The effect of granular material on stress state transducer

D Thungsotanon¹* and C Kulketwong¹

¹ Department of Engineering, King Mongkut's Institute of Technology Ladkrabang, Prince of Chumphon Campus, Chumphon, 86160, Thailand

Corresponding author: dithaporn.th@kmitl.ac.th

Abstract. Soil compaction is one of the serious problems in crop production. It occurs under stress conditions in soil, which are induced by agricultural machines. Therefore, it is necessary to characterize stress in the soil so as to predict soil compaction. A stress state transducer is a device used to derive the stresses in the soil. The purpose of this laboratory work was to study the effect of granular material, as a medium, on the static stress that occurs in each plane of the stress state transducer (σₓ, σᵧ, σz, σᵧz, σzₓ and σzᵧ). In the experimental test, a stress state transducer was placed inside dry sand with different granular sizes, then vertical pressure loading and unloading processes were applied to a range of 0-200 kPa. The z-direction stress was compared with the reference pressure and the results found that grade I sand gave a quite linear relationship between applied load as the equation σz = 0.747Peff + 16.5249, R² = 0.9866 and corresponding stress on the loading process. In the unloaded case, the pressure was higher than when load testing and had a hysteresis of 15.7305%. The relationship of stresses in the other planes was similar. A comparable tendency was observed in the larger granular sizes of sand, but with less linearity.

1. Introduction

Soil compaction is evaluated by using simple methods: soil bulk density, cone penetration, and infiltration. These methods approximate the final output result but do not explain soil-load deformation [1]. The phenomenon is determined by stress and strain. Timothy et al. [2] suggested and designed an instrument to measure soil stress state (σₓ, σᵧ, σz, τₓᵧ, τᵧz and τzₓ) having six pressure sensors buried in the designated plane. The octahedral normal stress and octahedral shear stress are calculated to define soil compaction and deformation, respectively. Many researchers use similar apparatus in their work.

Soil pressure measurement is divided into 2 types: internal soil mass and solid boundary. There is no single device available to measure the pressure in all soil types [3] because soil is very complex. The problem of the interface between the contact area of the sensor and soil [4] is important to researchers. A pressure sensor will be in direct contact with the soil. If the interfaces of the sensors have a higher stiffness than the soil, the value will higher. On the other hand, if the stiffness is lower, the pressure is less too [5]. The proportions of average sizes of granular material and the diameter of the sensors affect the hysteresis [6], in addition, the output signal is less than when testing with fluid [7]. Therefore, prior testing [3, 6] should estimate hysteresis, soil type, soil stiffness and load history and that the sensors are calibrated before use.
Much previous research found that calibration between sensors and granular material was required for accurate and credible results. At present, there is no research about the effect of stress state transducer (SST) in each plane ($\sigma_x$, $\sigma_y$, $\sigma_z$, $\sigma_{x1}$, $\sigma_{y2}$, and $\sigma_{z3}$) under a static load on granular material, therefore, this article focuses on the stress response for each SST plane.

2. Stress state transducer

The stress state transducer (SST) was a soil stress measuring device [2] that consisted of 6 pressure sensors. The 6 pressure sensors (Kyowa PS-10KD, Japan) were buried in each plane on a 50 mm aluminum ball. The ratio of sensitive area per overall area was less than 0.45 [2]. The INA 128 amplifier (Texas Instrument, the Philippines) in the SST was set up to amplify the output signal 1000 times, from mV to a range of 0-3 VDC to avoid the surrounding noise.

2.1. Calibration protocol

The sensitivity of the SST with the granular material under static calibrating considered the stress at each plane ($\sigma_x$, $\sigma_y$, $\sigma_z$, $\sigma_{x1}$, $\sigma_{y2}$, and $\sigma_{z3}$). The SST was mounted in a calibrated chamber as shown in figure 1. The chamber was designed with a large diameter to avoid the effect of the wall [4]. The material of the chamber was smooth steel and did not affect the friction between the granular material and the wall. The height of the sensor in the horizontal plane was equal to the value suggested by Dave and Dasaka [8]. Two types of sand were tested with particle size distribution that followed ASTM D422, as shown in figure 2. Dry sand, with a unit weight of a 16 kN/m$^3$, filled the chamber and enclosed the SST and the thickness was more than 1.5 times [8] the diameter of the pressure sensor ($\sigma_x$) for studying the impact of material thickness on the pressure transducer. Air pressure acted on a rubber membrane, the action impacted on the dry sand below the membrane. The reference pressure was measured by a pressure transducer (Bourdon Sedeme). The signal wire of the SST was connected to data acquisition that was NI 6210 (National Instrument, Finland) and the signal A/D was transmitted by using a USB wire to the computer to record and control, and processing was compiled by LabVIEW 2014.

2.2. Soil sensor calibration

This calibrating was to assess the sensitivity of the soil stress sensors. STT and dry sand were set up in the calibrated chamber, and then the pressure was gradually increased in the chamber from 0-200 kPa [9] and the air discharged at the same rate until 0 kPa. When the pressure was reached the required level, the data were recorded for 1 min. The data from the 6 pressure sensors and 2 kinds of dry sand were analyzed. The sensor in the horizontal plane ($\sigma_x$) was a parameter that explained the difference between testing and reference while the medium transformed by the referred pressure and sensor was the same direction. The sensors on the other planes were considered linearity because the pressure on the other planes did not act in the same way as the reference. The sensitivity of the sensors tested the hysteresis with discharge referred to pressure from the highest to the lowest value. The hysteresis
defined the difference between two pressure transducer output readings for the same applied load, one reading obtained by increasing the load from zero, the other by decreasing the load from the maximum rated capacity.

