Sensing of Lateral Seismic Earth Pressures in Geotechnical Centrifuge Models

S. Dashti, K. Gillis, M. Ghayoomi
University of Colorado at Boulder

Y. Hashash
University of Illinois at Urbana Champaign

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SUMMARY:
A reliable measurement of dynamic earth pressures is critical in the physical modelling of structures embedded in soil. Tekscan tactile pressure sensors are flexible, thin sheets containing a matrix of sensels, each capable of measuring pressure. This flexible sensor is able to measure a 2–D stress distribution with minimal intrusion. Although successful in static and 1-g shaking table tests, these sensors have previously not been reliable in capturing the full amplitude content of dynamic signals. This is in part due to signal aliasing and the sensor's own frequency response. This paper describes the use of new sensors capable of sampling at up to 4,000 Hz. A series of dynamic experiments were performed to characterize the frequency response of the sensors and successfully recover the original pressure time histories. Based on the satisfactory results, a testing methodology is proposed for the dynamic calibration of these sensors in centrifuge modelling.

Keywords: Centrifuge, Dynamic Pressure, Sensor, Lateral Earth Pressure, Physical Modelling

1. INTRODUCTION

Physical centrifuge modelling is an effective tool commonly used by geotechnical engineers to gain insight into the underlying damage mechanisms under 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. Tekscan tactile 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). Their flexibility is ideal for interface with soil, as they deform with the surrounding soil with minimal intrusion. Increased sampling rates are necessary to capture dynamic earth pressures in the high frequency environment of the centrifuge.

Although tactile pressure sensors have proven to be successful in measuring pressures in static and 1-g shaking 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 represented 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 instance, when spinning the model to 70 g, the frequencies are scaled by 70. For earthquake engineering applications we typically care about frequencies of up to approximately 15 to 20 Hz in the prototype scale. This translates to 15 x 70 Hz (=1050 Hz) in the model scale. To capture this range of frequency in the model scale without signal aliasing, the sensors must sample at a minimum rate of approximately 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 with a range of input motions that contained energy at higher frequencies to further validate the reliability of the filter.

This paper presents the testing methodology used to characterize the frequency response of Tekscan tactile pressure sensors. The recovered Tekscan data and the reference signals are then compared and the error in the recovered pressure measurements is quantified as a function of frequency. The testing methodology also presents a guideline for the calibration of tactile pressure sensors prior to use in future physical model studies.

2. TEKSCAN TACTILE PRESSURE SENSOR SYSTEM

The Tekscan system is comprised of a sensor, a “handle”, and the data acquisition board. Tekscan VersaTek components were selected due to their high sampling rate capability. The “handle” is clamped to the sensor and transmits data to the data acquisition board, which is then connected to a computer to control how data is saved and to visualize data in real-time. Each Tekscan sensor contains a matrix of sensing elements called “sensels”, as shown in Fig. 1. The sensels are arranged in rows and columns and each intersection measures data by acting as a variable resistor in a circuit. When sensels are not loaded, they have a high resistance. This resistivity decreases as load is applied to the sensor. Output resistances are converted to raw sum units ranging from 0 to 255, which can then be converted to force or pressure units once a static calibration factor is calculated. A detailed description of the various Tekscan components and their functions are provided by Paikowsky and Hajduk (1997) as well as Tekscan (2011).

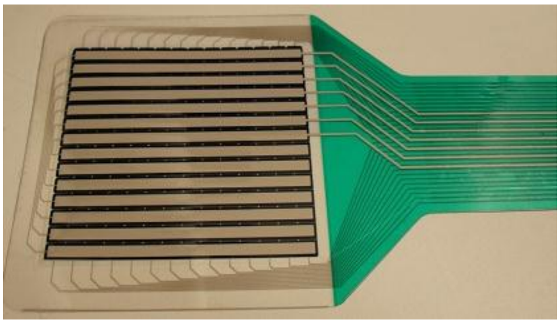

Figure 1. Tekscan sensor model 9500 employed in this study.

