

Measurement of Stress in Sand

Carola Vogt-Breyer
University of Applied Sciences, Stuttgart, Germany
Gabriel Sedran
In-Depth Geotechnical Inc., Hamilton, Ontario, Canada
Dieter Stolle & Peijun Guo
McMaster University, Hamilton, Ontario, Canada



ABSTRACT

The measurement of stress in a granular material is challenging given the frictional nature of the material. Measuring devices have tendency to distort the strain field in the area where measurements are taken. To gain insight into the difficulties associated with stress measurements, laboratory tests and finite element analyses of the laboratory tests were undertaken to illustrate stress distributions around pill-box sensors. Measurement of lateral stress in a sand box specimen was also undertaken to evaluate the performance of sensors within a well-defined geotechnical problem. It was observed that applying a shear over the surface of a sensor results in a noticeable change in the distribution of the vertical pressure at the sand-diaphragm interface, both experimental and numerically. Stress measurements in sand can only be successful to a meaningful degree of resolution provided a well-devised technique is adopted.

RÉSUMÉ

La mesure de la contrainte dans un matériau granulaire peut être difficile en considérant le frottement du matériau. Les appareils de mesure ont tendance à déformer le champ de déformation dans la zone où les mesures sont effectuées. Des tests en laboratoire et des analyses par éléments définis de ces mêmes tests ont été entrepris pour illustrer la répartition de contrainte autour des capteurs à piluliers, fournissant une meilleure compréhension des problèmes associés aux tests de contrainte. La mesure de la contrainte latérale dans un spécimen de sable en bac a aussi été entreprise pour évaluer la performance des capteurs dans un problème géotechnique défini précisément. L'application d'une force cisaille sur la surface des capteurs a démontré la modification de la répartition de la pression vertical a l'interface entre le sable et la diaphragme dans le test en laboratoire et l'analyse numérique. La mesure du stress dans le sable est seulement réussie à un degré significatif si une technique bien conçue est adoptée.

1 INTRODUCTION

The stress distributions within a soil mass before and after construction are of great importance in the process of geotechnical design. If they were to be fully known by direct in-situ measurement of stresses, design procedures for geotechnical structures would be more efficient than is currently realized in practice, given that the level of uncertainty would be reduced. Stress measurements in the field (in-situ) and in the laboratory remain a difficult task. Some measurement techniques are better than others. The objectives of this paper are to report on experiences observed in the measurement of stress, particularly with respect to pill-box type sensors, and to analyze the normal pressures on a sensor.

We begin with a brief literature review that addresses stress transmission in particulate material and stress measurement using embedded sensors including their most important limitation, the problem of *under- or over-registration* of stresses because of soil arching developing around the sensor unit. The experimental work section that follows describes the laboratory evaluation of a diaphragm-based transducer and its performance when utilized within a dry prismatic laboratory sand specimen. An important aspect of the laboratory investigation was to examine the influence of shear on stress measurements in soil of different density. An investigation of the measurement of horizontal pressure in a large sandbox, in which the sensors were embedded flush with the wall,

was also completed. Finite element analyses (FEA) of the interaction between a stress sensor and the soil within a direct shear box specimen is also presented to gain insight into the impact of shear stress on the stress measurements within a sand. Laboratory and FEA results are discussed with the last section of the paper being dedicated to concluding remarks.

2 LITERATURE REVIEW

2.1 Particulate material

Referring to Figure 1, which shows a structure consisting of disks 1-1/4, 2 and 2-1/2 cm in diameter, we have a portion of a structured material that is eccentrically loaded from above. The two fluorescent lights (labeled L) in the background, which are 18 cm apart, help identify how the forces are transmitted through the medium. The irregular line (yellow) highlights a primary force chain, with the zone labeled S consisting of secondary force chains that provide support for the primary one; see, e.g., Shi et al. (2018). A slight disruption, say by vibration or surface loading, can break the primary chain to yield new ones. Such a material does not follow Hooke's law, is anisotropic, takes no tension and does not have a unique stress-strain relation (Kallstenius and Bergau 1956). This makes normal stress measurement in sand sensitive to particle shape and size distribution, density variation and presence of shear. Particulate models based on statistical

distributions for stress variation have been developed to predict stress transmission in non-cohesive soils (Harr 1977).

