's degree has given me those skills, but I know that I could not have done it alone. I've been fortunate to be surrounded by people from a young age that have empowered me through their support. These people have had a positive impact on my life and have instilled a confidence that has made it possible to pursue my goal of completing a Master's degree in engineering. My acknowledgments here do not contain everyone I am thankful to, but I'm sure you know who you are.

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1. INTRODUCTION

1.1 Overview

Physical centrifuge modeling is an effective tool commonly used by geotechnical engineers to gain insight into the underlying mechanisms of realistic confining pressures and to validate numerical models. When investigating the seismic response of buried structures, retaining structures, or basement walls, a reliable measure of dynamic earth pressures is necessary. Obtaining reliable measurements with pressure cells has been challenging in the past due to soil arching effects, where soil displaces differently near a relatively stiff pressure cell than it would naturally (Filz and Brandon 1994). Tactile pressure sensors are flexible, thin sheets containing a matrix of sensels (sensors), each capable of measuring pressure at high sampling rates (as high as 20,000 Hz per sensel). The flexible and thin nature of these sensors allows them to measure pressure distributions with minimal intrusion and avoid soil arching effects. High sampling rates are necessary to capture dynamic earth pressures in the high frequency environment of the centrifuge.

Although tactile pressure sensors have been successful measuring pressures in static and 1-g shake table tests, they have previously not been reliable in capturing the full amplitude content of a dynamic signal. This is partially due to signal aliasing, which occurs when a signal is not accurately measured due to a slow sampling rate. Typically, a signal needs to be sampled at least twice as fast as the highest frequency, in order to avoid aliasing. For earthquake engineering applications, frequencies up to approximately 15 to 20 Hz in the prototype scale are of main concern typically. When multiplied by the g-level of the centrifuge during testing due to scaling relationships, this translates to 15 x 70 Hz (=1050 Hz) in the model scale. To measure this range of frequency in the model scale without signal aliasing, sensors must be capable of sampling at least twice as fast (2100 Hz).

A new type of tactile pressure sensor produced by Tekscan capable of sampling at up to 4,000 Hz was employed to avoid problems associated with aliasing. However, unreliable dynamic measurements are also due to the tactile sensor's own frequency response. As a result, a series of dynamic experiments were performed to characterize the frequency response of the sensors. Constant amplitude, sine-sweep loads were applied to the sensor with a materials testing machine to characterize its frequency response (in terms of amplitude modification). The identified pattern in their frequency response (i.e., filter) was used to recover the input signal of interest (i.e., pressure time history). Then, a series of blind tests were performed to validate the quality of the filter. These tests were followed by dynamic centrifuge experiments using water with a range of input motions that contained energy at higher frequencies to further validate the reliability of the filter.

In addition to dynamic calibration, basic static calibration of these sensors when used with granular materials has led to significant uncertainties in the past. Some researchers calibrate tactile sensors using a pneumatic air bladder device with a urethane–sensor–aluminum interface, while others use the centrifuge with soil–Teflon sheeting-sensor–aluminum interface. Optimal static calibration techniques were investigated for use with granular materials by comparing the performance of various methods.

The testing methodology used to characterize the frequency response of tactile pressure sensors, the accuracy of which was evaluated through a series of blind dynamic tests with a loading machine and the centrifuge is presented. Also, a recommended general, static calibration procedure is outlined and justified by comparing test results of different procedures. Overall, this thesis presents a guideline for the calibration of tactile pressure sensors prior to use in geotechnical centrifuge experiments.

1.2 Organization of this Thesis

Following the introduction of this thesis (Section 1), Section 2, the literature review will present the work of previous researchers focused on the geotechnical engineering research applications of Tekscan tactile pressure sensors. Section 3 describes the Teskcan tactile pressure system; details related to the components of the system, the sensors, and the operation software are provided. Section 4 of this thesis will explain the methods used to develop a dynamic calibration used to correct high frequency measurements of the pressure sensors. This section will also present the results from tests used to verify the effectiveness of the dynamic calibration. Static calibration methods and results are described in Section 5. The final section (Section 6) summarizes static and dynamic calibration methods and results.

2. LITERATURE REVIEW

2.1 Paikowsky and Hajduk (1997)

A number of researchers have previously used Tekscan tactile pressure sensors in geotechnical engineering research applications. Paikowsky and Hajduk (1997) performed a pioneering series of tests that examined loading rate, hysteresis, and creep effects of the Tekscan 5075 tactile pressure sensor in order to calibrate it for use in geotechnical engineering applications. Hysteresis effects of the sensor were studied by loading and unloading sensors at various rates. Hysteresis is the difference in the sensor's recording for a loading and unloading trial back to the same pressure. Loading of the tactile pressure sensor was done with an air bladder device developed by Paikowsky and Hajduk (1997) (Figure 2.1). The sensor was loaded at various rates to a maximum pressure, and then unloaded at the same rates back to the initial pressure. The initial stage of unloading showed a slow response followed by a linear and then asymptotic phase below 50kPa due to high resistivity values at low pressure ranges. These results are presented in Figure 2.2a.

Creep can be described by the drift in sensor response under a steady load. Their study determined that post-loading creep was a function of the load rate and magnitude, and that two distinct zones of post loading response exist: (1) a rate dependent, non-linear response within the first 30 minutes of loading; and (2) a linear response that does not appear to depend on loading rate. Figure 2.2b. shows the sensor's post loading creep response and the different zones of behavior. Creep was also shown to depend on the magnitude of the load applied.

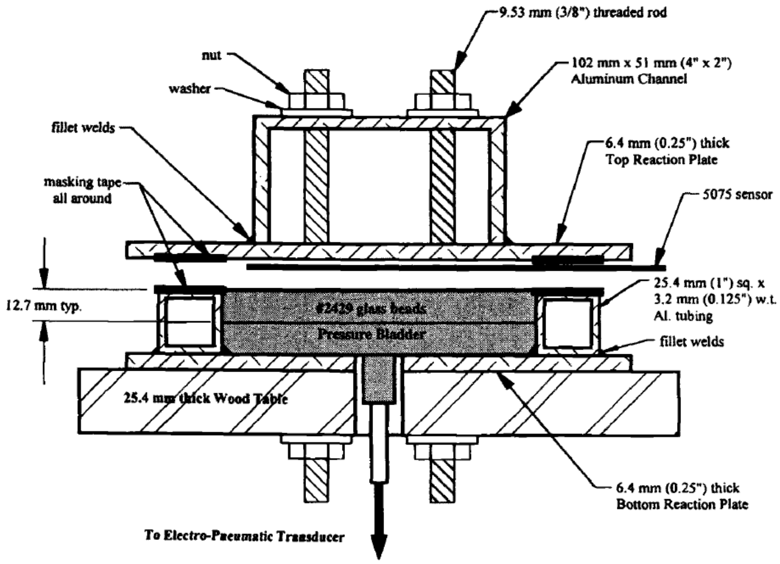

Figure 2.1. Cross section view of the pressure sensor calibration device (Paikowsky and Hajduk 1997).

A B

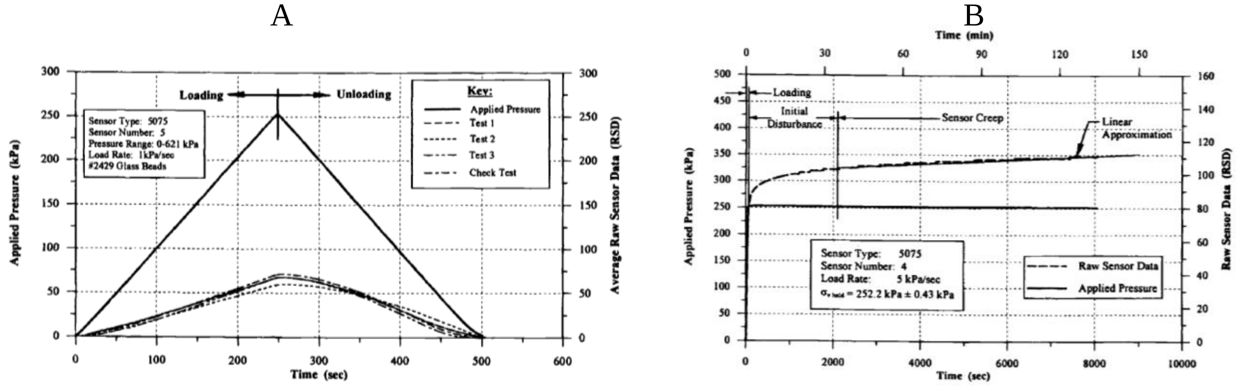

Figure 2.2. (a) Loading and unloading response; (b) post loading creep results.

Paikowsky and Hajduk (1997) initially attempted to calibrate tactile pressure sensors between a reaction plate and an air bladder, but found this method to result in unacceptable performance for several reasons: (1) the sensor was sensitive to imperfections in the reaction plate; (2) the sensor was sensitive to lateral and vertical stretching of the air bladder during pressure application; (3) blockage of small air ducts in the sensor caused inconsistent response in the sensor. Paikowsky and Hajduk (1997) avoided these issues by using glass beads as part of their calibration process.

Glass beads were used to simulate an interface condition similar to granular material used in actual testing. The glass beads were placed between the air bladder of the calibration device shown in Figure 2.1 and the sensor, with the reaction plate placed on the back side of the sensor. The glass beads tested had a D50 of 0.1mm. It was estimated that roughly 100 beads would occupy the area of each sensel on the sensor. Figure 2.3 exhibits the size of the glass beads relative to the size of each sensel.

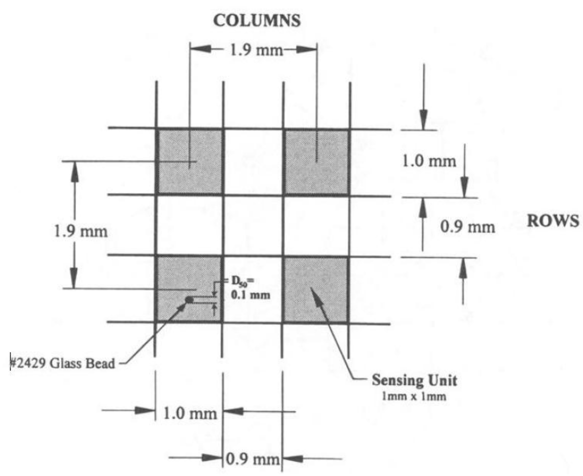

Figure 2.3. Glass bead size relative to an individual sensel size (Paikowsky and Hajduk 1997).

Paikowsky and Hajduk (1997) calibrated the pressure sensors by loading them at different constant rates. The sensor was shown to exhibit a nonlinear response below approximately 50 kPa of applied load, which they attributed to high sensel resistance values at close to zero loading. The 5075 sensor showed a linear response after loading surpassed 50 kPa. These results are shown in Figure 2.4. They found that in general, sensor error was greater than ± 10% when the sensor is loaded at less than 15% of the sensor's capacity, and reduces to less than ± 10% above this level. Calibration was calculated by taking a best fit through the pressure sensor loading data. Typically, the best fit line does not pass through zero due to the non-linear response of the sensor below 50 kPa of loading shown in Figure 2.4. The solid line represents the applied pressure, and the dashed line with an initial negative value, is the best fit line of the pressure sensor data. The sensor's linear calibration equation used in this study was:

$$Pressure\ (kPa) = K_{NC} * (RSD - b) \tag{2.1}$$

where "K_{NC}" is the static calibration factor calculated by dividing the slope of the applied pressure by the slope of the best fit line representing the pressure sensor response, "RSD" is the averaged raw sensor data, and "b" is the offset value shown in Figure 2.4 (created by the nonlinear response of the sensor idealized as linear). It was observed that the K_{NC} factor varied within a small range and was not influenced much by loading rate. The offset term, b, did not seem to follow any trend when plotted against loading rate and was generally inconsistent.

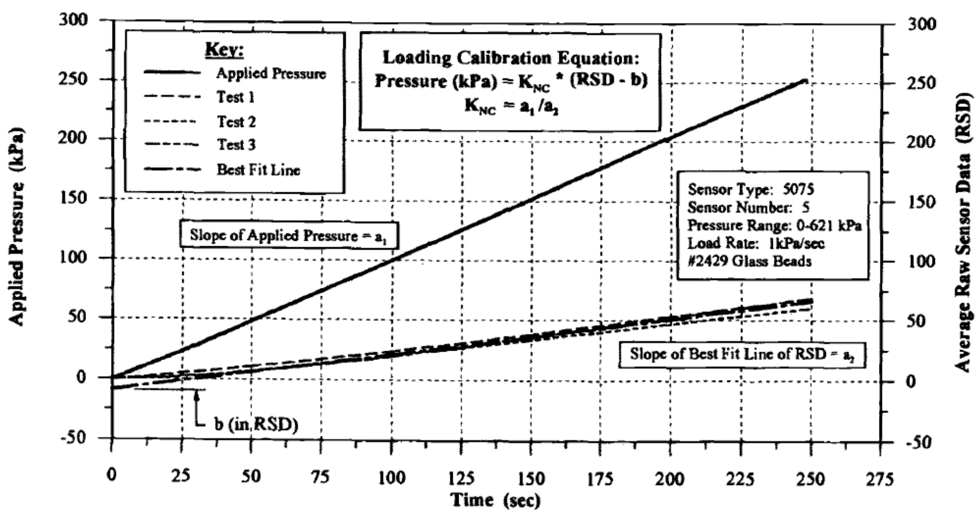

Figure 2.4. Calibration test results

2.2 Springman et al. (2002)

Springman et al. (2002) summarized the use of tactile pressure sensors at the Swiss Federal Institute of Technology (ETH) during the early 2000's. In this work, the pressure sensors measured the distribution of soil stresses beneath a circular footing in a centrifuge at 50 g of spin acceleration. Further, they investigated the impact loading response of the tactile pressure sensors by mimicking rock falls on the roof of a protection structure at 1g. These impact tests were performed using a rubber hammer, and a cylindrical piece of rock weighing 1.5 kg dropped from heights ranging between 0.25 to 1 m.