Tekscan Inc. is not the only manufacturer of flexible pressure transducers, but their product has been used more widely in geotechnical engineering applications. Tekscan Sensor model number 9500 was used in this study, which is flexible due to its small thickness of approximately 0.1 mm. Its sensing matrix is comprised of 14 rows and 14 columns of semi-conductive ink totalling 196 sensels that cover an area of 71.1 by 71.1 mm. The 9500 sensors used in this study have a sampling rate of 4000 Hz per sensel and were custom-designed with increased sensitivity over the pressure range of interest (e.g., less than 100 psi) for geotechnical testing applications.

3. PRIOR WORK ON PRESSURE SENSOR

A number of researchers have used Tekscan tactile pressure sensors in geotechnical engineering research applications. Paikowsky and Hajduk (1997) performed a series of tests to evaluate the influence of loading rate, hysteresis, and creep on measurements made by Tekscan sensor model number 5075. Post-loading creep appeared to be a function of the loading rate and magnitude with two distinct zones: (1) a load rate dependent, non-linear response within the first 30 minutes after loading;

and (2) a second linear zone that did not depend on the loading rate. Hysteretic and loading rate effects were studied by applying different constant loading and unloading rates to the sensor. A nonlinear response was observed upon initially unloading the sensor followed by a linear unloading phase.

Springman et al. (2002) conducted a successful study of the distribution of soil stresses beneath a circular footing that was pushed into the soil at a constant displacement rate under 50 g of spin acceleration using Tekscan sensors. .Further, they investigated the dynamic, impact loading response of these sensors to mimic rock falls on the roof of a protection structure at 1g. These tests demonstrated the sensor's ability to reliably measure a dynamic, quick, impulse event under 1g testing conditions. The dynamic response of these sensors under higher levels of spin acceleration and higher frequency contents, however, was not investigated.

Tessari et al. (2010) described the static calibration process of Tekscan sensors used at Rensselaer Polytechnic Institute (RPI) in geotechnical centrifuge experiments. They calibrated the sensor by placing it at the bottom of a centrifuge container filled with soil and spinning the model to specific accelerations. In this way, they obtained two calibration points corresponding to the upper and lower limits of the overburden stress expected for their tests. This method of static calibration closely models the intended interface conditions of metal with soil. After statically calibrating the sensor, Tessari et al. (2010) affixed the sensors to the side of the centrifuge container filled with soil and spun up the model; a stress distribution increasing with depth was found to correspond closely to a theoretical distribution with a K_o value of 0.38 under static conditions.

Following the successful static calibration of Tekscan sensors at RPI, Olson et al. (2011) employed the same sensors to record seismic earth pressures on model foundations for large bridges in a series of centrifuge tests conducted at RPI. Although the team had success accurately recording hydrostatic pressures, the sensors captured roughly only 50% of the amplitude of dynamic pressures recorded by pore pressure transducers (PPTs) in a centrifuge experiment with water (shown in Figure 2). These observations indicate a clear need for the dynamic characterization and calibration of Tekscan sensors, particularly for higher frequencies expected in dynamic, centrifuge experiments.