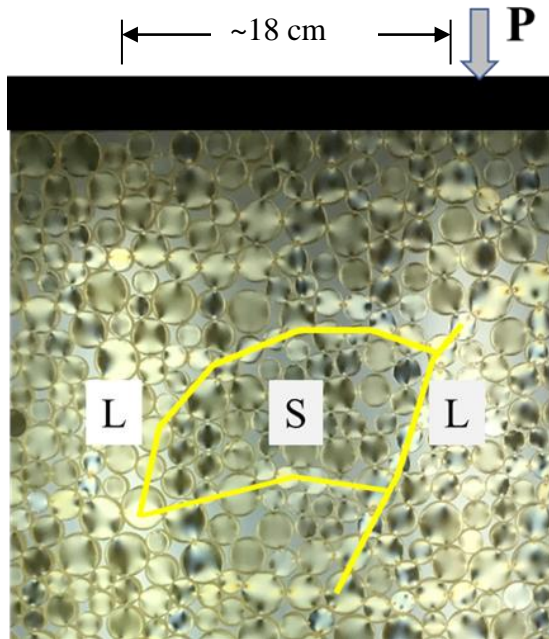


Figure 1. Particulate material in vertically mounted light table.

2.2 Stress measurements

Available procedures for measuring stresses may be classified within two general categories; *i.e.*, active and passive stress measurements (Dunncliff 1982 and 1988; Hanna 1985). Whereas active measurements may involve relatively large soil displacements to probe the stresses, passive stress measurements do not displace the soil significantly during measurements. Active measurements are usually attempted in the case of pre-existing soil masses or natural occurring soils, in which the stresses are estimated by probing the soil mass. Intrusive testing such as the Cone Penetration Testing (CPT) and the Flat Plate Dilatometer Testing (also known as the Marchetti Dilatometer, or DMT) are considered to belong to the active category. The stresses in the soil are estimated indirectly by means of empirical correlations that are specific to each testing technique (Houlsby and Hitchman 1988).

Passive techniques are adopted when a stress sensor can be inserted into the soil mass; *e.g.*, during backfilling operations. Such measurements are typically carried out in geotechnical applications involving, for example, footings, retaining walls, braced cuts, shoring structures, silos, embankments, and diverse laboratory research applications. Most passive stress measurements in geotechnical applications are performed by using earth pressure cells (Lazebnik 1998). To enhance the quality of

pressure measurements, the distortion of the stress field, due to the presence of the measuring device, must be minimized. Unfortunately, distortions cannot be fully avoided since the techniques usually involve straining the material for measurement purposes or introducing a foreign object into an assumed homogeneous medium that distorts the strain field. To help reduce the effects of distortion, a null soil pressure system was utilized by Talesnik (2015) that tolerated no compliance of the sensor. The corresponding approach would likely still have introduced an error if the strain field of the soil around the measuring device had been distorted.

2.3 Transduction of stresses

Stress sensors may operate according to different physical transduction principles; for instance, hydraulic pressure, strain gauge, vibrating wire, inductive and piezoelectric principles. One aspect common to all these devices is that they interact with the soil through a flexible diaphragm as a sensing surface (Hanna 1985). Ullidtz et al. (1996) reported the results of loading experiments in dry granular material for two different diaphragm sensors. In their experiments, the stress sensors were embedded in a shallow layer of dry sand, where the normal stresses acting over the surface of the sensor were approximately uniform; *i.e.*, very low normal stress gradients. In their report, the free-field stresses were evaluated by correcting the sensor output using an algebraic expression that accounted for the applied normal stress as well as the lateral confinement acting around the sensor. The algebraic expressions were derived from calibration tests under both fluid and soil pressure loading. Under these nearly ideal testing conditions, the use of diaphragm sensors was reported to provide satisfactory results.