As a simple first calibration, Springman et al. (2002) proposed placing 0.1 mm thick pieces of rubber above and below the sensor and then stacking two polished aluminum plates with dimensions of 56 mm x 56 mm x 20 mm on top of the sensor, resting on the upper rubber piece (as shown in Figure 2.5). If unsuccessful, they planned to calibrate with an air bladder and sand similar to the process used by Paikowsky and Hajduk (1997).

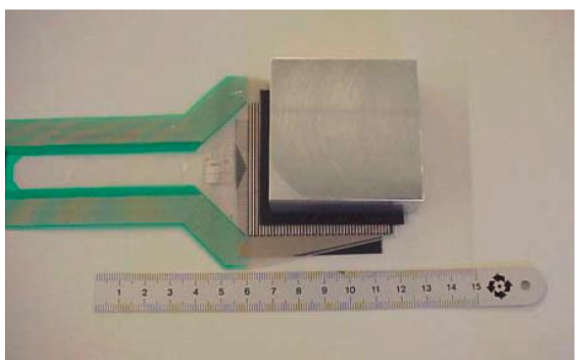

Figure 2.5. Springman et al. (2002) proposed calibration setup. Springman (2002).

2.3 Palmer et al (2009)

Palmer et al. (2009) investigated methods to reduce the effects of shear stress on the tactile pressure sensor recordings using different materials. Time-dependent characteristics of these sensors were also studied by looking into creep effects. Palmer et al. (2009) suggest that the sensors are advantageous in geotechnical physical modeling over soil stress cells because of their flexibility and geometry, but that the sensor does have limitations due to their construction and material properties. For example, shear stress can cause relative slip between the two polymeric sheets that make up the sensor and affect registered voltages. Also, the polymers used to construct the sensor have their own viscoelastic response that require a better understanding before the sensor can be properly calibrated and test data is interpreted.

Palmer et al. (2009) calibrated the Tekscan tactile pressure sensors by following steps outlined by the manufacturer. They used a pneumatic device that applies air pressure by means of a urethane air bladder to “condition” and “equilibrate” sensors before calibration. The pneumatic device loads the sensor by placing a reaction plate on one side of the sensor and inflating a urethane bladder with a known air pressure against the other side. Conditioning means that the sensor is repeatedly loaded to or beyond the maximum expected load of testing. This process helps reduce hysteresis and creep effects in the sensor’s response. Equilibration requires loading the sensor uniformly, so that each individual sensing element of the sensor may be set to an equal gain.

Results of how various materials performed to reduce shear effects of the sensor are shown in Table 2.1. Two Teflon sheets placed between the sensor and the shearing surface worked best to reduce shear effects of the sensor. Figure 2.6 compares the results of direct simple shear tests performed on the sensor with different interface materials. The ratio of applied shear to normal stress is presented in the top row for two different materials. The bottom row presents the ratio of measured to applied normal stress. The LDPE-sensor interface showed a reduction in this ratio around a shear displacement of around 0.4 mm. The Teflon sheet-Teflon sheet-sensor interface appeared to sustain a more steady normal stress measurement through shearing when compared to the LDPE-sensor interface.

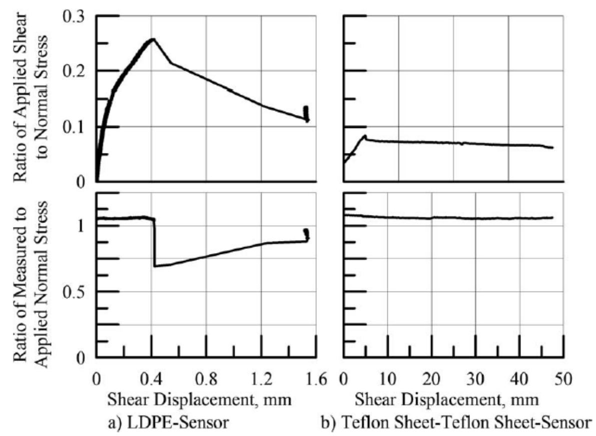

Figure 2.6. Top Row: The ratio of applied shear stress to normal stress for two different materials. Bottom Row: The ratio of measured to applied normal stress versus displacement for two different materials.

Table 2.1. Shear test results for different materials.

Horizontal test layers	Number of tests	Observed response
Single 0.5-mm-thick sheet of LDPE	10	27–41% reduction in measured normal force during shear
0.5-mm-thick sheet of LDPE underlying a 6-mm-thick sheet of rubber	1	13% reduction in measured normal force
Two 0.5-mm-thick sheets of LDPE	4	29–35% reduction in measured normal force during shear
Two 0.5-mm-thick sheets of LDPE with Teflon spray lubricant between the sheets	8	2% reduction in measured normal force during shear, accompanied by increased shear effects over time
0.5-mm-thick sheet of LDPE overlying a 0.5-mm sheet of Teflon	2	27–41% reduction in measured normal force during shear
Two 0.5-mm-thick sheets of Teflon	2	2% reduction in measured normal force during shear

2.4 Tessari et al (2010)

Tessari et al. (2010) performed centrifuge experiments at Rensselaer Polytechnic Institute (RPI) using Tekscan tactile pressure sensors. They recommend first laminating the sensors for use in a water environment to avoid damage, as these sensors are not water-proof. A small hole is then placed at the electrical connection so that any trapped air in the sensor can escape and not influence the recordings. Tessari et al. (2010) used an air bladder system similar to Palmer et al.

(2009) to “condition” and “equilibrate” sensors. They also placed Teflon sheeting between the sensor and the air bladder device to reduce shear stress accumulation that may reduce the normal stress readings (Palmer 2009).

Tessari et al. (2010) calibrated the tactile sensors by placing them at the bottom of a centrifuge container overlain by the soil to be used in actual testing. Each sensor was calibrated at two points corresponding to the anticipated load range in the experiment. Tessari et al. (2010) note that calibration accuracy is improved by calibrating the sensor in a narrow range corresponding to expected test pressures. Different overburden pressures were produced by spinning the centrifuge to different g-levels. They indicated that this calibration method leads to more reliable static pressure measurements in granular materials when compared with results calibrated using an air bladder device. The pressure sensors were attached to the sides of the centrifuge container to test this hypothesis. Figure 2.7 compares lateral earth pressure measurements of the tactile sensor calibrated using the centrifuge and air bladder methods. Measurements calibrated using the centrifuge method revealed a lateral stress distribution increasing with depth corresponding closely to a theoretical distribution assuming a $K_0 \approx 0.38$. This comparison shows the importance of using the test-specific soil and boundary conditions for the static calibration of tactile sensors.

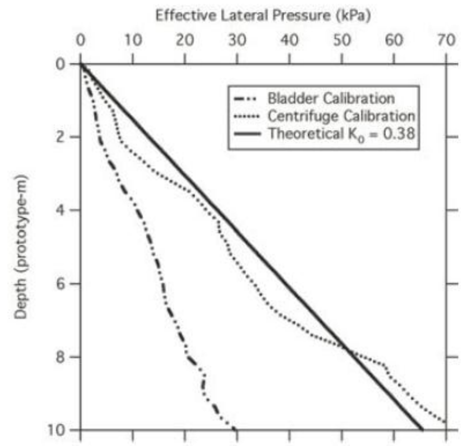

Figure 2.7. Test results using the air bladder calibration and the centrifuge calibration.

2.5 Olson et al. (2011)

Olson et al. (2011) employed Tekscan sensors to record seismic earth pressures on model foundations for large bridges in a series of centrifuge tests at the Rensselaer Polytechnic Institute (RPI). Pressure sensors were calibrated in a centrifuge experiment performed with water. Although the team had success accurately recording hydrostatic pressures, the tactile pressure sensors captured roughly only 50% of the dynamic amplitude of pressures recorded by pore pressure transducers (PPTs) also present in the test (Figure 2.8). They concluded that these sensors cannot reliably measure dynamic variations in pressure in high-frequency environments like the centrifuge, but can reliably measure static earth pressures if properly calibrated.

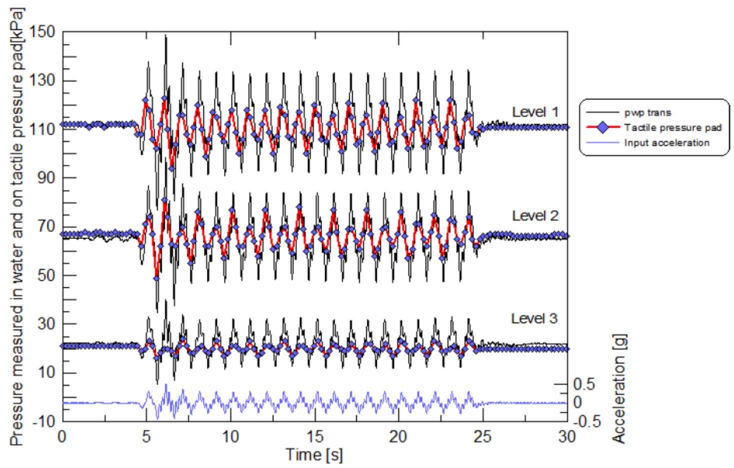

Figure 2.8. Dynamic pressure sensors response compared to reference pore water pressure transducer at three different elevations.

2.6 Summary

All of the previous researchers provided important insight into the tactile pressure sensor's performance and response to different calibration processes, interface materials, gravity fields, and loading scenarios. Paikowsky and Hajduk (1997) were instrumental in initially understanding properties related to creep, loading rate, and hysteresis of the sensor. Springman et al. (2002) and Olson et al. (2011) proved that the Tekscan system can operate under increased gravity fields. Palmer et al. (2009) helped quantify how different materials reduce the shear effects of the sensors. Tessari et al. (2010) demonstrated an effective method of calibrating the Tekscan sensors for use with granular material in the centrifuge and Olson et al. (2011) performed dynamic centrifuge testing that exhibited the inability of the Tekscan tactile pressure sensors to fully capture dynamic behavior. To build on the work of previous researchers, this thesis aims to: (1) summarize work aimed to characterize the frequency response of the sensor so that high frequency content can be accurately represented by Tekscan pressure sensors, and (2) investigate the effectiveness of two distinct calibration methods.

3. TEKSCAN TACTILE PRESSURE SENSOR SYSTEM DESCRIPTION

3.1 Overview

The tactile pressure sensor system manufactured by Tekscan Inc. is comprised of a pressure sensor, “handle”, and data acquisition hub. The “handle” clamps onto the sensor to send data to the hub, which is connected to a computer. These components make up the VersaTek line from Tekscan. The Tekscan software, I-Scan is used to specify data acquisition parameters, visualize data, and save data among other features. Figure 3.1 shows the components that make up the Tekscan system.

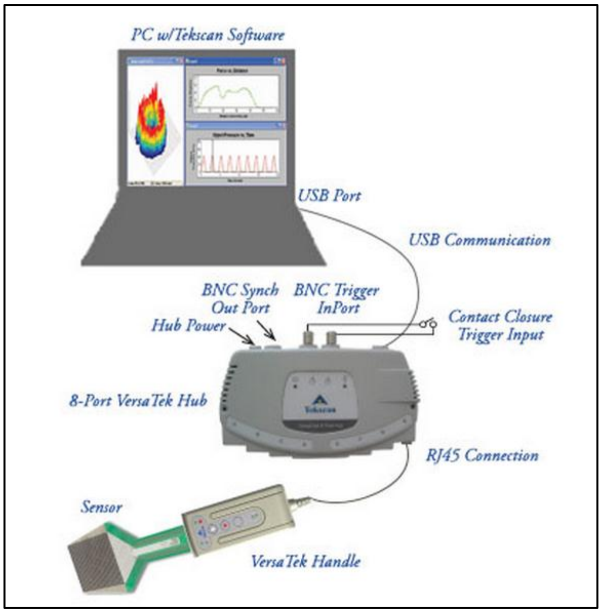

Figure 3.1. Tekscan system components. (Tekscan Inc.)