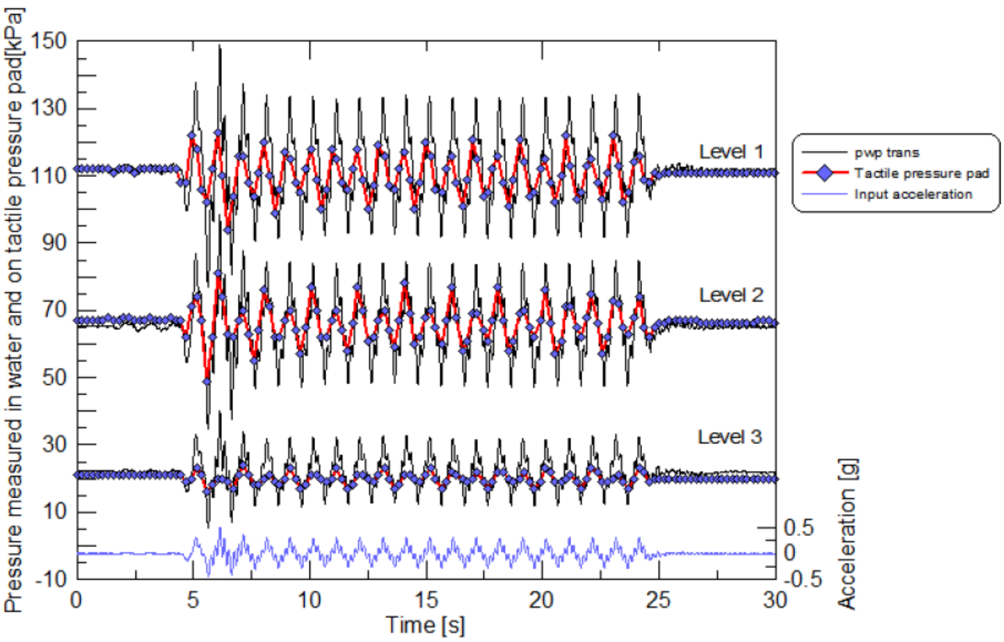

Figure 2. Comparison of pressure time histories recorded by Tekscan sensors and pore water pressure transducers (PPT) during centrifuge tests with water (Olson et al. 2011)

Due to their high cost and the difficulty of obtaining reliable dynamic pressure measurements from the aforementioned Tekscan sensors, individual tactile pressure Flexiforce sensors (type A201-1) were instead used by Al Atik (2008) and Sitar et al. (2012) testing at UC Davis' Center for Geotechnical Modeling (CGM). These sensors have a limited sampling rate and similarly have their own dynamic response. However, they are more economical and can be used as a secondary tool to measure pressure time histories, in parallel with indirect measurements with strain gauges. The reliability of these sensors for capturing high frequency dynamic pressures, however, is similarly not well-understood.

4. CHARACTERIZING SENSOR RESPONSE

The Tekscan sensor model used in this study (9500) had the capability to sample at 4000 Hz on each sensel, thus eliminating problems associated with aliasing observed with older sensor models. However, the inability of the sensor to capture the full amplitude response of dynamic loading remained. The sensor behaves in a similar manner to a spring: when loaded in compression, the sensor measures load that each sensel "feels". If the spring is compressed and unloaded at a high frequency, then the spring is unable to transfer the full magnitude of the load to the sensing elements before that load is released. By characterizing how the sensor records load over a range of frequencies, a filter may be developed to compensate for the loss of amplitude information at higher frequencies. In order to characterize the dynamic response of the sensor, a testing method was developed to load the sensor to relatively high frequencies using the Instron E10000 machine and centrifuge shake table at the University of Colorado, Boulder.

4.1. Loading Machine Tests

Material testing machines are commonly used in Mechanical and Civil Engineering to test the tensile, compressive, or cyclic fatigue properties of materials. An Instron model E10000 used in this study is capable of applying either force or displacement controlled static and dynamic loads to a material. The maximum frequency of its dynamic load depends on the load amplitude. For example, a sinusoidal load with an amplitude of 20 pounds may be accurately achieved by the Instron machine for up to a frequency of approximately 50 Hz. For higher frequency ranges, the Instron machine starts to produce varying amplitudes up to approximately 120 Hz, beyond which the signal to noise ratio reduces significantly. Centrifuge shake tables, however, can produce dynamic, broadband motions containing frequency content up to approximately 400 Hz or higher. Fig. 4 and 7 show variations in the achieved loading amplitudes at different frequencies obtained by the Instron machine.

Using the Instron machine, sine-sweep loads were applied to the Tekscan sensor. Both the Instron load cell and the Tekscan software simultaneously recorded the applied forces. In earlier tests, the Tekscan sensors appeared to have a strong component of noise near 60 Hz. Placing a grounding wire from the Tekscan data acquisition system to the base platform of the Instron machine helped eliminate the observed noise in its recordings.

In order to apply a sine-sweep loading sequence with the Instron machine, a test sequence was developed in steps: 1) the sensor was loaded from 0 to 150 pounds in compression; 2) a load-controlled, 20 pound-amplitude, sinusoidal load with a frequency of 1 Hz was applied for three cycles; 3) the frequency of the sinusoidal load was increased by increments of 1 Hz to reach 140 Hz; 4) the sensor was unloaded from its offset load of 150 pounds. The testing setup is shown in Fig. 3.