Labuz and Theroux (2005) performed similar experiments with attention to the fact that the distribution of normal stress on a diaphragm is not necessarily uniform over the sensor-soil interface owing to soil arching effects. They used a sensor with a diaphragm below a film of hydraulic oil that could transmit a more uniform pressure to the deflecting diaphragm. Another sensor design, in which mercury is placed behind the sensing diaphragm to reduce its deflection, is described by Berthoz et al. (2013). The small deflections were assumed to reduce the pressure variations along the soil-sensor interface. By performing 55 calibration tests with different characteristics (including, sensor orientation, density, grain size distribution and water content) the coefficients of proportionality between the voltage delivered and the applied pressure were determined. Zhu et al. (2009) in their study concluded that detailed calibration tests for appropriate soil conditions and an anticipated loading history are essential when making in-situ stress measurements. Unfortunately, in many geotechnical applications the stress conditions and stress histories in the field are far from being ideal. Filz and Duncan (1993) and Filz and Brandon (1994) suggested that in most cases, stress measurements with diaphragm-based sensors are frequently erratic and difficult to interpret. The more recent studies just described show

that carefully considered calibration tests, which are customized to the prototype problem, are required to enable an acceptable reliability.

In terms of transducer output under fluid pressure, most diaphragm-based sensors provide highly accurate, stable, linear, and repeatable readings. This is due to the fluid pressure being hydrostatic. The fundamental limitation of diaphragm sensors when used in soil is the uncertainties associated with the measurement of distorted stresses at the soil-diaphragm interface. Owing to this limitation, earth stress sensors are rarely used to measure precise and accurate values of in-situ stresses, but rather are employed to acquire an approximate estimation of the changes in total stresses; see, e.g., Dunclicliff (1982).

As already alluded to, diaphragms sensors tend to introduce distortions in the stresses that are to be measured. The deflection of the diaphragm together with the stiffness of the sensor's housing tends to generate soil-arching over the sensing surface, causing local stress redistribution on the surrounding soil. A typical consequence of the stress redistribution is that the sensor under-registers the free-field stresses. Figure 2 presents two possibilities pertaining to under-registration. For both cases, corresponding to a horizontally mounted sensor above a rigid surface and flush with a rigid surface, respectively, we observe a load transfer from over the diaphragm to the wall of the sensor. For the case where a sensor's diaphragm is stiffer than the soil's skeleton, an inverse soil-arching occurs, resulting in an increased output of the sensor and an over-registration of the free-field stresses. Any mismatch between sensor and soil stiffness leads to over- or under-registration of the actual free-field stresses.

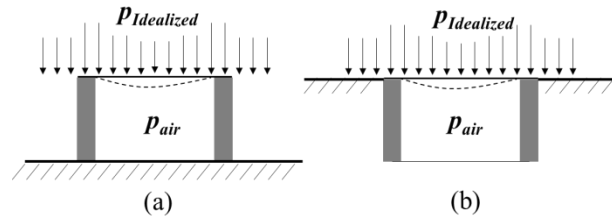


Figure 2. Idealized pressure distributions over sensors for horizontally mounted sensor: (a) above surface and (b) flush with horizontal surface.

To quantify over- or under-registration, Weiler et al. (1982) introduced the concept of a registration ratio $R = \sigma_c / \sigma_s$ where σ_c is the normal stress measured by the pressure sensor during calibration under fluid pressure, and σ_s is the free-field stress in the soil acting in the direction normal to the plane of the sensor. Values of R greater than one imply over-registration, and less than one mean under-registration. According to Hanna (1985), this ratio depends primarily on the sensor's aspect ratio; *i.e.*, the thickness-to-diameter ratio, and its overall stiffness. In general, diaphragm sensors with very small aspect ratio tend to minimize the effects of soil disturbance, thus reducing strain/stress distortions.

3 EXPERIMENTAL PROGRAMME

3.1 Calibration of sensors under isotropic loading

Granular materials play an important role in our daily lives, including geological and industrial processes. Depending on the conditions, sand can behave as a gas, liquid or solid (Jaeger and Nagel 1996), which makes it difficult to perform reliable measurements and model sand. Sedran (1999) investigated three types of stress transducers, one of which is the pill-box sensor shown in Figure 3. This sensor (12.7 mm in diameter, 4 mm thick) was investigated under two different loading conditions: isotropic loading in a triaxial cell, and vertical loading combined with shearing in a direct shear box

Given that this sensor was originally studied by Sedran (1999), the description of the calibration is only briefly repeated here. The first step for calibrating the sensor was to test it under fluid pressure with the sensor placed and sealed on the pedestal of a triaxial cell. The output, in micro-strain ($\mu\epsilon$) units, was correlated with the fluid pressure. The registration ratio of this sensor was then estimated by comparing the calibration under fluid pressure with the sensor readings for the case where the sensor was placed in dry "Ottawa" sand under isotropic loading. Referring to Figure 3, the registration ratio was estimated as $R = 0.2$. From this very simple example we find that sand for a geotechnical application does not behave as a fluid.