3.2 Tekscan Pressure Sensors

Tekscan sensor construction begins with printing conductive ink onto two polymeric sheets. One sheet receives a pattern of rows and the other a pattern of columns. A layer of adhesive and dielectric are put on the sensor so that conductive traces do not short-circuit. A patented semi-conductive ink is then printed onto the existing row and column patterns of each sheet. Lastly, the two sheets are laminated together. Each intersection of the printed ink rows and columns creates a sensing element known as a "sensel". Tekscan pressure sensors can contain thousands of sensels on a single sensor. When the sensel is loaded, the resistance of the semi conductive ink changes; this change is measured by the system. When sensels are not loaded, they have a high resistance; this resistivity decreases as load on the sensor is applied. Output resistances are converted to raw data units ranging from 0 to 255, which can then be converted to force or pressure units once a calibration factor is calculated. A detailed description of the various Tekscan components and their functions are provided by Paikowsky and Hajduk (1997) and Tekscan (2012).

Tekscan sensor model 9500 was used in this study due to its quick sampling rate, size, and spacing between sensels. The tactile sensor is extremely flexible due to its geometry and construction materials; it measures approximately 0.1 mm in thickness. The sensing matrix is made up of 14 rows and 14 columns of semi-conductive ink making a total of 196 sensels that cover an area of 71.1 by 71.1 mm. The 9500 model sensor (shown in Figure 3.2) has a sampling rate of 4000 Hz per sensel. This implies that during each recording, a matrix of pressure data is recorded by 196 sensels at a maximum rate of 4000 samples per second (sps).

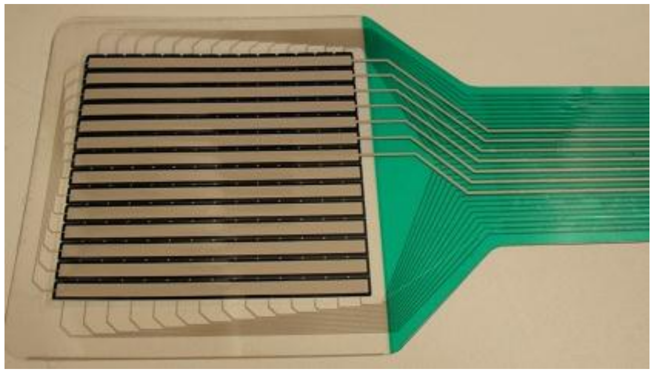

Figure 3.2. Tekscan 9500 tactile pressure sensor.

3.3 Conditioning Sensors

The manufacturer recommends that new sensors or sensors that have not been used for a lengthy period be “conditioned” before they are calibrated (Tekscan 2012). Conditioning involves loading a sensor to approximately 120% of the maximum anticipated testing load three to five times. This process minimizes drift and hysteresis effects in sensor recordings.

3.4 Equilibration

After conditioning has taken place, the manufacturer recommends equilibrating the sensor before calibration is performed. Equilibration is a process that sets all sensels on a sensor to the same gain while a uniform pressure is applied to the sensor surface. Applying a uniform load to the sensor can be difficult due to its extreme sensitivity; therefore Tekscan has built an equilibration device with a urethane bladder that applies uniform pressure by filling with air. Figure 3.3 shows a diagram of the air bladder device. In general, equilibration may correct for the small variations in sensel sensitivity due to the construction process for new sensors or changes in sensel sensitivities due to repeated use or age of the sensor. The equilibration process is unique to each sensor and is performed using Tekscan’s I-Scan software.

Equilibration may be performed at one or multiple loading points. Using more equilibration loading points ensures that sensel gains remain more consistent throughout a broad loading range. Air may sometimes get trapped between the two sheets that make up the sensor affecting the measured result. Trapped air may be released by cutting a small hole in between traces on the sensor. The manufacturer also recommends running multiple tests and taking an average if air is believed to be trapped in the sensor.

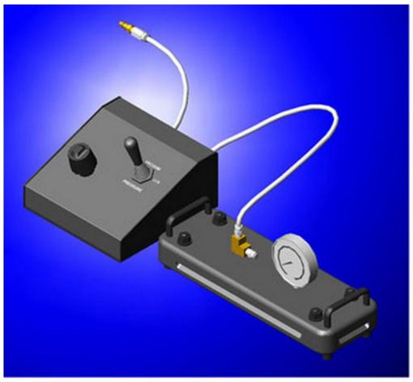

Figure 3.3. Air bladder device for loading the sensor uniformly. (Tekscan Inc.)

3.5 Calibration

Calibration allows one to convert pressure sensor raw units to engineering units. The manufacturer's software allows users to calibrate pressure sensors using a number of options. The most basic calibration method is a linear, one point calibration; it is performed by loading the sensor with a known quantity. The software then fits a linear calibration function through zero to the applied load. A one point calibration can be sufficiently accurate for tests where the applied load has a limited range. In tests with large load variations, a "2-power law calibration" is recommended. This calibration requires the user to load the sensor with two known loads at 20% and 80% of the expected maximum test load. The software calculates an exponential function that follows the form:

$$y = ax^b \quad (3.1)$$

The variable "y" is the output in engineering pressure units, "a" and "b" are calculated by the software based on the two load points, and "x" is the raw scale data reading.

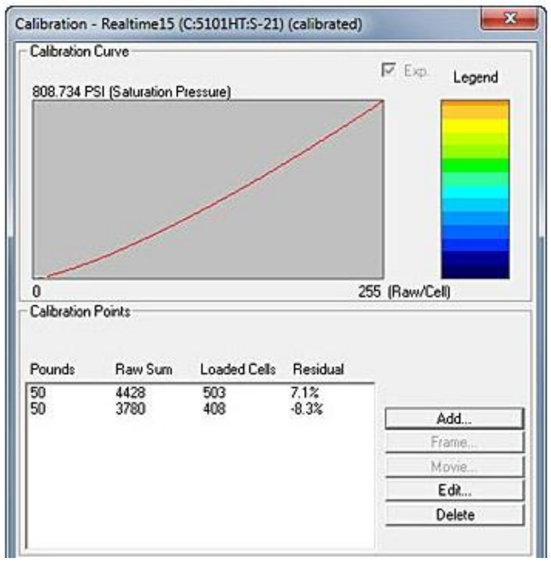

Figure 3.4. I-Scan calibration window showing two load points and calibration curve. (Tekscan Inc.)

The Multi-point calibration is developed in the same way as the 2-point power law calibration, except it makes use of additional points to reduce error when finding parameters "a" and "b". Frame calibration works by using frames from an existing data set to calculate a calibration. Tekscan uses the terms, "frame" and "movie", to refer to a single data point and a complete data set, respectively. Movie calibration is a new calibration feature and allows the user to use every frame from a pressure sensor movie as a calibration point. The user must input a text file containing the load information associated with each frame of the pressure sensor data set. The advantage to movie calibration is that thousands of points may be used to develop the exponential calibration equation. All calibration methods, with the exception of the linear, one point calibration, follow the form, $y = ax^b$. The obtained calibration factors may be applied to data sets prior to or after testing is complete.

3.6 Sensitivity Adjustment

Before testing, sensitivity of tactile pressure sensors may be adjusted through Tekscan's I-Scan software. Sensitivity adjustment allows the user to adjust the pressure limits of what can be measured with a sensor and fine tune the range for a specific test. At the extreme ends of sensitivity adjustment, a sensor can be made to be about three times more or less sensitive. For example, a 100 psi rated pressure sensor can be made to behave as a 33 psi sensor or a 300 psi sensor. By increasing the sensitivity, a sensor will lose the ability to measure a wide range of pressures, but will gain a finer resolution of measurement; the opposite is true if the sensitivity is decreased.

The resolution of pressure sensor measurements change when the sensitivity is adjusted. This is because as sensitivity settings change, the range of pressures the sensor can measure will change, but the sensor's digital output is fixed from zero to 255. For instance, if the sensitivity of a sensor is increased to the point that a 100 psi sensor behaves as a 33psi sensor, one will be able to measure a change of 33 psi/ 255, whereas if the sensor's sensitivity was decreased, so it behaved as a 300 psi sensor, the resolution would be 300 psi/ 255.

3.7 Data Acquisition and Review

Before a test, the sampling rate and the duration of a recording are adjusted using the I-Scan software. Triggering data recording to begin when another process begins is also possible. Pressure sensor test data can be reviewed after a test is complete in a number of ways. The movie files are saved in a “.fsx” format. Tekscan’s software can plot data from the “.fsx” format movies, and has the ability to export the data set as a “.mat” file that can be opened using Matlab.

4. PRESSURE SENSOR DYNAMIC CALIBRATION

4.1 Overview

The tactile pressure sensor system requires a two-part calibration for geotechnical centrifuge testing: static and dynamic. Static calibration converts tactile pressure sensor raw units into engineering pressure units, which is detailed in the following section. By characterizing how the sensor records load over a range of frequencies, a frequency-dependent filter may be developed to compensate for the loss of pressure amplitude at higher frequencies that was observed by Olson et al. (2011). We refer to the development and application of this filter to tactile pressure sensor recordings as the dynamic calibration. Figure 4.1 shows our recommended two part calibration procedure for tactile pressure sensors, assuming that the sampling rate is fast enough to avoid signal aliasing. The order in which these calibrations are applied does not affect the end result.

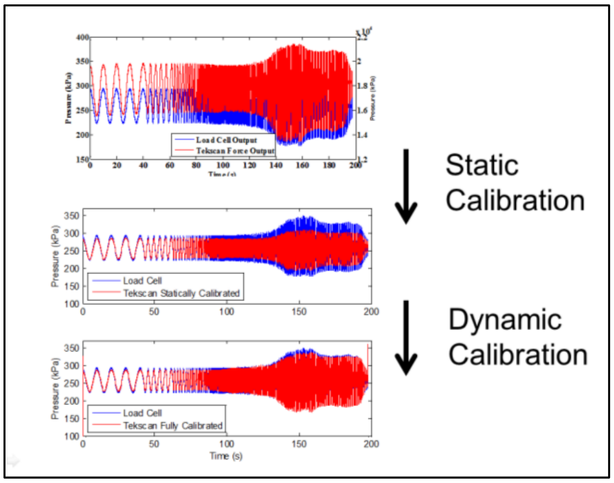

Figure 4.1. Demonstration of our recommended two-part sensor calibration: 1) static calibration to convert raw sensor measurements to pressure units; 2) dynamic calibration to correct for the sensor's frequency response.

4.2 Prior Challenges

4.2.1 Overview

Tactile pressure sensors have been used in geotechnical centrifuge testing by many researchers (e.g., Springman et al. 2002; Al Atik 2008; Tessari et al. 2010; Olson et al. 2011, and Sitar et al. 2012). Olson et al. (2011) used tactile pressure sensors to measure lateral earth pressures on model bridge foundations in the centrifuge. To test the reliability of tactile pressure sensors in capturing dynamic pressure variations, they placed sensors in a centrifuge container filled roughly half way with water, as shown in Figure 4.2. The container was spun with the centrifuge at Rensselaer Polytechnic Institute (RPI) and subject to sinusoidal loading. Figure 4.3 shows how the tactile pressure sensors captured about 50% of the dynamic amplitude that was measured with pore water pressure sensors. They did not observe any phase lag between the tactile pressure sensor and pore water pressure sensor measurements.

Figure 4.2. Centrifuge water tests performed at RPI to calibrate tactile pressure sensors (Olson et al. 2011).

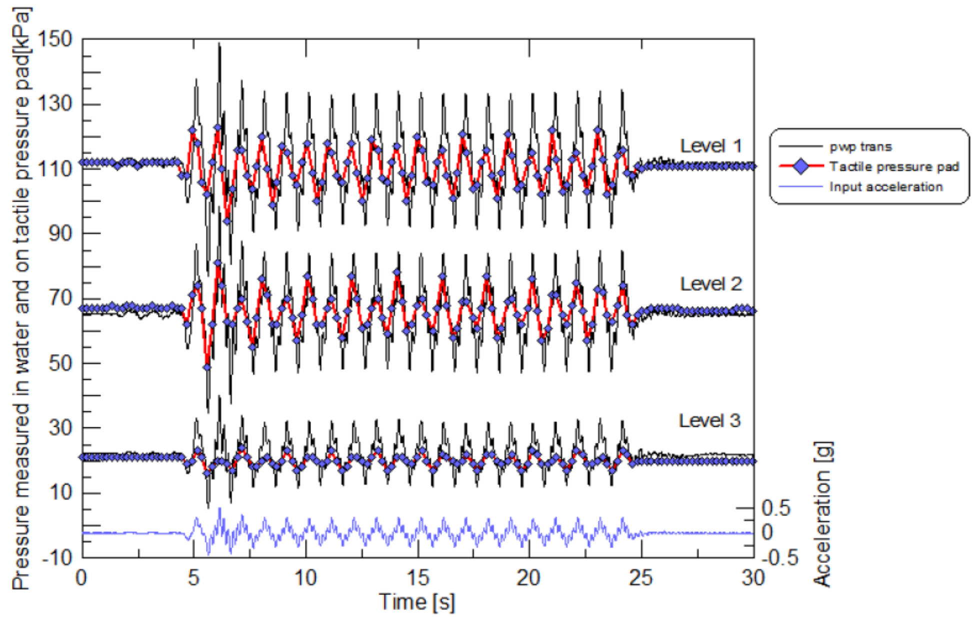

Figure 4.3. Tactile pressure sensor centrifuge water test results measured at three different elevations (Olson et al. 2011).