It is recognized that the initial testing setup used in this study does not reflect the soil-metal interface intended for the geotechnical centrifuge tests and that the interface is expected to play a major role in the static calibration factor. The influence of different material-sensor interface conditions (e.g., sand and metal) will be investigated in future static centrifuge tests.

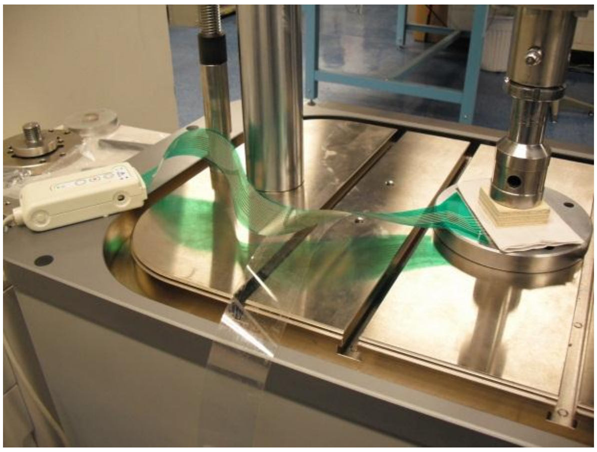

Figure 3. Instron testing setup for the dynamic calibration of Tekscan sensors

4.1.1. Static Calibration

The static calibration of Tekscan sensors is a sensitive process. The Tekscan manual (Tekscan 2011) recommends that the test material interface, contact pressure, temperature, and time duration of testing be mimicked as closely as possible to the actual test conditions. Once these conditions are met, one load point is sufficient to calibrate the sensors. Palmer et al. (2009) investigated the difference between using one, two, and five point calibrations. Using a two-point calibration appeared to provide increased accuracy over one-point calibration, but no difference was observed between two- and five-point calibrations. Calibration is unique for each sensor even under static loading; therefore each sensor requires individual calibration.

In this study, a preliminary static calibration factor for the Tekscan sensor was found using data from the sine-sweep test. This calibration factor was applied to all tests carried out using the Instron machine including the verification blind tests. The static calibration factor was calculated by dividing the average load cell value by the average Tekscan value recorded in the test. A calibration value of 0.0149 was then multiplied by all Tekscan data points to obtain pressure.

4.1.2. Dynamic Calibration

Data recording by the load cell and Tekscan began at slightly different times, therefore the two datasets needed to be aligned before calculating their transfer functions. Alignment was performed by identifying the first prominent peak in each set. Fig. 4 shows the data from the load cell and Tekscan after static calibration and alignment.

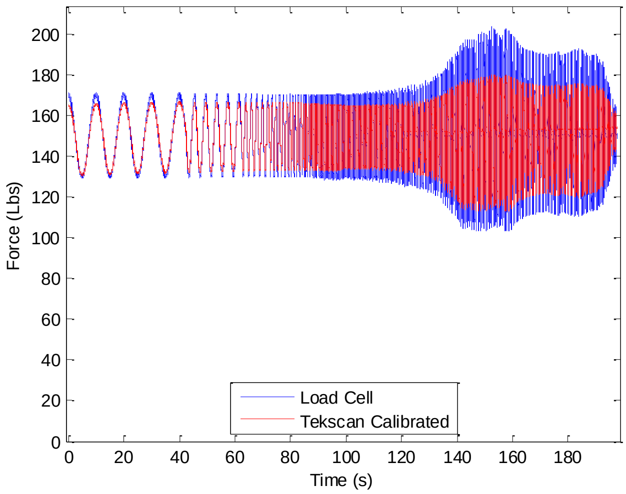

Figure 4. Comparing statically calibrated and aligned Tekscan data to Instron load cell data

For a sine-sweep load that had content up to approximately 120 Hz, the transfer function between the Tekscan data and the Instron load cell data (reference) was calculated. An optimum single parameter curve fit was then established for the transfer function. For this particular case, the best fit was defined by the function:

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

where A is a constant, in this case estimated to be 0.1085, X is the frequency input, and Y is the magnitude output of 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. Fig. 5 shows the transfer function developed to relate Tekscan and Instron data sets. Fig. 6 and 7 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 Instron data. The error between the two recordings in the frequency domain is presented in Fig. 8.