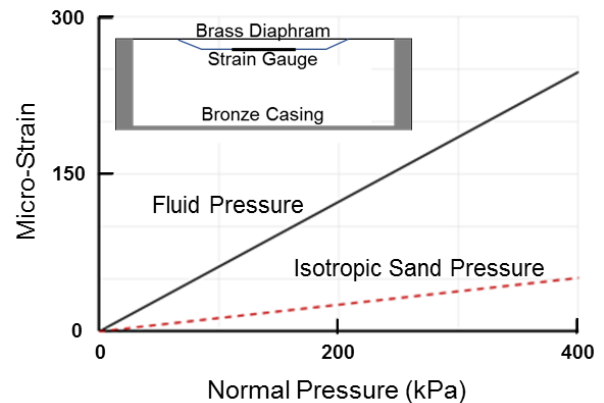


Figure 3: Pill-box diaphragm sensor and calibration response to triaxial loading.

3.2 Sandbox setup

The second part of the experimental program involved a larger scale test in a 1 m x 1 m x 1.2 m high sandbox, shown in Figure 4. Diaphragm sensors were installed vertically at different positions flush with the container walls, the bottom two sensors (out-of-view back and side walls) being 30 cm above the bottom. The purpose of these sensors was to measure the horizontal earth pressure under K_0 conditions. Air pressure was applied on the backside of each diaphragm to control the diaphragm movement; *i.e.*, to maintain zero displacement

of the diaphragm. The small deformations, which were recorded before corrections, were tracked by strain gauges on the underside of membranes. To reduce the effects of friction along the container walls, they were covered with two layers of plastic sheets with a thin film of mineral oil between the layers. Two series of tests were completed, one set involved loose sand that was placed by raining it slowly into the box, with the second prepared to a dense state using a vibratory compactor. An important consideration for building up the soil height was the minimization of the non-homogeneity of soil density in the box. The material was classified as poorly graded (dirty) sand that had a coefficient of curvature of 1.26 and a coefficient of uniformity of 4.09 with 6.26% passing the 0.075 mm sieve. The minimum and maximum void ratios (and corresponding unit weights) were $e_{min} = 0.335$ ($\gamma_{max} = 19.5 \text{ kN/m}^3$) and $e_{max} = 0.750$ ($\gamma_{min} = 14.9 \text{ kN/m}^3$), respectively.

A Marchetti dilatometer (DMT) blade was embedded horizontally in the center sandbox, 30 cm above the bottom to measure the vertical geostatic stress. The DMT blade, located at the geometric centroid of the box when viewed from above, was fitted with a 6 cm sensing membrane (diaphragm). Unlike the vertically mounted sensors, the DMT membrane was supported by the stiff blade (seat), which limits inward indentation (Marchetti 1980; and Marchetti, et al. 2001). Within the context of stress measurements within the sand box setup, it was however noticed that the initial vertical geostatic stress (~ 15 kPa assuming loose sand) at a depth of 0.8 m was not high enough to deflect the DMT membrane with regards to normal operation procedures. Estimates of vertical stress were subsequently based on the depth of soil above a sensor and assuming a unit weight of 17 kN/m^3 .