4.2.2 Causes of Dynamic Signal Underestimation

Dynamic signal underestimation by the tactile pressure sensors may be attributed to two factors. The first factor is signal aliasing, which occurs when an instrument does not sample at least twice as fast as the highest frequency of interest in a signal. The maximum frequency content of concern in earthquake engineering is approximately 20 Hz at 1 g. If spinning the soil specimen in centrifuge to 70 g of acceleration, the maximum model-scale frequency of interest in the data is approximately 1400 Hz (= 20 Hz x 70). Thus, the tactile pressure sensors are required to have a sampling rate greater than 2 x 1400 Hz = 2800 Hz, to avoid signal aliasing. The Tekscan pressure sensor model used in this study (model 9500) has the capability to sample at 4000 Hz on each sensel; hence, problems associated with aliasing observed with older sensor models were avoided.

The other factor contributing to dynamic amplitude underestimation is the time delay in the sensor's response due to its mechanical properties. The sensor may struggle to measure or "feel" high frequency load amplitudes if they are applied and released at a very fast rate. In other words, the sensor behaves similar to a spring; when compressed and unloaded at a high frequency, the full magnitude of the load is unable to transfer to the sensing elements before that load is released or reversed. By characterizing how the sensor records load over a range of frequencies, a transfer function may be developed to compensate for the loss of dynamic content through a range of frequencies.

4.3 Dynamic Calibration

4.3.1 Testing Setup

Materials testing machines are commonly used in mechanical and civil engineering to test the tensile, compressive, or cyclic fatigue properties of materials. Using an Instron loading machine at the Mechanical Engineering Laboratory at the University of Colorado, Boulder (Figure 4.4), a sine-sweep was applied to the sensor to characterize its frequency response. The sine-sweep test was developed in steps using the loading machine software:

1) The sensor was loaded from 0 to 120 lbs in compression.
2) A load-controlled, 20 lb amplitude sine wave with frequency of 1 Hz was applied over 3 cycles.
3) The following steps were identical to the second, but the loading frequency was increased by 1 Hz for each step up to 140 Hz. 20 loading cycles were applied for frequencies greater than 5 Hz.
4) The sensor was unloaded from its offset load of 120 lbs.

The testing setup is shown in Figure 4.5; the sensor is placed between a flat machined steel plate and a wooden block. The wooden block has dimensions of 2 in. by 2 in. and was placed centrally within the roughly 3 in. by 3 in. sensor. A paper towel was placed between the sensor and the wooden block to achieve a more uniform pressures sensor reading. Thin rubber sheets were also placed between the sensor and the wooden block to produce a uniform pressure reading, but this method did not work as well as the paper towel. It is recognized that the initial test set up explained herein does not reflect the soil-metal interface intended for upcoming geotechnical centrifuge tests and that the interface is expected to influence the calibration factor. The influence of different material-sensor interface conditions (e.g., sand and metal) is taken into account by the static calibration.

The Instron model E10000 loading machine used for dynamic calibration tests is capable of applying either force or displacement controlled static and dynamic loads. The maximum frequency of dynamic load the machine can apply to a material depends on the amplitude of that load. For example, a sine-sweep test used to dynamically characterize the sensor had an amplitude equal to 20 lbs and was cleanly produced by the Instron up to a frequency of approximately 50 Hz. For subsequently higher frequency ranges, the loading machine produced sine waves that varied in amplitude. Mostly, the amplitude was overrepresented by the Instron loading machine until it began to decay at approximately 120 Hz. This trend is shown in Figure 4.10 and Figure 4.11, where the applied loads are presented in time and frequency domains, respectively. In early testing, the pressure sensors contained a strong component of noise around 60 Hz. Tekscan Inc. recommended placing a grounding wire from the hub of the data acquisition system to the base platform of the loading machine. This successfully eliminated the noise observed in the recordings. During testing, the loading machine load cell and tactile pressure sensor software simultaneously recorded the applied forces during each test. In all, six sensors were tested either in calibration testing, centrifuge testing, or both. Table 4.1 lists which sensors were used in each type of test. Sensor 1 was used to develop the dynamic calibration described in this section.

Table 4.1. Tactile pressure sensor identification and test information.

		Dynamic Calibration			Static Calibration		Centrifuge Testing
Sensor No.	Capacity (PSI)	Loading Machine Test	Blind Test Series, Loading Machine	Centrifuge Water Test	Loading Machine Test	Centrifuge Test	Model Tunnel Centrifuge Test
1	100	X	X	X			
2	100	X			X	X	X
3	5	X			X	X	X
4	5	X			X	X	X
5	5	X			X	X	X
6	5	X			X		X

Figure 4.4. Instron E10000 machine.
(Instron Inc.)

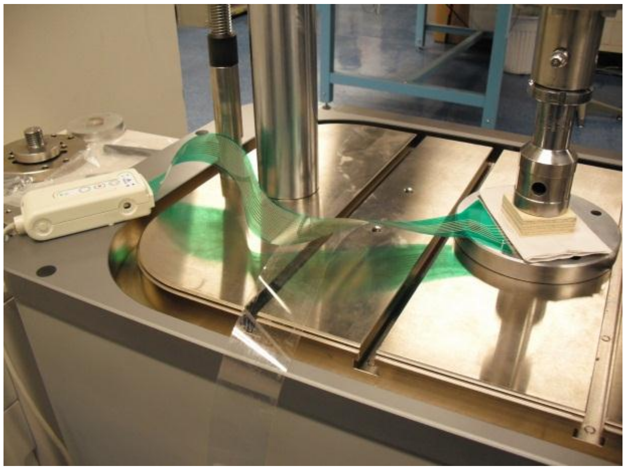

Figure 4.5. Instron loading machine test setup.

4.3.2 Dynamic Loading Machine Test Results

A sine-sweep with frequencies ranging from 1 to 140 Hz at 1Hz intervals and an amplitude of 20 lbs was applied to Sensor 1 using the Instron loading machine, as described in Section 4.3.1. Figure 4.6 compares data obtained from the tactile pressure sensor and the loading machine load cell. Figure 4.7 compares the statically calibrated pressure sensor data (converted to pressure units) with the load cell data on the same axis. The pressure sensor data was statically calibrated by taking the average reading of the pressure sensor and the load cell to calculate a static calibration factor.

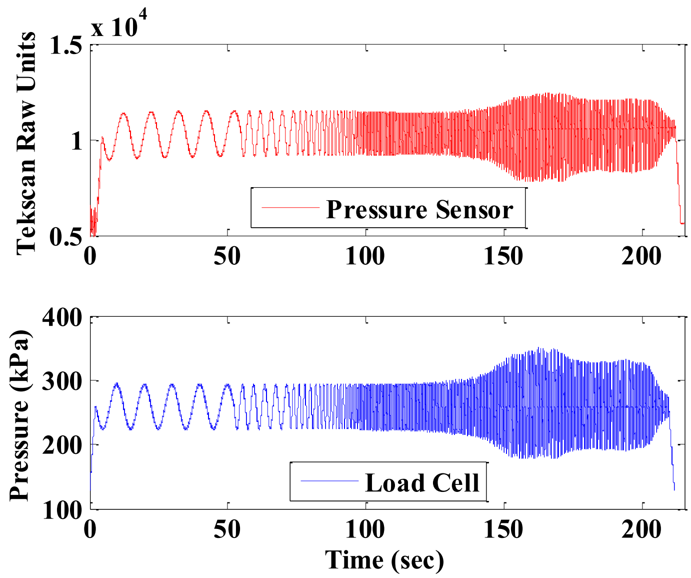

Figure 4.6. Sine-sweep load recordings from: a tactile pressure sensor (top) and the loading machine load cell (bottom).

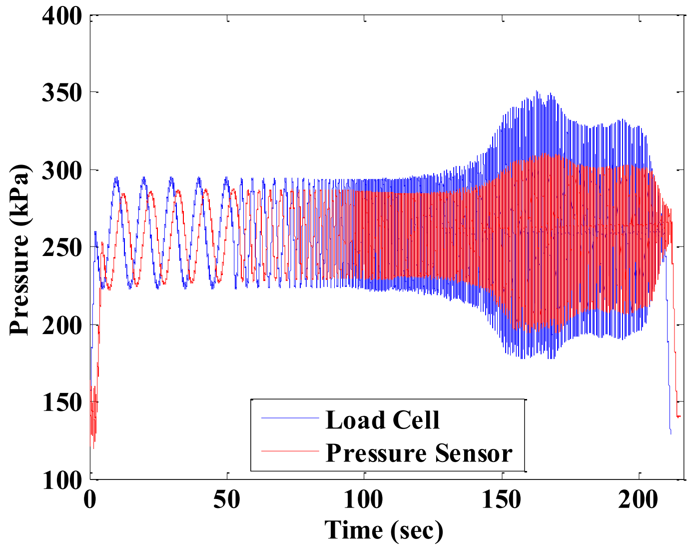

Figure 4.7. Loading machine load cell data plotted against statically calibrated tactile pressure sensor data.

4.3.2.1 Aligning and Resampling Data Sets

Data recording for the tactile pressure sensors begins before the loading machine program. The loading machine applies the specified loading pattern, while simultaneously recording data. Aligning the two data sets (from the pressure sensor and the load cell) is critical before their measurements can be compared or taken to the frequency domain. Data alignment was accomplished by setting the first prominent peak in the loading cell and tactile pressure sensor recordings to equal times. Further, the loading machine's sampling rate of 5000 Hz was reduced to match that of the pressure sensor (i.e., 4000 Hz) for a proper processing and comparison of the two signals. Down sampling the loading machine data was performed using the "resample" function in Matlab. Figure 4.8 shows the two data sets after alignment and resampling.

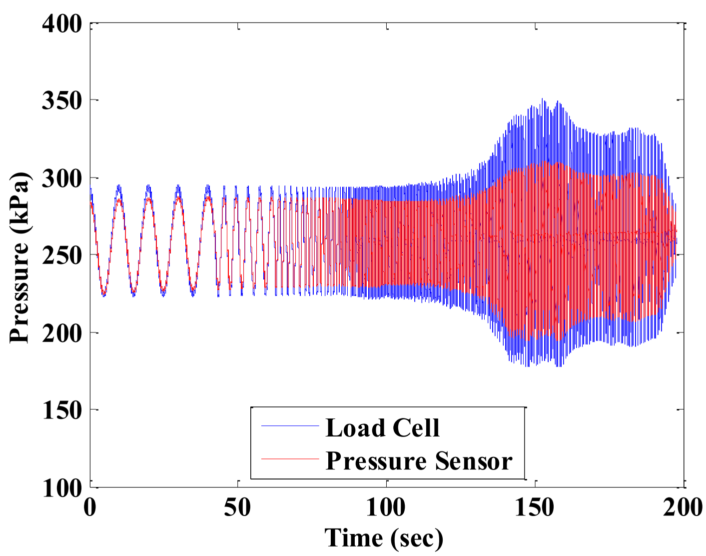

Figure 4.8. A comparison of aligned datasets obtained from the tactile pressure sensor and the Instron load cell. Pressure sensor data has been statically calibrated.

4.3.3 Obtaining the Transfer Function

After the sine-sweep datasets are aligned and resampled, the frequency response of the tactile sensors may be characterized with reference to the loading machine measurements via a transfer function in the frequency domain. An optimum single parameter curve fit was then established for the transfer function representing |load cell (f)| / |pressure sensor (f)|, shown in Figure 4.9. The best fit was defined by the function, as recommended by Tekscan Inc.:

$$Y = A * [\log(X + 1)] + 1 \tag{4.1}$$

where "A" is a constant, in this case estimated to be 0.11, "X" is the frequency input, and "Y" is the magnitude output of the transfer function. After identifying an appropriate transfer function between the two data sets, a digital filter was developed to remediate the problem of amplitude attenuation at higher frequencies for the Tekscan measurements and recover the original signal. Figure 4.9 shows the transfer function developed to relate pressure senor and loading machine data sets. Figure 4.10 and Figure 4.11 show the filtered and calibrated (recovered) Tekscan data measurements compared with the reference load cell readings in frequency and time domains, respectively. The results show reasonable agreement between the recovered Tekscan and loading machine data. Error between the two datasets in the frequency domain is presented in Figure 4.12.

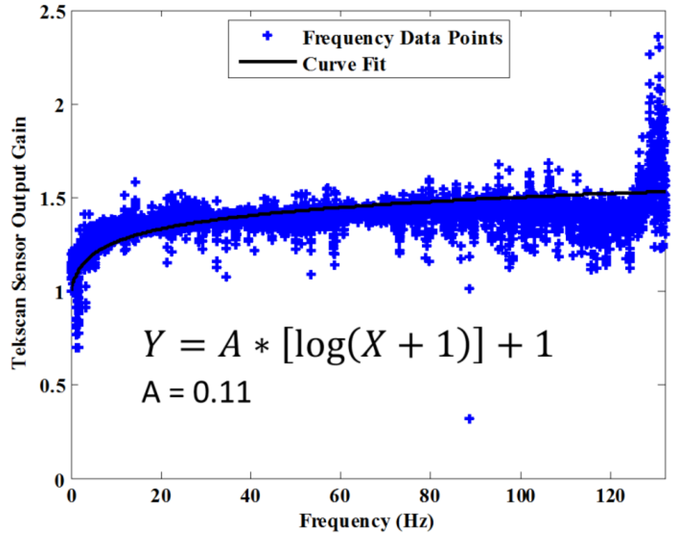

Figure 4.9. Transfer function relating tactile pressure sensor measurements and the load cell recordings.

