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The Use of Tactile Sensor Technology for Measuring Soil Stress Distribution

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Abstract
The commonly existing methods of evaluating stress distribution in soils rely on the use of buried or surface mounted load cells. These measurements are difficult to perform and are limited in their ability to capture the stress variation. A relatively new technology, which makes use of flexible, grid-based, tactile pressure sensors, allows to measure stresses at a large number of points in proximity to one another, hence providing a realistic normal stress distribution. Their thin (0.1mm) flexible film overcomes the effect of stiffness variation introduced by rigid load cells and thus allows for measurements that better represent the existing stress conditions. The application of the tactile pressure technology to soils requires adaptation and calibration due to its innovative principle of operation. Examples of work carried out over the past ten years are provided. The presented research addresses three subjects in soil mechanics: (i) the effect of grain size on stress distribution measurement along a boundary with a solid surface, (ii) the pressure dip under the sand heap, and (iii) the contact stresses under a rigid strip footing.

Introduction
Grid based tactile sensor technology enables to measure stresses at a large number of points in close proximity, thus allowing for a realistic normal stress distribution. The technology was originally developed at MIT’s Artificial Intelligent Laboratory by Hillis (1981) and Purbrick (1981), stimulated by dental application (Podoloff and Benjamin, 1989). A firm by the name of TEKSCAN has enhanced the product and its utilization for medical and engineering applications. TEKSCAN holds the proprietary and patented sensor technology.

TEKSCAN tactile pressure sensors are constructed of two polymeric sheets with pressure sensitive semi-conductive ink printed on one side of each sheet. The sheets are then laminated together with the printed sides facing each other. Usually, the ink is printed in rows on one sheet and columns on the other. When the two sheets are pressed together a grid of sensing areas (a.k.a. sensels) is formed. A “handle” which is clapped to the end of the sensor and product specific software allow for data acquisition and real time data manipulation and display. The sensor is scanned sequentially by rows and columns and the change in resistance is recorded in each of the sensels. This resistance change is then converted into Raw Sensor Data (RSD) units (0-255 scale using 8bit), which are then correlated to a pressure using a calibration process. Each individual sensor has its own unique properties and must be calibrated separately. For additional details and procedures, see Paikowsky and Hajduk (1997) describing the first application of the technology to geotechnical engineering. A brief presentation of sample applications follows.

Grain Size Effect on Stress Distribution
The effect of grain size relative to the measurement area was investigated. Seven natural sands and glass beads ranging in size from a very fine sand (#2429 round glass beads, D50 = 0.10mm) bordering silt to a very coarse sand (uniform 4mm rounded glass beads) bordering gravel were investigated (see Figure 1) in a specially constructed pressure chamber. The pressure was applied by a rubber bladder via the soil to the sensor positioned, (a) against a smooth metal surface and (b) embedded in the soil. Presented are sample results for the normal stress distribution against the solid surface in a soil-structure interaction mode. Figure 1 presents a schematic of the sensel area of the specific sensor used containing 16x8 sensels. A blown-up detail is provided to demonstrate the relative grain size/sensel dimensions. Figure 2 presents the stress variation along one column, i.e. 16 measurements showing that the larger grain sizes provide singular contact points arched in between by areas of no contact. The phenomena appears in both glass beads and sand, but is enhanced in the glass. Figure 3 provides 2-D and 3-D presentation of the stress distribution of the 4mm glass beads with the entire contact area.
Figure 1. Sensel detail, grain size distribution and grain sizes tested materials relative to a sensel area.

Figure 2. Interfacial stress distribution along one row of sensels; (a) glass beads.
Figure 2. Interfacial stress distribution along one row of sensels; (b) natural sands

4 mm glass beads against a solid smooth surface (Test# G4P9814)

Figure 3. 2-D and 3-D details of stress distribution of 4mm glass beads against a solid surface with histogram
The Pressure Dip Under the Sand Heap

The classical problem of the pressure distribution under a pile of sand was best described by Watson (1996), “The question is this; where does a conical pile of poured sand exert its maximum amount of pressure on the ground? Common sense would say in the middle, directly under the apex, but in fact the pressure maximum is a ring around the center point, there is actually a dip in pressure in the middle.” Investigation of the phenomenon using a pile of Ottawa sand poured over a mat sensor (421.5x482.5mm sensing area comprised of 48x42 grid of 7.5mm square sensels) is depicted in Figure 4 with the two and three-dimensional presentation of the results provided in Figures 5 and 6, respectively. The pressure dip is clearly visible and measurable consisting of about 77% stress reduction relative to the expected peak geo-stress. An excellent match exists between the integrated stresses and the weight of the poured sand (1.1% difference). In addition, a successful match was found between the measured stress distribution and a simplified elasto-plastic theoretical model.

Figure 4. Test set-up

Figure 5. Vertical stress distribution at the base of a sand pile
Contact Stress Under a Rigid Strip Footing

Common design of shallow foundations assumes simplified linear approximation of contact stress at the base of the foundation. In reality, however the distribution of the contact stresses is neither constant nor linear as pointed out by Terzaghi and Peck (1948). An investigation was carried out utilizing a model strip footing (3inch W, 24inch L, 2inch embedment) loaded in a tank of Ottawa sand with details provided by Paikowsky et al. (2000). The two and three dimensional stress-distribution under the footing at failure are presented in Figure 7. Figure 8 provides the average column stress distribution (across the base of the foundation) and a comparison between the average tactile sensor measurements resulting with an agreement of 1.5% differences between the two.
Conclusions

Tactile sensor technology is both revolutionary and promising. The technology provides the ability to observe physical behavior that previously could have only been imagined or theoretically predicted. Calibration process mimicking the expected test conditions resulted in accurate measurements of detailed stress distributions that were often validated through known forces. Successful implementation of the technology in geotechnical applications was carried out over the past ten years with three examples presented herein.

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