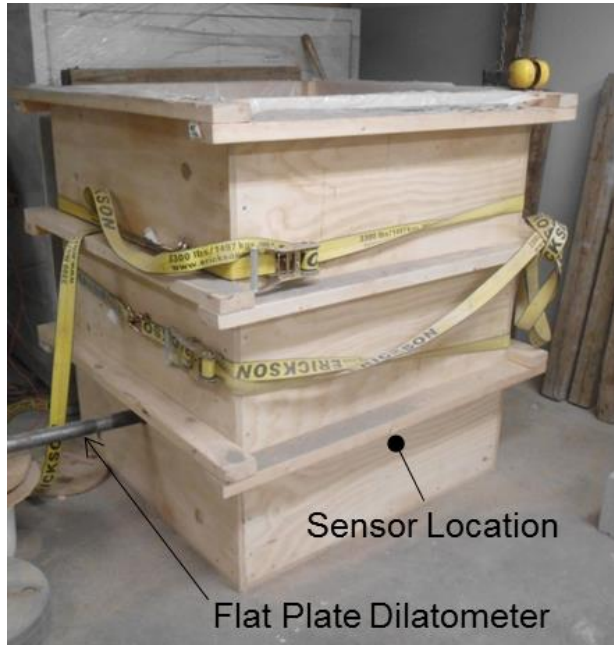


Figure 4. Sandbox showing location of sensors and DMT

4 FINITE ELEMENT ANALYSES

In addition to the laboratory tests, 2-D and 3-D finite element analyses were carried out to simulate the direct shear tests illustrated in Figure 5 and discussed by Sedran and Stolle (2001) using the commercial code PLAXIS. For the 3-D analysis the 10-node tetrahedral quadratic element was adopted to examine the performance of the diaphragm transducers under combined normal and shear loading, whereas the 15-node element was used for the 2-D simulations.

The test devices and transducers were assumed to be linearly elastic, with the soil behavior being modelled by the Hardening Soil (HS) model. In this model both a cap type yield surface and shear yield surface were used to model irreversible strains due to primary isotropic compression and deviatoric loading (Schanz 1998; Schanz et al. 1999). Unlike the Mohr–Coulomb Model, the relation between the axial strain ϵ_1 and the deviatoric stress q in primary triaxial loading is assumed to be a hyperbolic curve in the HS-model. The ultimate deviatoric stress at failure q_f is derived from the Mohr–Coulomb failure criterion involving the strength parameters cohesion c' and friction angle ϕ' . In the HS-model, an asymptotic value of the shear strength q_a is slightly above q_f that corresponds to failure. In addition, the dilatancy angle ψ serves to model dilatant behavior. Total strains are calculated by using a stress-dependent stiffness that is different for both loading and unloading/reloading. The following, optimized parameters were adopted for the analyses: unit weight $\gamma = 20.5 \text{ kN/m}^3$; $e_{init} = 0.5$; $E_{50} = 75 \text{ MPa}$; $E_{ur} = 255 \text{ MPa}$; $p^{ref} = 100 \text{ kPa}$; $m = 0.5$; $c^{ref} = 0.1 \text{ kPa}$; $\phi' = 35.45^\circ$; $\psi = 12^\circ$; $K_0 = 0.42$; and $OCR = 1.0$.

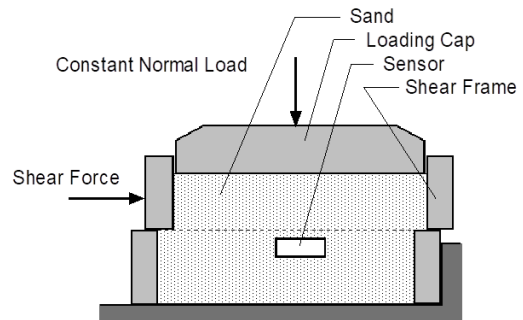


Figure 5. Direct shear experiment setup

4.1 Experimental and numerical results

4.1.1 Isotropic pressure loading in triaxial cell (400 kPa)

It has already been noted that the sand does not behave as a fluid, in which the stresses are hydrostatic. The stresses close to the sensor inside the sand and under normal loading were initially analyzed with a 2-D, axisymmetric finite element model. The plot of the directions of the principal stresses shown in Figure 6 demonstrates a non-fluid type stress distribution that led to a predicted under-registration ($R = 0.2$), which is the

same as that determined experimentally. It should be noted that the rotated principal stresses reveal the arching effect around the sensor. The calculation of the vertical stresses on the diaphragm shows that soil arching is mainly caused by the very stiff rim and soft response over the diaphragm sensing surface, which is reflected by the higher normal interface stress (603 kPa) at the rim when compared to the smaller value (80 kPa) at the center. The integration of the vertical stresses over the entire surface of the sensor gives a resultant force of 45.4 N, which corresponds to an average stress of 342 kPa. This means that the vertical resultant force acting on the transducer is less than what one would expect for the given confining pressure, which implies an average apparent registration ratio of $R = 0.86$. In other words, the transducer cannot properly estimate the pressure even when summing up the vertical forces on the transducer owing to the stress redistribution induced by arching.