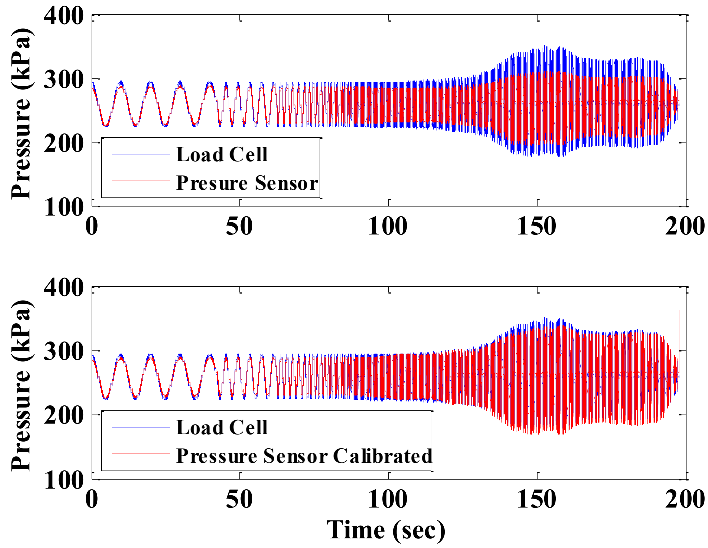

Figure 4.10. Statically and dynamically calibrated pressure sensor data compared with load cell in the time domain.

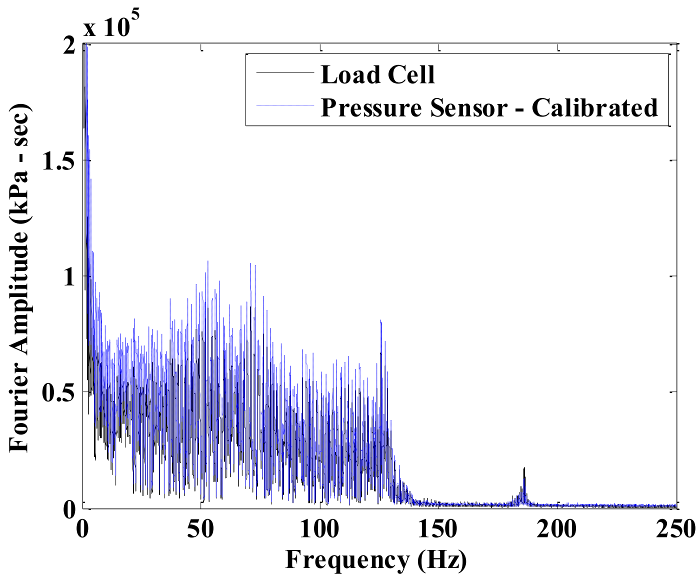

Figure 4.11. Comparison of Fourier amplitude spectra of the recovered Tekscan data with Instron load cell recordings.

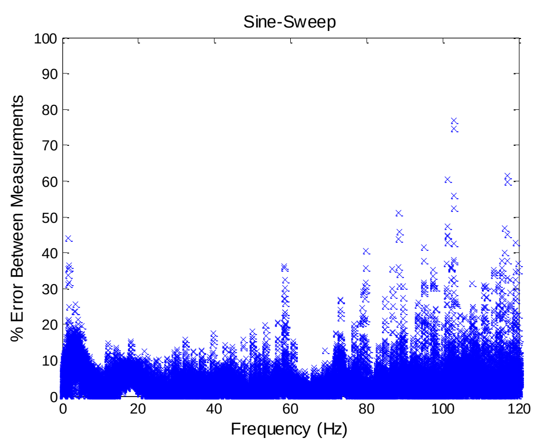

Figure 4.12. Percent error in the recovered pressure sensor data compared to the reference, load cell recordings as a function of frequency.

4.4 Dynamic Calibration Verification Tests

4.4.1 Loading Machine Blind Tests

Two blind tests were performed to quantify the ability of the developed filter to accurately recover the Instron load cell data; they are described in Table 4.2. Blind Test 1 consisted of a sine-sweep beginning at a frequency of 140 Hz and decreased toward 1 Hz at intervals of 1Hz.

Each frequency was run for 20 cycles at an amplitude of 20 lbs, except frequencies less than 5 Hz, which were run for only 3 cycles. The offset load for Blind Test 1 was 120 lbs, this is the load at which the sinusoidal loads oscillate about.

Blind Test 2 applied random frequency and amplitude sine waves to the tactile pressure sensor at a 100 lb. offset load. Sine waves were applied in sets, each set containing 10 to 200 cycles of a wave with the same frequency and amplitude. The number of cycles depended on the frequency of the wave, higher frequency sets typically contained more cycles. High frequencies sine wave sets were designed to have lower amplitudes and lower frequency cycles were paired with larger amplitudes. Amplitudes ranged from 0.5 lbs to 60 lbs, and frequencies ranged from 10 Hz to 200 Hz. In total, about 20 sets were applied to the sensor.

Table 4.2. Blind test sequence specifications.

Blind Test	Sensor No. Tested	Load Offset	Signal Amplitude	Frequency Content
1	1	120 lbs	20 lbs	Reverse sine-sweep: 140 to 1Hz , 1Hz intervals, 20 cycles each
2	1	100 lbs	Random	Random

Results from Blind Test 1, the reverse sine-sweep are compared in Figure 4.13; a good match between data sets exist in both time and frequency domain. Figure 4.14 presents the results from Blind Test 2. The flat portions of the figure represent low amplitude, high frequency cycles or dead zones between sets of sinusoidal loading. The more distinct loading sets are large amplitude, low frequency cycles. In general, a good match is seen between the load cell and recovered pressure senor measurements. All results have been statically and dynamically calibrated.

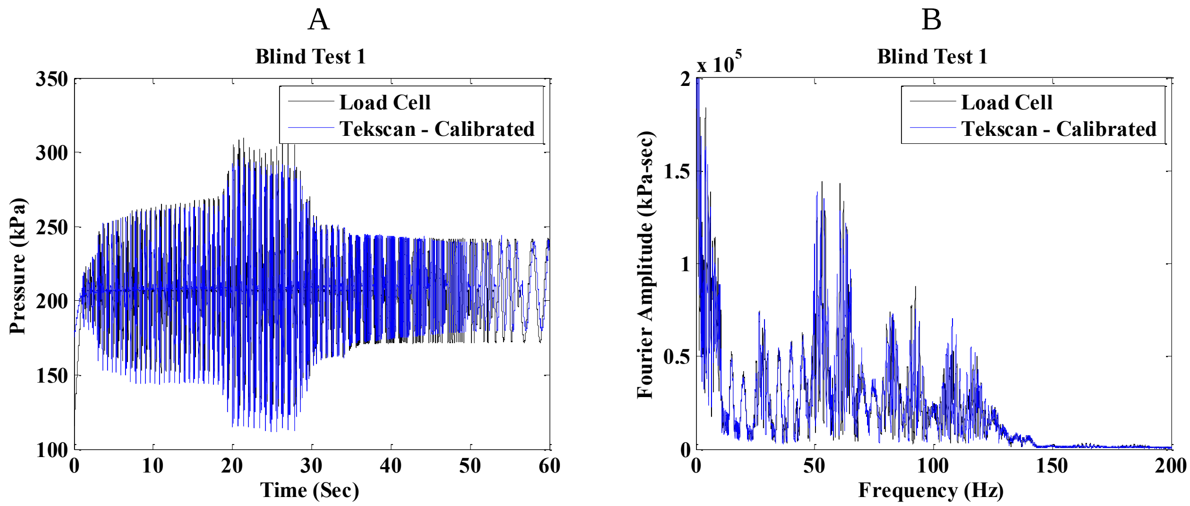

Figure 4.13. Statically and dynamically calibrated tactile pressure sensor data versus load cell recordings during Blind Test 1 in: (a) time domain and (b) the frequency domain.

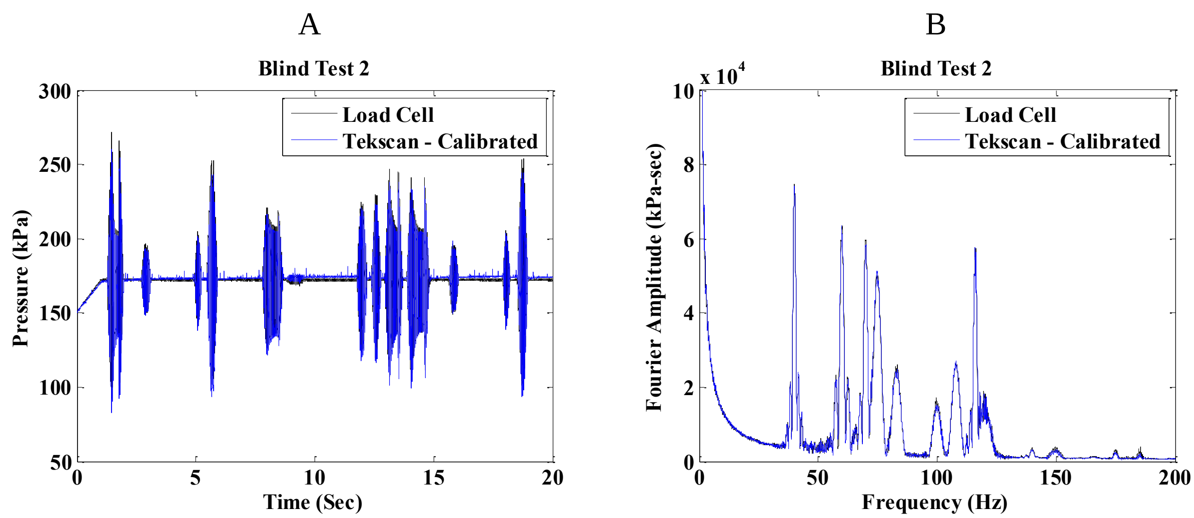

Figure 4.14. Statically and dynamically calibrated tactile pressure sensor data versus load cell recordings during Blind Test 2 in: (a) time domain and (b) the frequency domain.

4.4.2 Centrifuge Water Tests

The 400 G-ton centrifuge at the University of Colorado was used to perform a second set of verification tests of the tactile pressure sensor's dynamic calibration under high frequency loading. Pore water pressure transducers (PPTs) and tactile pressures sensors were placed on the wall of a centrifuge container filled with sufficient water to cover the sensors (following the testing procedure of Olson et al. 2011). Miniature PPTs are commonly used in dynamic centrifuge modeling as relatively reliable instruments. Water was selected in these verification tests so PPTs could be used as reference instruments. This is because no other reliable sensor was available to measure dynamic earth pressure. The container was then mounted on a shake table on the centrifuge bucket, spun up to 77 g, and shaken laterally in flight to create high frequency waves. Due to the centrifuge scaling laws, the centrifuge shake table is typically capable of generating high frequency motions at the base of the container (up to approximately 350 Hz), which was useful in this study. The water pressure induced on the container wall was measured by both tactile sensors and reference PPTs during a series of base motions. As tactile sensors are not water resistant, it is ideal to properly seal and laminate them. Tactile sensors were taped to the inside of the centrifuge container wall next to two Druck model PDCR 81 PPTs mounted at two elevations. The PPTs are identified as PPT-1 and PPT-5. Figure 4.15 and Figure 4.16 show the layout of the centrifuge water test.

PPT-1 did not function for this test, so data from PPT-5 and the tactile pressure sensor is compared. The ninth row of sensels (from the top of the pressure sensor) correspond in elevation to PPT-5. These sensel values were averaged to produce one pressure sensor value per time step. A static calibration was calculated for the pressures sensor and the PPT by using the height of water above them (7.0 cm). Dynamic calibration was applied using the filter obtained in Section 4.3.3. Fully calibrated (statically and dynamically) tactile pressure sensor data and PPT-5 results are compared during one of the shaking events (the Izmit earthquake base motion) and are presented in Figure 4.17. The comparison is reasonable in both time and frequency domain, further verifying the performance of the proposed dynamic calibration for high frequency signals.

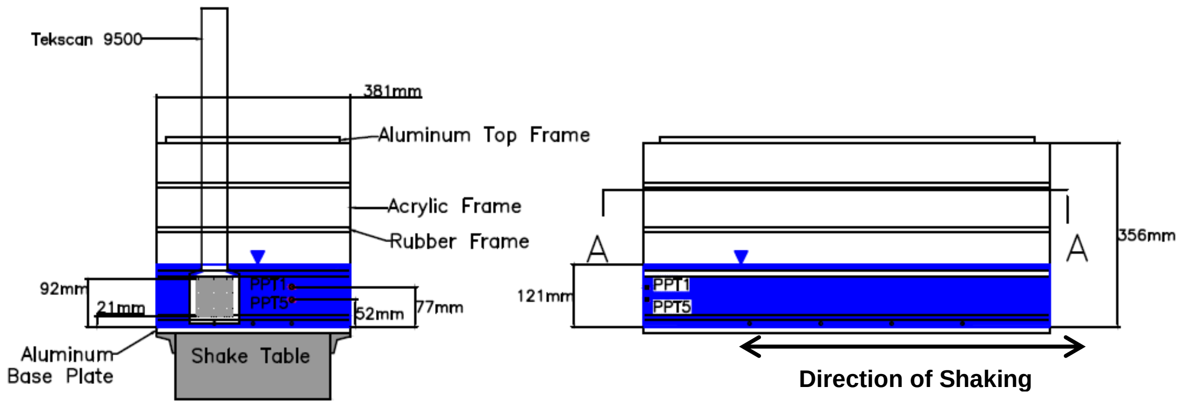

Figure 4.15. Centrifuge water test setup.