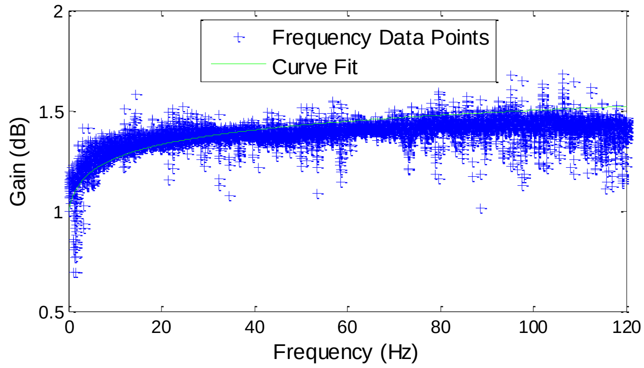

Figure 5. The transfer function relating Tekscan sensor measurements and the Instron load cell recordings

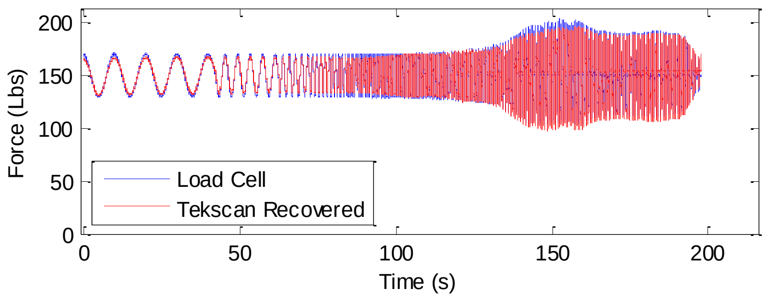

Figure 6. Comparison of the filtered (recovered) Tekscan data with the reference Instron recordings

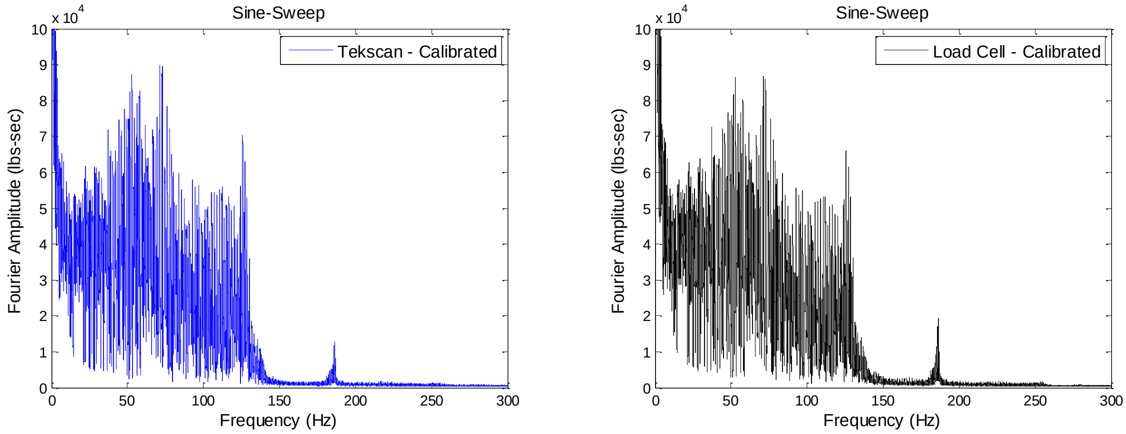

Figure 7. Comparison of Fourier amplitude spectra of the recovered Tekscan data with Instron recordings

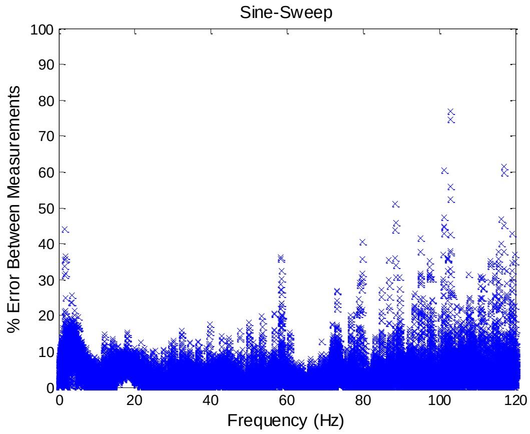

Figure 8. Error in the recovered Tekscan data compared to the reference, Instron recordings