The use of average pressure explains why the Labuz and Theroux (2005) procedure enhances the quality of the soil pressure measurements; *i.e.*, the presence of the oil provides a pressure redistribution over the diaphragm that better reflects the average vertical stress on the measuring device. Via a sensitivity analysis it was observed that the registration ratio improves as the diaphragm stiffness increases, which provides some support for Talesnik's (2015) procedure for improving soil pressure measurements.

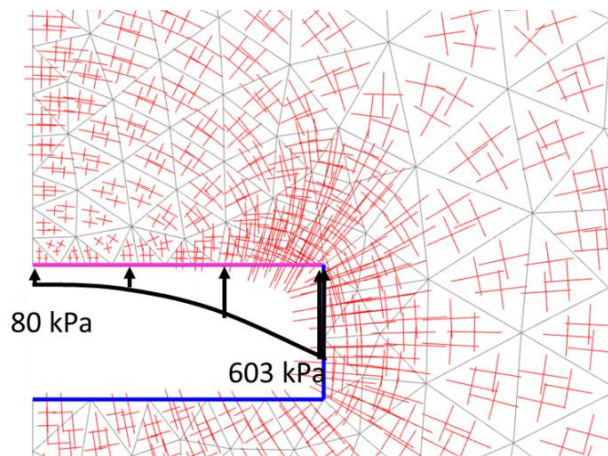


Figure 6. Direction of principal stresses and vertical stress on diaphragm surface

4.1.2 Shear (deviatoric) loading

In actual applications, we tend to have a combination of normal and shear loading, which begs the question: what influence does shear have on soil arching? The effect of soil-arching in the vicinity of the sand-diaphragm interface during shear was investigated experimentally and numerically. For this test the diaphragm sensor was placed within a direct shear sand specimen as shown in Figure 5. Under a constant normal stress of 38 kPa during the test, the initial normal stress was measured to

be 20 kPa, indicating under-registration. Even though the applied normal load was kept constant throughout the test, the adjusted sensor reading was found to increase with the applied shear force, which suggests that the soil-arching mechanism that initially formed above the sand diaphragm interface was dislodged or eliminated leading to a reorientation of principal stresses. For a horizontal displacement of 1.35 mm the measured normal pressure increased to 37 kPa.

Figure 7 shows the shear pattern for the direct shear test. Small pellets had been placed to keep track of what happened along the shear plane. Comparing the bottom (sheared state) to the top (initial state), dilation occurred as well as a counterclockwise rotation of the right side of the sand relative to the left. This somewhat counter intuitive behavior, when one considers how the load is applied, is attributed to soil dilation. Results from a 2-D finite element analysis shown in Figure 8 compares what happens along the shear plane for the cases of without and with a pill box placed just below the assumed shear plane. Even without a diaphragm sensor, the shear concentration is not planar, as is normally assumed. With the presence of the sear box, the shear concentration pattern is distorted with the distortion being consistent with the deformation that is observed in Figure 7.

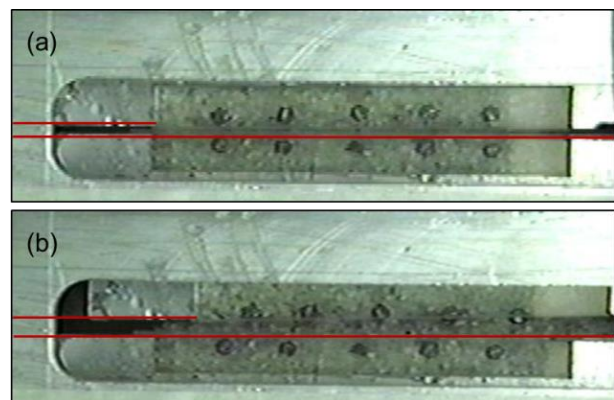


Figure 7. Direct shear pattern: (a) before shear and (b) after shear

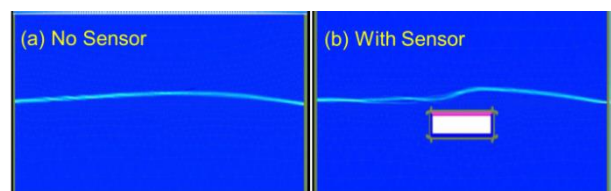
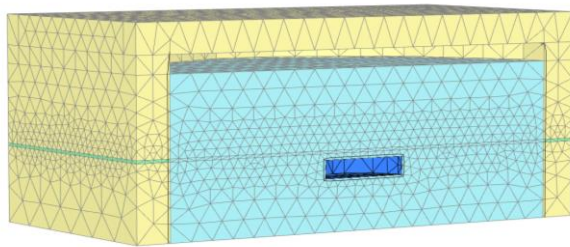