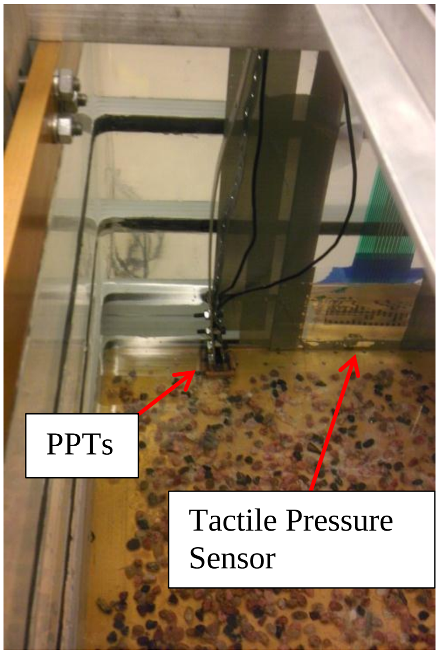

Figure 4.16. Two PPTs and a Tekscan pressure sensor placed on the wall of the centrifuge container filled with water.

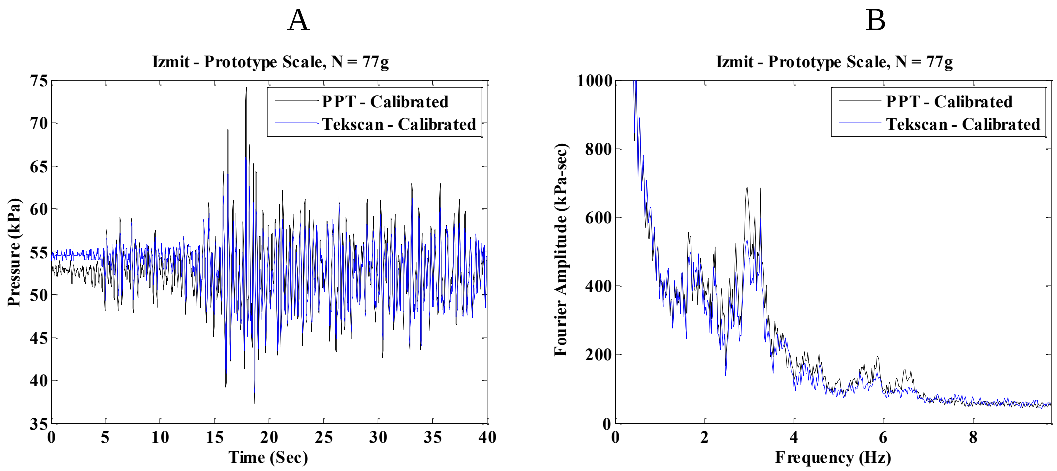

Figure 4.17. Comparison of the statically and dynamically calibrated tactile pressure sensor data with PPT recordings during the Izmit motion (at the same elevation): (a) in the time domain; (b) in frequency domain. (Note: all measurements are presented in prototype scale units)

4.5 Influence of Variations in Tactile Sensor Model, Sensitivity, and Interface Materials on Dynamic Calibration

To investigate whether the established dynamic calibration serves different sensor models, sensitivities, and interface conditions, two sensors were subject to sine-sweep loading using the Instron loading machine to create a unique digital filter (dynamic calibration) for each sensor. The sensor ID, capacity, sensitivity setting, test interfaces, and dynamic calibration associated with each sine-sweep test are presented in Table 4.3.

The first filter (Dynamic Calibration 1 listed in Table 4.3) was developed using Sensor 1, a 100 psi sensor set at a default sensitivity value of 29. The interface for this test placed the senor on top of a very flat, precisely machined steel plate; a paper towel was then placed between the sensor and a wooden block used to transfer load from the loading machine. The setup can be seen in Figure 4.18. The interface condition for Sensor 2 and Sensor 6 was similar to the Sensor 1 test setup, except that two thin sheets of Teflon were placed between the sensor and the paper towel (setup similar to actual centrifuge tests planned with underground structures).

Figure 4.18. Steel plate – pressure sensor – paper towel – wooden block – loading machine interface

Table 4.3. Sensor and test interface conditions for dynamic calibration verifications tests.

Sensor ID	Capacity (PSI)	Sensitivity	Interface Condition	Dynamic Cal. No.
1	100	29	Aluminum Plate - Sensor - Paper - Wooden Block - Loading Machine	1
2	100	30	Aluminum - Sensor - 2 Thin Teflon Sheets - Paper - Wooden Block - Loading Machine	2
6	5	5	Aluminum - Sensor - 2 Thin Teflon Sheets - Paper - Wooden Block - Loading Machine	6

Figure 4.19 compares load cell data with Sensor 2 data dynamically calibrated using two different dynamic calibrations, Dynamic Calibration 1 and 2. Note, Dynamic Calibration 2 was developed using Sensor 2. These dynamic calibrations were developed for two different capacity sensors with different sensitivity settings and interface conditions using methods outlined in the section 4.3.1, and the results compare quite closely. Figure 4.20 similarly presents a portion of the sine-sweep test of Sensor 6 with two different dynamic calibrations applied. The dynamic calibration developed specifically for Sensor 6 does a slightly better job recovering the original load cell measurement than the calibration developed for Sensor 1. Overall, sensor data filtered using different dynamic calibrations have similar output, showing that dynamic calibration may be independent of the sensor model, sensitivity, or interface conditions.

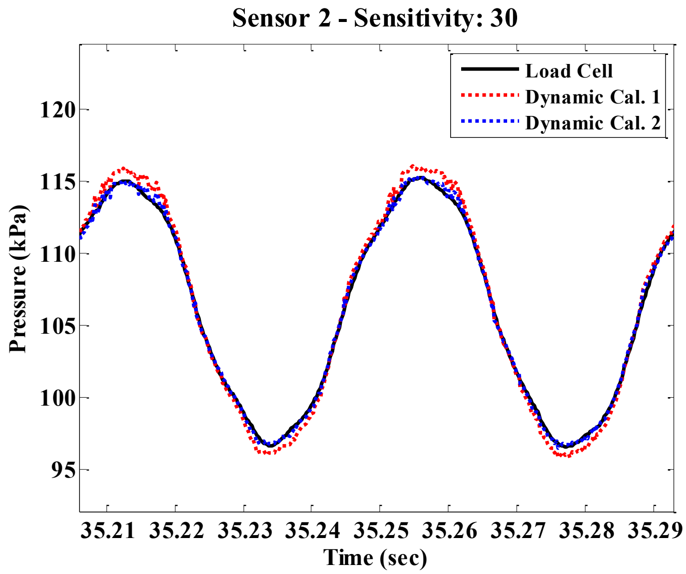

Figure 4.19. A portion of the sine-sweep loading test for Sensor 2.

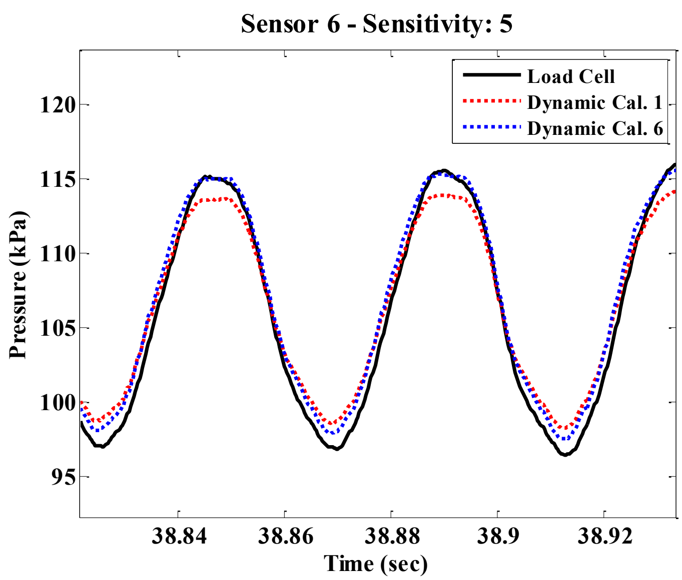

Figure 4.20. A portion of the sine-sweep loading test for Sensor 6.

4.6 Summary and Conclusions

The tactile pressures sensors have trouble measuring high frequency signals due to the material properties of the sensor and signal aliasing. The polymeric sheets that make up the sensor have a distinct response that needs to be characterized before the sensor can be used to measure high frequency signals. Signal aliasing was avoided by selecting sensors with sampling rates quicker than the nyquist frequency of the signals being measured. Characterization of the tactile pressure sensor's frequency response led to the development of a transfer function relating the pressure sensor's measurements to those of the loading machine (reference). This transfer function was used to build a digital filter that when applied to the original tactile pressure sensor dataset, closely recovered the loading machine dataset. The digital filter is referred to as the dynamic calibration.

The dynamic calibration was proven to work well for different sensor models, sensitivities, and interface conditions. Blind tests performed with the loading machine and centrifuge showed that the proposed dynamic calibration methodology successfully recovers dynamic pressure signals at high frequencies.

5. STATIC CALIBRATION

5.1 Overview

The static calibration process converts tactile pressure sensor raw units to engineering pressure units. In the previous section, static calibration of the tactile pressure sensor was easily achieved because a reference instrument, like the loading machine load cell or pore water pressure transducer was present for the dynamic calibration and verification tests. A static calibration procedure for the pressure sensor is needed so that pressure data can be measured in future testing without the need for extra instrumentation.

Two static calibration procedures will be discussed and compared. The first method uses a loading machine to apply known loads to the sensor; the second method involves loading the sensor by placing it at the bottom of a centrifuge container filled with the test sand (at a target relative density and known height) spun to different g-levels. Previous researchers (Paikowsky and Hajduk (1997), Tessari (2010)) have shown the importance of mimicking the expected interface conditions in the static calibration of tactile pressure sensors. Actual centrifuge testing conditions involved a metal-pressure sensor-Teflon sheet-Teflon sheet-sand interface condition. The Teflon sheets were placed on top of each other, between the sensor and sand to minimize the friction transferred to the sensor from the adjacent sand movements (Palmer 2009). Both static calibration methods mimicked expected centrifuge test conditions with metal on one side of the sensor and two Teflon sheets on the other. However, the loading machine applied pressure to the Teflon sheet side of the sensor through a wooden block, shown in Figure 4.18, whereas static centrifuge testing enabled a transfer of load to the sensor through sand particles similar to expected centrifuge testing conditions.

5.2 Previous Challenges

The static calibration is not easily achieved and it is usually associated with some degree of error. Some error is attributed to the extreme sensitivity of each sensel on the sensor. Equilibration is a method that sets all the sensels of a pressure sensor to an equal gain under an even load to reduce error during calibration (as discussed in section 3.4). However, applying a uniform load to the pressure sensor is difficult. Tekscan Inc. has built an equilibration device that uses a urethane bladder that fills with air to apply an even load to the sensor. Paikowsky and Hajduk (1997) found that their calibration device, (which is similar in concept to the Tekscan equilibration unit) can induce shear effects to the sensor through the stretching of the urethane material. Also, unevenness in the metal reaction plate and air trapped within the two sheets that make up the sensor can cause problems. These factors can introduce some error into the equilibration and calibration processes when using a system similar to Paikowsky's calibration device or the Tekscan equilibration unit.

5.3 Loading Machine Calibration

5.3.1 Test Setup

The loading machine static calibration tests were setup and performed similar to the dynamic calibration tests, except that two thin sheets of Teflon were placed between the sensor and the wooden block in order to more closely mimic actual testing conditions. The Teflon sheets are used in centrifuge testing to reduce shear effects of the sensor (Palmer 2009). The test setup is seen in Figure 4.18.

5.3.2 Loading Sequence

Constant loads of 50, 100, 150 and 200 lbs were applied to the sensor and held for 3 s each with 2 s linear transitions between each load. The applied loading sequence is presented in Figure 5.1a as the data series labeled, “Load Cell”.