5. VERIFICAITON TESTS

5.1. Blind Tests with Loading Machine

Three blind tests were performed to quantify the ability of the developed filter to accurately recover the reference signal recorded by the Instron load cell, as detailed in Table 1. The first blind test was a reverse sine-sweep that began with a frequency of 140 Hz and progressed toward 1 Hz. The second and third blind tests involved an application of random frequencies and amplitude contents at 100 and 130 lbs of loading offset, respectively. A comparison of the load cell pressure measurements with the recovered Tekscan data during Blind Tests 2 is shown in Figs. 9.

Table 1. Instron Blind Test sequence specifications

Blind Test	Load Offset	Signal Amplitude	Frequency Content
1	100 lbs	20 lbs	Reverse Sin Sweep: 140 to 0.5 Hz
2	100 lbs	Random	Random
3	130 lbs	Random	Random

Fig. 10 presents the error in the recovered Tekscan data compared to the reference, Instron recordings in Blind Test 2. The error in Blind Test 2 was less than approximately 12% for the duration of the test with an average value of just over 1%. Results for Blind Test 3 were similar to Blind Test 2, because the same sequence of random frequency and amplitude content was applied at a slightly greater load offset of 130 pounds.

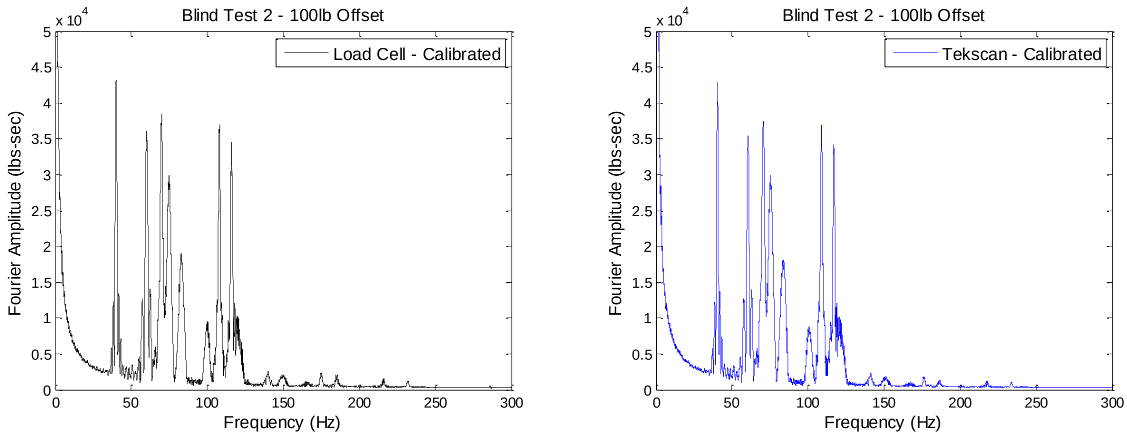

Figure 9. Fourier amplitude comparison between the recovered Tekscan and Instron load cell measurements in Blind Test 2

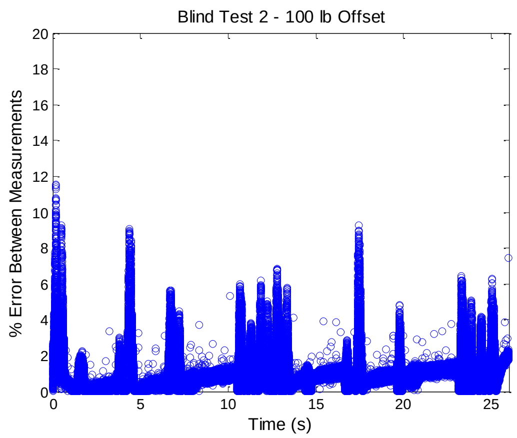

Figure 10. Error in the recovered Tekscan data compared to the reference, Instron recordings In Blind Test 2