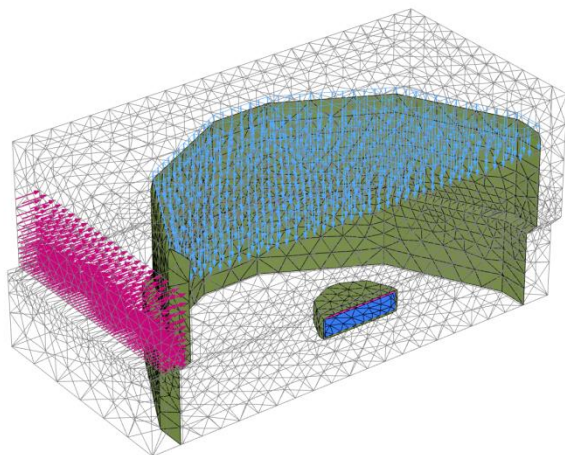
Figure 8. Predicted direct shear pattern (light curve)

A 3-D finite element model, as well as the distorted mesh of a direct shear test including a diaphragm sensor placed in the sand is shown in Figure 9. Along the outer sides of the transducer and the vertical surfaces of the shear box, interface elements were implemented. To

avoid singularities at corners associated a square shear box, an equivalent circular shear box was modeled. The effect of the shape of the shear box on the results in the vicinity of the sensor was assumed to be small. After generating the initial stresses, a constant normal surface traction was applied. This is different, when compared to the experiments, in which a rigid load plate is used to apply the vertical load. Shear was introduced by prescribing horizontal displacement without vertical fixity.



(a) Initial mesh



(b) Distorted mesh

Figure 9. Geometry of 3-D FE-mesh

Referring to Figure 10, the shape of the registration ratio curve at the center of the diaphragm was similar to that of the sensor reading for the 2-D simulation (not shown); i.e., it increased with increasing horizontal displacement (long-dashed curve). The sensor reading at the rim had a much higher value than that at the center in absence of shear and decreased with increasing horizontal deformation (short-dashed curve).

The variations of vertical stress when a sensor is present, before and after the specimen is sheared, are presented in Figure 11. An important observation is that the normal vertical stresses above the sensor become more uniform, although the stress distribution is no longer symmetrical. The higher normal stresses on the bottom right hand side are expected when one considers how the load is being applied.

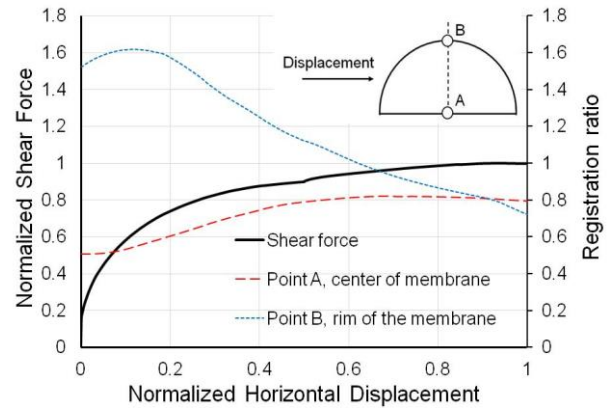
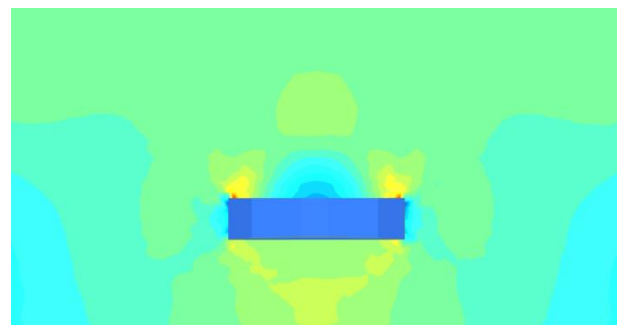
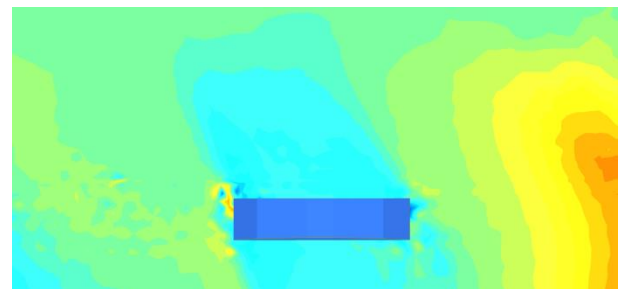