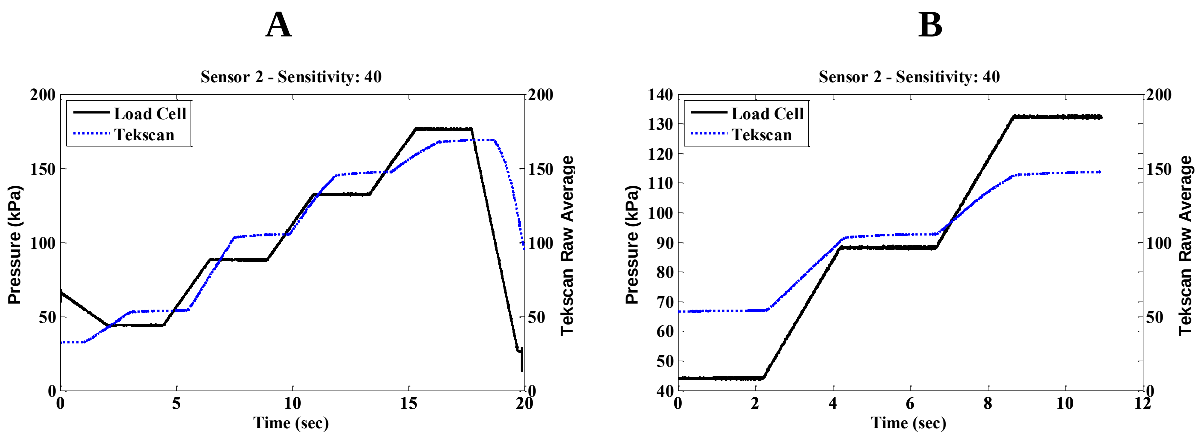

Figure 5.1. Loading machine load cell measurement versus pressure sensor reading during a loading machine test: (a) raw records; (b) data sets aligned and trimmed.

5.3.3 Calibration Procedure

Tekscan’s I-Scan software was used to calculate a static calibration for Sensor 2. The I-Scan “Movie Calibration” feature was used, which pairs each “frame” of a “movie” with a reference force value read from an input file (Tekscan 2012). Tekscan, the manufacturer, uses the terms, “frame” and “movie”, to refer to each data point, and a complete dataset, respectively. The reference input file contains the same number of data points as the movie has frames. As discussed in the Tekscan System section, all multi-point calibrations follow the form $y = ax^b$, where “y” is the output in engineering pressure units and “x” represents the average raw recordings from all the sensels. More than 40,000 data points were used to calculate calibration coefficients “a” and “b” for Sensor 2. By using many calibration points, error is reduced in the calculation of the static calibration coefficients.

Since the movie calibration feature requires that every frame of a Tekscan movie be matched to a known load, load cell data was down sampled from 5000 to 4000 Hz to match the sampling rate of tactile pressure sensors using the “resample” function in Matlab. No filtering was associated with resampling the data set. Next, the two data sets were aligned in time and then trimmed. For Sensor 2, a portion of the data was removed because the sensor became saturated (loaded beyond the capacity of the sensor) under a high load. Figure 5.1a compares the loading machine and tactile pressure sensor raw recordings during the static calibration test. Figure 5.1b shows the two data sets after data alignment and clipping. A text file was then generated from the aligned and clipped loading machine data.

Figure 5.2 shows a screenshot of the initial pressure distribution of the tactile pressure sensor in the loading machine calibration test. Small variations in color are due to slight non uniformities in the applied pressure to different sensels. Black colored sensels represent zero load or non-working sensels caused by wear or damage. The I-Scan multi-point calibration feature calculates the static calibration coefficients “a” and “b” by iteratively, minimizing the difference between the input force and the sum of all sensels (more details are provided in section 5.5).

The software does not take into account non-working sensels. To work around this, the known force associated with each frame was scaled by a ratio equal to the number of working sensels divided by the total number of sensels. It is important to try to differentiate between non-working sensels and ones that are reading zero, because non-working sensels will affect a calibration by reporting zero when they should have a value. For example, Figure 5.2 shows that 37 of the 196 sensels are not working or read zero load. Of the 37 black colored sensels, 28 in the lower right part of Figure 5.2 are estimated to be nonoperational, while the others appear to read zero. The load cell readings associated with each frame are then multiplied by (196 – 28) / (196) = 0.86. This factor was applied to each load cell data point in the text file and was assumed to provide reasonable accuracy (confirmed with Tekscan Inc.).

Using I-Scan, the tactile pressure sensor movie was opened and trimmed to remove all frames not corresponding to the generated load cell text file. Next, the input file was imported into I-Scan and associated with the Tekscan data set. If the number of Tekscan pressure sensor movie frames does not match the number of loading machine data points in the text file, an error message is produced. Once the input file is properly imported, movie calibration may be performed. The calibration can then be saved and applied to other tactile pressure sensors data sets.

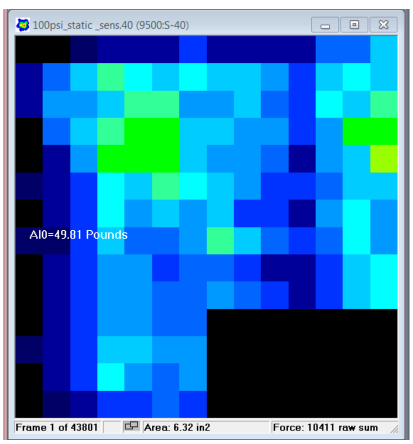

Figure 5.2. I-Scan calibration window prior to loading machine test for Sensor 2.

5.4 Static Centrifuge Calibration

5.4.1 Test Setup

The centrifuge static calibration test began by taping the tactile pressure sensors to two polished aluminum plates (e.g., Figure 5.3). A thin Teflon sheet was then placed over the sensor and taped down using electrical tape (similar to the setup expected during actual tests). A second thin Teflon sheet was placed on top of the first sheet and held in place with a non-viscous oil (allowed to slide). The aluminum plates were placed at the bottom of a centrifuge container (Figure 5.4) and the test soil (Nevada Sand) was dry pluviated at a relative density of 60% to a height of 25cm above the sensors as seen in Figure 5.5. The selected soil relative density and sample preparation method was based on the actual centrifuge testing conditions. The container was then moved onto the centrifuge where it was spun at different g-levels to provide different loads to be used as calibration points. At each g-level, the response of the sensor set to various sensitivity levels was recorded. Table 5.1 shows the g-level and sensitivity settings tested for each sensor. Sensors 3-6 – with 5psi capacity – were tested at the same g-levels and sensitivities as one another. Sensor 2 – a 100 psi capacity sensor – was tested at higher sensitivity levels for higher g-levels, as shown in Table 5.1. The gravitational accelerations listed in Table 5.3 represent the acceleration level at the mid depth of the soil column covering the sensors.

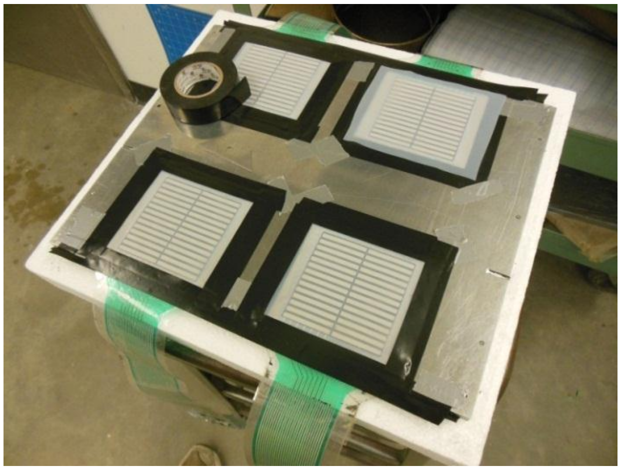

Figure 5.3. Tactile pressure sensors and the first Teflon sheet taped to a polished aluminum plate.

Figure 5.4. Polished aluminum plates with attached tactile pressures sensors and two Teflon sheets placed at the bottom of a centrifuge container prior to sand pluviation.

Figure 5.5. Dry pluviation of Nevada sand over tactile pressure sensors in the centrifuge container.

Table 5.1. List of sensors, sensitivities and g-levels tested during centrifuge calibration test.

Sensor No.		*G-level*						**Sensor No.**		*G-level*					
2		1.0	11.1	23.0	35.6	47.6	59.1	**3-6**		1.0	11.1	23.0	35.6	47.6	59.1
Sensitivity	1	X	X	X	X	X	X	*Sensitivity*	1	X	X	X	X	X	X
	5	X	X	X	X	X	X		5	X	X	X	X	X	X
	10	X	X	X	X	X	X		10	X	X	X	X	X	X
	20	X	X	X	X	X	X		20	X	X	X	X		
	30	X	X	X	X	X	X		30	X					
	40	X	X	X	X	X	X		40	X					

5.4.2 Loading Sequence

The loading sequence for the static centrifuge calibration test was created by spinning the centrifuge container to six different g-levels. The weight of sand placed on top of the sensor depends on how dense the sand is. Properties of Nevada sand at different densities are listed in Table 5.2. Table 5.3 shows the normal pressure associated with each g-level; these six loads were used to calibrate Sensor 2 using the centrifuge test data. Figure 5.6 presents the pressure sensor response at each g-level for Sensor 2 with a sensitivity setting of 40.

Table 5.2. Nevada sand relative density, void ratio and unit weight information.

Nevada Sand Properties								
D_R =	0	%	e_{min} =	0.59	γ_{min} =	16.37	kN/m^3
D_R =	60	%	e =	0.69	γ =	15.36	kN/m^3
D_R =	100	%	e_{max} =	0.85	γ_{max} =	14.02	kN/m^3

Table 5.3. Normal pressure calculated at the sensor level (bottom) of the container corresponding to each g-level.

G-level at Soil Mid Depth	Normal Pressure (kPa)
1.0	3.8
11.2	46.1
23.0	92.2
35.6	99.8
47.6	184.3
59.1	257.7

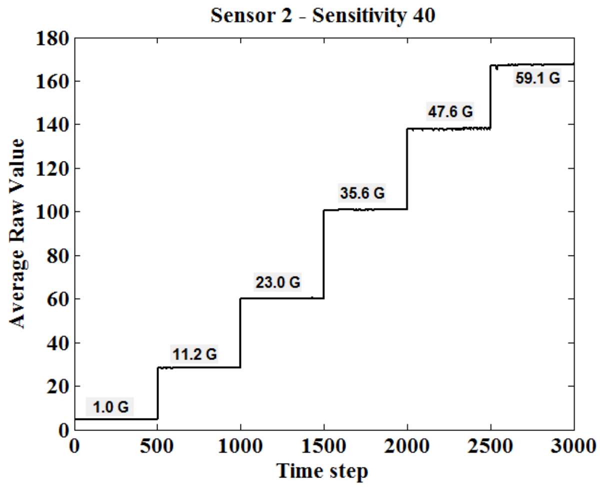

Figure 5.6. Tactile pressure sensor response to loading sequence.

5.4.3 Calibration Procedure

To calibrate the sensors using the centrifuge tests results, the I-Scan "Frame Calibration" feature was used. This feature pairs specific frames from a movie with known loads. For the centrifuge test, 500 frames were recorded at each g-level and were connected together using the I-Scan software. A frame from the middle of each 500 frame set corresponding to a distinct g-level was used for each calibration point. The I-Scan software uses the calibration points to calculate the calibration coefficients, "a" and "b", for the non-linear best fit equation, $y = ax^b$.

Similar to the loading machine calibration, a scalar value was multiplied by the theoretical load associated with each g-level to account for non-working sensels. Figure 5.7 shows the pressure distribution of Sensor 2 at 24 g of spin acceleration. This particular frame has 22 black sensels; only the 7 sensels in the left half of row 7 (from the top of the sensor) are estimated to be non-working. A factor of (196-7)/196 equal to 0.96 was applied to the theoretical values associated with each g-level load.

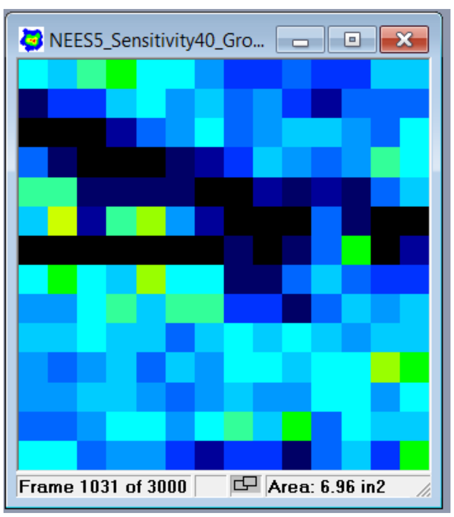

Figure 5.7. Pressure distribution on Sensor 2 at 24 g of spin acceleration during the centrifuge calibration tests.

5.5 I-Scan Calibration Method

Multi-point calibrations are calculated in I-Scan using a minimization function:

$$\boldsymbol{Min}\left[\ \sum_{i=1}^{n}\ \left|\ \boldsymbol{Force_i} - \boldsymbol{a} * \sum_{j=1}^{m} \boldsymbol{Sensel_{i,j}^{b}}\right|\ \right], \qquad (5.1)$$

where "i" represents the calibration point number, "n" the total number of calibration points, "j" the sensel number, "m" the total number of sensels, and "a" and "b" are the calibration equation coefficients. This equation solves iteratively to find coefficients "a" and "b" that minimize the sum of the differences between the input force and the sum of all sensel values associated with each calibration point. When a sensor contains non-working sensels, as shown in the lower right hand portion of Figure 5.2, the I-Scan minimization equation introduces some error into the calibration. To account for this error, the applied pressures by the loading machine, or the weight of sand in the centrifuge container were multiplied by a scalar proportional to the number of non-working sensels, this method is discussed in sections 5.3.3 and 5.4.3.