5.2. Dynamic Centrifuge Tests

Following the initial validation tests with the Instron machine, the 400 G-ton centrifuge at the University of Colorado, Boulder with its 1-D shake table were used to test the reliability of Tekscan pressure sensors at higher frequency ranges not achieved by the Instron machine. Miniature pore pressure transducers (PPT's) were expected to measure high frequency dynamic pore water pressures relatively accurately and were used as reference pressure sensors (Olson et al. 2011). PPT's and Tekscan pressure sensors were placed in a transparent Flexible Shear Beam Container (Ghayoomi et al. 2012) filled with water to compare their measurements. A sequence of ground motions were applied to the base of the container, ranging from sine-sweeps to random vibrations and broadband earthquake motions. The testing configuration is shown in Figs. 11 and 12. Figures 13 and 14 compare the recovered Tekscan and PPT pore water pressure measurements during the application of a representative sinusoidal motion and an earthquake motion, respectively, in both time and frequency domains. The test results were generally satisfactory in terms of comparisons between the recovered Tekscan measurements and those of PPTs. However, additional centrifuge experiments are underway to better quantify the bias and reliability of Tekscan pressure sensors at higher frequency ranges in parallel with static centrifuge tests to model the intended material interface under increased gravity.

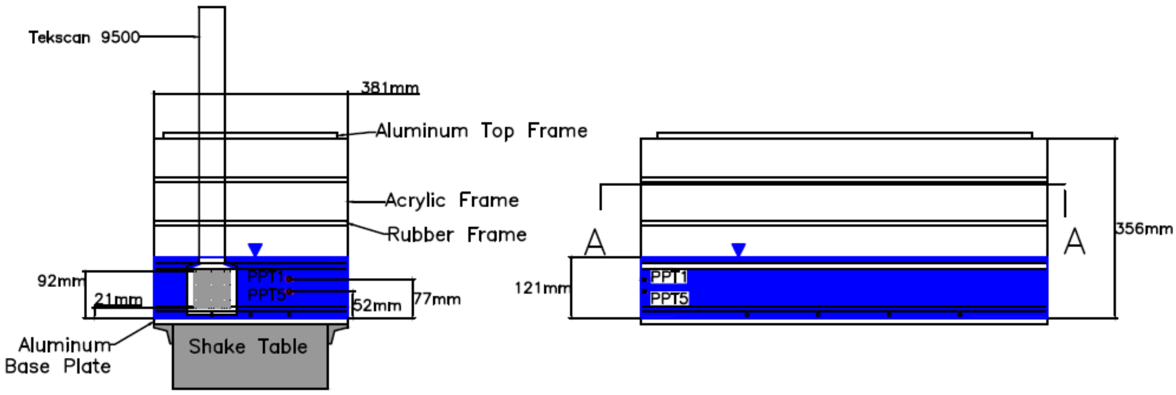

Figure 11. The schematic of dynamic centrifuge tests with water

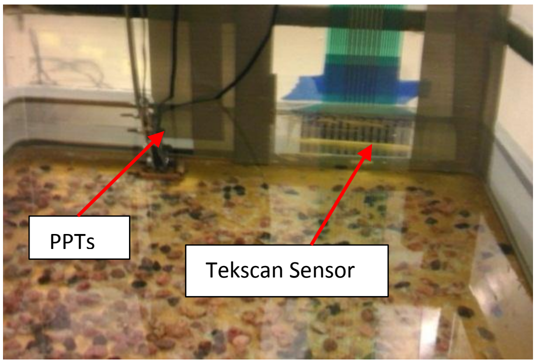

Figure 12. Setup for the dynamic centrifuge test