Figure 10. 3-D FE-analysis of shear test: registration ratio versus horizontal displacement



(a) Initial vertical stresses with zero applied shear



(b) Vertical stresses at maximum applied shear

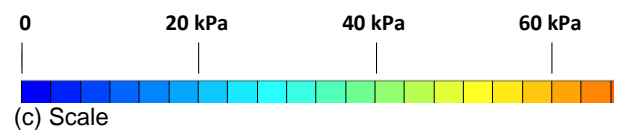


Figure 11. Vertical stress distribution corresponding to an applied vertical normal stress of 38 kPa

4.1.3 Sandbox test

The main purpose for this phase of the study was to attempt to measure the horizontal pressure under K_0 conditions (zero lateral strain). Horizontal stresses measured along a wall are known to be sensitive to the

manner, in which the sand is placed; i.e., statically compacted versus use of vibration.

It was found that recording the measured horizontal pressures was tricky given the sensitivity of the measuring devices and the arching that developed after the diaphragm was pushed in, however small. When increasing the horizontal pressure to accommodate the increase in pressure due to filling the container, it was observed that overshooting the zero displacement (based on membrane strain) and then trying to compensate by reducing the air pressure to attain zero strain introduced errors for both dense and loose soil states, which led to errors in the lateral earth pressure measurement. Subsequent decreasing and increasing of pressure resulted in non-unique pressure measurement. This was attributed to the frictional properties of sand and the corresponding soil arching.

Loading and unloading led to normal stress-displacement hysteresis involving passive-active loading cycles. By rodding the sand in front of sensor with a 12.5 mm diameter steel bar (similar to what is done during a slump cone test for concrete) or by hammering the container wall, the K_0 value could be increased for both the loose and dense state. The disturbance by cyclical loading destroyed any arch that may have developed in the vicinity of the sensor, as well as the influence of the previous loading-unloading history. For loose sand this was not expected since shear tends to decrease void ratio and cause local stress relaxation, which in turn should have reduced the K_0 value. Most important is that after the first movement of the diaphragm further loading-unloading was not accompanied by a repeatable pressure-strain behavior even though the displacement amplitudes were small. On the other hand, the measured pressure on the sensor for both loose and dense states displayed consistency in value after rodding; i.e., after the soil in the vicinity of the sensor was sheared. Based on the initial measurements, the K_0 -value ranged between 0.4 and 0.5, compared with $K_0 = 0.42$ from Jaky's equation.

5 CONCLUDING REMARKS

The measurement of stress/strain in a granular material can be quite challenging given the frictional nature of the material. Measuring devices have a tendency to distort the strain field in the area where measurements are taken. An important tool in the interpretation of results is the use numerical modeling; i.e., finite element analysis.

The following additional observations are noteworthy:

- The registration ratio of diaphragm sensors depends significantly on the stiffness-relation between sand and diaphragm and on the stress state above the sand-diaphragm interface. Isotropic loading leads to pronounced soil arching particularly for high density sand. Applying a shear force in a direct shear test results in a noticeable change in the distribution of the vertical stresses on the sand-diaphragm interface, both experimental and numerically. In the shear test, the responses and hence also the registration ratio

of the diaphragm sensor increases with increasing horizontal displacement.

- The principle of a flat plate dilatometer (DMT) using a rigid plate (seat) under the membrane and measuring the pressure for minimally raising the plate (loosing contact to the seat) is generally suitable to register existing stress conditions because of the very small deformations. Nevertheless, the stiffness of membranes used in a standard DMT dilatometer for field investigations tends to be too stiff for model tests at low stress levels; i.e., stresses corresponding to depths below 2 m.
- Diaphragm sensor readings are sensitive to local variations in soil density. As a result, the shearing of soil that changes the local density has an impact on the readings. In other words, the measurement of the actual global variation of normal stress can be distorted.

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