5.6 Calibration Results

The results obtained from the two static calibration techniques applied to Sensor 2 data with a sensitivity setting of 40 are presented in Figure 5.8. The centrifuge calibration is more sensitive than the Instron loading machine calibration for Sensor 2. The calibrations have been adjusted to take into account non-working sensels.

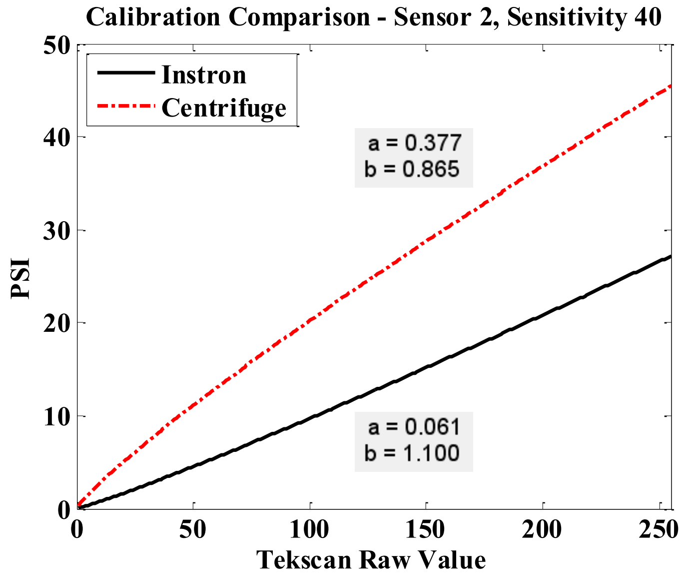

Figure 5.8. Static calibration curves for the Instron loading machine and the static centrifuge tests.

5.7 Evaluation of Static Calibration Results in Centrifuge Testing of Underground Structures

The obtained static calibration results may be applied to the raw tactile pressure sensor recordings for a specific sensor model and sensitivity. Calibrations developed for Sensor 2 were applied to Sensor 2 data from a centrifuge test performed at the Center for Geotechnical Modeling (CGM) at the University of California at Davis. The centrifuge test was part of a project aimed to investigate the seismic performance of shallow underground structures in dense urban environments. During this test, tactile pressure sensors were placed on the walls of a model tunnel and braced excavation to measure lateral earth pressures during seismic loading (Figure 5.9). Pressure sensor recordings prior to the application of earthquake loading in these centrifuge tests enabled an evaluation of the reliability of the two static calibration procedures. The initial sensor recordings were compared with theoretically expected, at-rest lateral earth pressures acting on the walls of the underground structures in these experiments. The soil used in these experiments was Nevada sand, dry pluviated at a relative density of approximately 60%.

Data obtained from the sensels in each of the 14 rows were averaged to obtain the static lateral earth pressure on the wall at 14 different elevations (shown in Figure 5.9). Matlab was used to omit any non-working sensel values in the averaging process to be consistent with the methods used to calculate the static calibrations. The static calibration factors obtained from the two calibration procedures (shown in Figure 5.8) were applied to the initial, raw tactile sensor recordings for each elevation to compute static, at-rest lateral earth pressures acting on the wall.

Figure 5.10 presents a comparison between theoretically expected lateral earth pressures, and Sensor 2 lateral earth pressure data statically calibrated using each of the two methods. Theoretical lateral earth pressures are expressed as a range due to minor uncertainty in the relative density of the placed Nevada sand. Relative density was estimated to have an error of ±10%, corresponding to a range of Nevada sand friction angles of 33 to 38, (Popescu 1993) and K_0 values of 0.38 to 0.46. Data calibrated with the loading machine procedure appear to more closely follow theoretically expected lateral earth pressures. This may be due to the complexities of pressure distribution in granular materials in the vertical and horizontal directions, affecting the applicability of vertical pressures in static centrifuge tests to lateral earth pressures even within the same type of sand. Hence, we decided to employ the static calibration factors obtained from the Instron loading machine tests to each sensor.

Figure 5.9. Centrifuge testing configuration of tactile pressure sensor on tunnel wall. Sensel readings in each row were averaged.

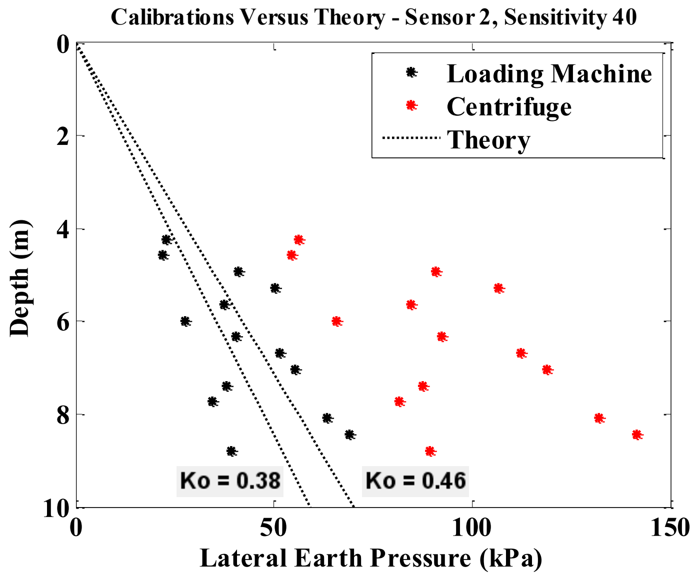

Figure 5.10. Comparison of lateral earth pressure distribution on the tunnel wall at 65 g of spin acceleration using two static calibration methods (loading machine and static centrifuge testing) with theoretical estimates.

Figure 5.11 and Figure 5.12, present lateral earth pressure recordings on the tunnel wall during the first earthquake motion in the same centrifuge test at the CGM. The horizontal component of the 1994 Northridge Earthquake recorded at the Newhall West Pico station was applied to the base of the container. Sensor 2 recorded the corresponding earth pressures on the tunnel at a sensitivity setting of 40. Figure 5.11 presents pressure sensor data from row 14 of the sensor, the deepest row. Figure 5.12 displays data for all 14 rows of the sensor after both static and dynamic calibration. In general, deeper rows experience more lateral earth pressure as expected. Each row shows a unique response before and after shaking. Some rows report higher pressures after shaking than before, some are the same, and some are lower. No trend is observed in this behavior.

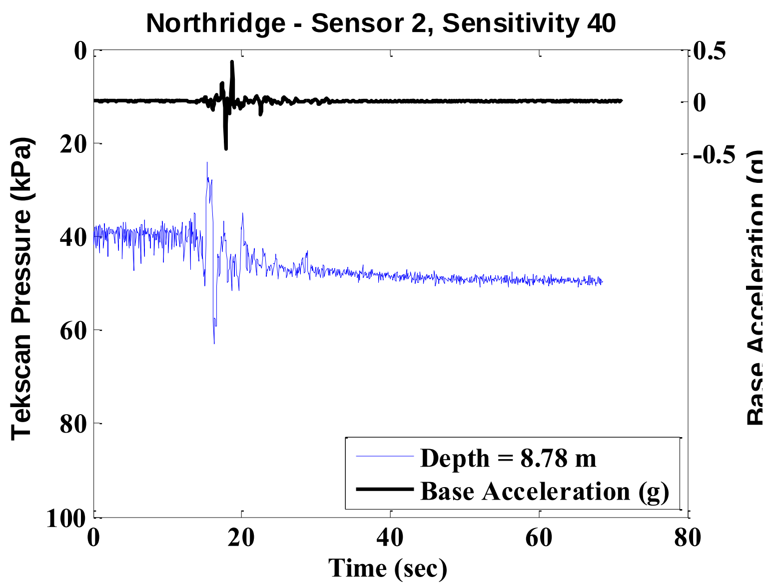

Figure 5.11. Row 14 lateral earth pressure results of the tunnel wall subject to the Northridge ground motion. Static and dynamically calibrated.

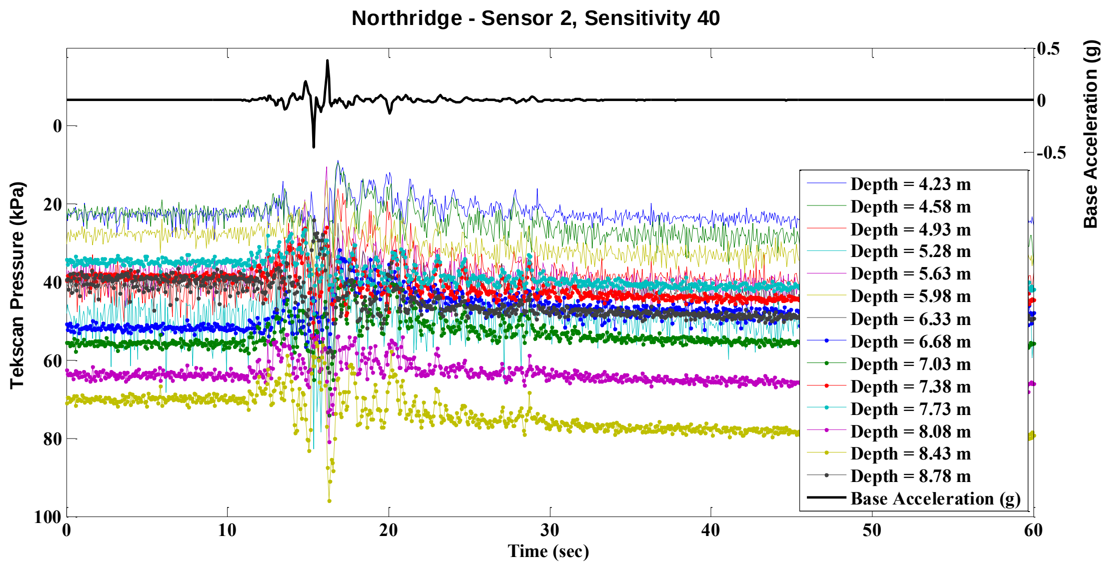

Figure 5.12. Lateral earth pressures recorded on the tunnel wall at 14 elevations in centrifuge during the Northridge earthquake event (statically and dynamically calibrated).

5.8 Summary and Conclusions

The static calibration was developed through two distinct methods, the first loaded tactile pressure sensors with a loading machine; the second used the weight of sand on top of sensors placed at the bottom of a centrifuge container spun to different g-levels. Tekscan's I-Scan software calculated non-linear calibration functions by combining known force values with the corresponding pressure sensor data. The I-Scan software will introduce some error into a static calibration if sensor data contains non-working sensels. Non-working sensels were differentiated from sensels reading zero and omitted from pressure sensor calibration test data. By reducing the reference loads proportionally to the number of non-working sensels on the sensor, error introduced to the static calibration is minimized.

To maintain consistency, non-working sensels were also omitted from the performed centrifuge test data before static calibrations were applied. The loading machine and centrifuge developed static calibrations were applied to a test investigating the lateral earth pressures of a tunnel wall. For Sensor 2, the comparison showed that the loading machine static calibration produced results that better matched theoretically expected at-rest, lateral earth pressures. Static calibration results need to be further analyzed before more conclusive observation can be made about each calibration method.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 General

There is currently no standard technique for the static and dynamic calibration of tactile pressure sensors for use in geotechnical centrifuge modeling using granular materials. A pioneering work was performed by Paikowsky and Hajduk (1997) to evaluate basic characteristics of the tactile pressures sensors (e.g., creep under a steady load, hysteretic behavior, and loading rate effects). More than a decade later, Tessari et al. (2010), and Olson et al. (2011) explored and described the existing challenges in the static calibration of Tekscan tactile pressure sensors for use with granular materials.

6.2 Dynamic Calibration

Olson et al. (2010) showed the shortcomings in the tactile pressure sensor's ability to accurately measure high frequency signals in centrifuge calibration tests. High frequency loading tests used to characterize the frequency response of the tactile pressure sensors were performed at CU Boulder with a controlled Instron loading machine. A transfer function was developed to relate the measured output of the pressure sensor to the loads measured by the machine load cell. The transfer function was used to develop a digital filter, that when applied to the pressure sensor data, recovered the original measured signal. The reliability of the proposed dynamic calibration method was successfully tested through blind dynamic tests using the loading machine and centrifuge with water.

The dynamic calibration developed specific for one sensor was applied to other tactile pressure sensors with different sensitivities and interface conditions. The results showed that the dynamic filter is applicable to different sensors, sensitivity levels, and interface conditions. Hence, we recommend its application to future dynamic centrifuge modeling studies.

6.3 Static Calibration

Two methods were employed in this study to statically calibrate the tactile pressure sensors. One method loaded the sensors with an Instron loading machine; the second method loaded the sensors by placing them at the bottom of a centrifuge container filled with the test sand spun to different g-levels. In both procedures, a metal-sensor-Teflon sheet-Teflon sheet interface was adopted, similar to the expected interface conditions in future centrifuge testing. Tekscan's I-Scan software was used to calculate the static calibration coefficients from the two methods. Non-working sensels were omitted from the calibration process.

Calibration results from each method were applied to sensor recordings of static lateral earth pressure on a tunnel wall during a centrifuge model test. For one sensor analyzed in this study, the loading machine static calibration method produced at-rest, lateral earth pressure that agreed better with theory than the centrifuge method. More work is needed to investigate the calibration results of other sensors with different sensitivities and evaluate the trends and underlying mechanisms.

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