3. Results and discussion

3.1. Effect of particle size
The SST was calibrated with 2 kinds of sand in order to evaluate the sensor sensitivity in each plane. In fact, the selected sensors their properties were reported by the manufacturer. But in this testing, the sensors were laid on inclined planes that were different from the normal set up. The medium in testing was different from the water and air that are normally used for calibration [5]. It caused the issue of the pressure accuracy from the sensor.

Before, the sensor sensitivity was calibrated with dry sand and compared with manufacturer data sheet. The z-direction stress sensor was loaded and unloaded, the data were considered between 2 types of sand and reference pressure ($P_{\text{ref}}$) as shown in figure 3. The result found that the different sand grade affected the pressure at the z-direction sensor on the SST. Under load conditions, the pressure that was transmitted from grade I sand was closer to the reference pressure than with grade II sand. For grade I sand, the pressure of over 80 kPa had a lower tendency than the reference pressure due to the sand grain lock interaction changing, and caused pressure distribution on the membrane surface. The grade II sand also had the same trend. On occasion, the pressure of both grades of sand was higher than the reference pressure because of the stiffness between medium and membrane. This phenomenon was non-uniform stress distribution under over-registration state [4]. The obtained data was close and the trends were lower than the reference pressure when the pressure increased.

The sensors on all planes ($\sigma_z$, $\sigma_x$, $\sigma_y$, $\sigma_{n1}$, $\sigma_{n2}$ and $\sigma_{n3}$) were only considered linearity with the reference pressure. The linearity was important for the accuracy of the measurement devices. From testing, when sensors were calibrated with grade I sand, the sensitivities of sensors were linearity as shown in figure 4 and the linear regression analysis of every experiment as shown in table 1. The setup situations did not affect sensors. These results were similar to the calibrating with grade II sand.

![Figure 3. Relationship of z-direction stresses between load and unload.](image1)

![Figure 4. Relationship of stresses on x, y, n1, n2 and n3 under loading with grade I sand.](image2)

3.2. Unload effect
When the sensors were unloaded, the observed stresses were higher than the load testing. The difference between load and unload condition appeared in the middle of the tested pressure range as shown in figure 3 and figure 5. The result agreed with Miura et al. [7]. Under grade II sand conditions, the hysteresis of $\sigma_z$, $\sigma_x$, $\sigma_y$, $\sigma_{n1}$, $\sigma_{n2}$ and $\sigma_{n3}$ were 17.4998, 28.0130, 15.1277, 14.9611, 15.1898 and 12.9938 %, respectively. This phenomenon occurred similarly when using grade I sand. The hysteresis might arise from various factors: sensor properties, sand physical properties, the measurement device, and the surroundings. Therefore, the hysteresis was not caused by the sensor’s properties but might come from the sensor’s stiffness, side wall friction or particle distribution [7].
Table 1. Linear regression equations of different grades of sand.

| Stress | Grade I Sand | Grade II Sand |
|--------|--------------|---------------|
|        | $y = mP_{ref} + c$ | $y = mP_{ref} + c$ |
|        | $m$ | $c$ | $R^2$ | $c$ | $R^2$ | SEE | $c$ | $R^2$ | SEE |
| $\sigma_x$ | 0.3056 | -0.2286 | 0.9974 | 0.3991 | 2.1325 | 0.9973 | 1.287 |
| $\sigma_y$ | 0.2484 | 3.8239 | 0.9869 | 1.773 | 0.2619 | -0.7335 | 0.957 | 1.070 |
| $\sigma_z$ | 0.747 | 16.5249 | 0.9866 | 5.3913 | 0.8186 | 34.9757 | 0.9619 | 10.108 |
| $\sigma_n1$ | 0.4707 | 12.6803 | 0.9786 | 4.312 | 0.6327 | 5.5036 | 0.9957 | 5.1716 |
| $\sigma_n2$ | 0.6318 | 9.9066 | 0.9918 | 3.5553 | 0.5459 | 9.824 | 0.9772 | 5.1716 |
| $\sigma_n3$ | 0.6261 | 11.2928 | 0.9819 | 5.2663 | 0.4806 | 4.287 | 0.9949 | 2.1374 |

4. Conclusion

Particle size distribution affected by the obtained pressure. If the particle size were proximate, the accuracy of output would have been higher. The hysteresis behavior of the SST appeared when the pressure decreased. The grades of sand in this experiment slightly influenced the increasing or reducing of hysteresis and this phenomenon was not caused by the sensor properties. The hysteresis may from sensor stiffness, sand or the friction in the chamber. These sensors could rely on applying in the SST because their behaviors were linearity. The SST should be calibrated with the studied soil and dynamic test before using in the field. Moreover, the SST was applied to measure the absolute soil stress in rice and sugar cane fields during operating with a combine harvester and the sugar cane harvesting machine and transportation by a tractor that had a towed-trailer.

References

[1] Raper R L 2005 J. Terramechanics 42 259–80
[2] Timothy A N, Bailey A C, Clarence E J and Robert D G 1987 T. ASAE 30(5) 1237–41
[3] Talesnick M 2005 Geotech. Test. J. 28(2) 171-9
[4] Dave T N and Dasaka S M 2011 Int. J. Earth Sci. Eng. 4(6) 1031–4
[5] Labuz J and Theroux B 2005 Geotech. Test. J. 28(2) 188–96
[6] Miura K, Otsuka N, Kohama E, Supachawarote C and Hirabayashi T 2003 Soils Found. 43(5) 133–47
[7] Ramírez A, Nielsen J and Ayuga F 2010 Comput. Electron. Agr. 71 71–6
[8] Dave T N and Dasaka S M 2013 Geomech. Eng. 5(1) 1–15
[9] Pytka J J. Terramechanics 46 241–9