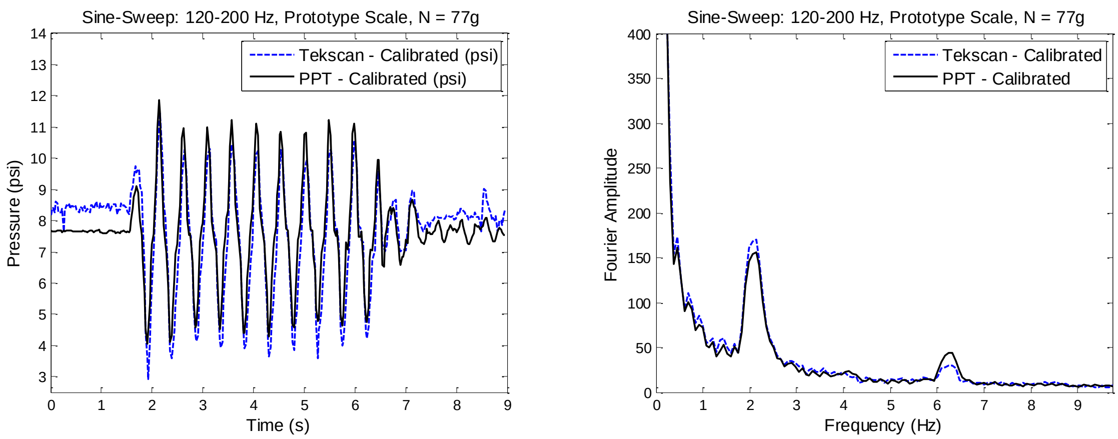

Figure 13. Comparison of the recovered Tekscan and PPT measurements in centrifuge with a representative sinusoidal input motion at 160 Hz in model scale (2 Hz in prototype scale) – measurements shown in the prototype scale

6. CONCLUSIONS

The characteristics of a promising Tekscan tactile pressure sensor technology used to measure dynamic earth pressures in geotechnical earthquake engineering applications was investigated. The primary goal was to enhance the sensor's reliability in measuring dynamic loading at higher frequencies. Sine-sweep loads were applied to the sensor with an Instron loading machine to characterize and calibrate its dynamic response. The transfer function relating the Tekscan sensor's measurements to those of the load cell was calculated, in order to develop a digital filter used to restore amplitude degradations. To test the performance of the filter, blind tests were performed with the Instron machine in addition to a series of dynamic centrifuge tests with water. It was shown that the digital filter significantly enhanced the ability of Tekscan sensors to more reliably measure dynamic pressures by better representing the amplitude content of the signal across a range of frequencies. Although additional tests are under way to better quantify the reliability of these sensors, the proposed testing methodology appears to be promising for dynamic centrifuge tests with high frequency ranges.

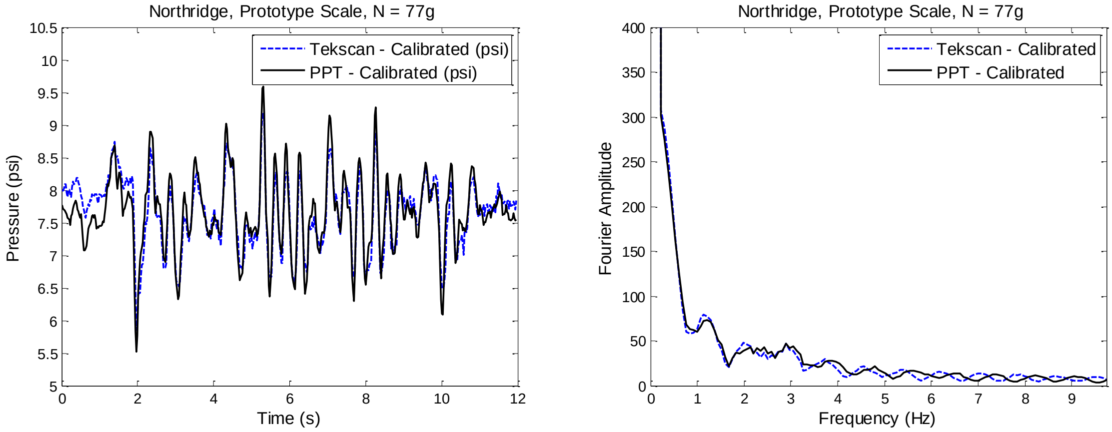

Figure 14. Comparison of recovered Tekscan and PPT measurements in centrifuge with a representative earthquake input motion – measurements shown in the prototype scale

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