Tactilus® Sensor

Potential applications for surface mapping sensors in the area of civil engineering: Structural and geotechnical applications

By:

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April, 2009

Background

The Transportation Research Board Soils and Rock Instrumentation Committee has identified a need for research in the field of earth pressures measurements (TRB 2007):

> Measurement of earth pressure, both within granular soil deposits (e.g. embankments and dams) and at the contact interfaces with rigid structural elements (e.g. sheet pile walls, retaining walls, piles, and buried culverts) is of increasing importance in engineering practice. Recent advances in geotechnical/structural systems (e.g., geofoam and lightweight foam concrete embankments, and integral abutment bridges, among others) present innovative solutions for design engineers, but also need field performance verification and monitoring. Accurate and reliable measurement of earth pressures has been an elusive goal for many decades, and with these new foundation and wall systems, has taken on more importance than in previous, more conventional applications. Valid earth pressure measurements will assist state DOTs and their contractors in developing reliable load combinations for new geotechnical/structural systems as well as those associated with traditional systems. These measurements will also be valuable for health monitoring and long-term performance evaluation.
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> The importance of, and high degree of uncertainty in earth pressure measurements is reflected in relatively conservative design assumptions. This typically results in solutions that may not be cost effective. With the current transition in the AASHTO code from allowable stress design (ASD) to load and resistance factor design (LRFD) for all transportation facility design, this high level of uncertainty will be further exposed.
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> To date, instrumentation for earth pressure measurements have traditionally focused on the diaphragm hydraulic or strain-gage based sensors, commonly known as earth pressure cells (EPC). As is well documented, the sensor deformation required for measurement can induce localized arching and produce unreliable earth pressure measurements that will tend to be higher than the actual in situ earth pressure. Various installation methods of EPCs have been developed to minimize these compliance issues. In spite of these and other developments, issues including calibration, installation, hysteresis, and arching have not been resolved regarding sensor design and installation methods. New technologies, such as tactile pressure sensors, may offer new opportunities to achieve more accurate earth pressure measurements at lower costs.

Liu and Yeung (2008) successfully performed laboratory-scale experimental work with a tactile sensor to determine the vertical stress distribution underneath sand columns. Paikowsky et al. (2006) reported the results of three experiments to investigate the performance of tactile sensors. First, they investigated the effect of grain size on the stress distribution measured by a tactile sensor. They found that larger grain sizes provide singular contact points arched in between by areas of no contact. Second, they utilized a tactile sensor to investigate the classical problem of pressure distribution under a pile of sand. The experimental results agreed with the solution described by Watson (1996) indicating that the maximum pressure occurs in a ring around the center point and there is a dip in pressure in the middle. The integrated stresses also showed an excellent match (1.1%) with the measured weight of the sand. Third, a tactile sensor was used to measure the stresses under a rigid strip footing at failure. It was found that the average measured stress was within 1.5% of the calculated average stress.

In conclusion, TRB (2007) has identified a clear need for reliable and accurate instrumentation to measure earth pressures. The reasons behind this have been summarized here. The disadvantages of traditional earth pressure cells have been identified and tactile sensors have been proposed as a solution for obtaining these measurements at lower costs. Recent studies have also been briefly summarized that have successfully implemented tactile sensors. Considering this, a series of potential applications for the Tactilus® sensor are described below. The applications are divided into two main categories: applications in structural testing and geotechnical applications.

Applications in Structural Testing

Load application and support conditions – Load application and support conditions require special attention when performing structural testing of compliant or non-prismatically shaped structures. As a specific example, airbeams (see Davids et al. 2007 for more information) are generally compliant and have a circular cross-section, so it can be challenging to apply loads perpendicular to the structure without causing localized stress concentrations. Further, it is important to apply loads in such a manner that the contact stress does not exceed the inflation pressure. If this occurs, localized deformations may develop that would invalidate the assumption of a circular cross-section prior to wrinkling. Thus, the Tactilus® sensor could be utilized to measure the applied stresses determined if they exceed the inflation pressure of the specimen in this case. The stresses measured by the Tactilus® sensor could also be implemented in a 3D finite element model in order to more rigorously study the effect of nonuniform contact stresses at the supports and load points. This is just one specific example, but there are countless applications in structural testing where the Tactilus® sensor could be utilized to measure contact stresses at the supports and load points in order to better understand the response of the structure as a whole.

Compression testing – Concrete and asphalt strength and stiffness are often quantified by performing compression testing on core samples (ASTM C 31 and AASHTO TP 62-03, respectively). Ideally, a constant compressive stress is applied to each end of the core. However, typically only the total force is recorded, so a uniform stress is assumed. The Tactilus® sensor may be utilized in this scenario to measure the actual contact stresses between the testing fixtures and the specimens. This information may allow different fixtures to be examined to determine which results in the most uniform stress distribution. Additionally, this information could be implemented in a finite element model to examine the significance of the measured non-uniform stress distribution as compared to the typically assumed uniform stress distribution.

Confining stresses – Tension-resisting materials are sometimes wrapped around concrete core specimens in an effort to increase the strength and stiffness of the specimens in compression (e.g. Monti 2001). As the concrete specimen is loaded vertically in compression, it expands horizontally, but this expansion is restrained by the confining material and compression is developed at this interface. The Tactilus® sensor can be utilized to measure the compressive stresses at the interface of the specimen and the confining material by placing it along the inside surface of the confining material and then casting the specimen. This information may lead to a better understanding of the constitutive relationships of the composite material.

Blast testing – Structural performance under blast loads is an area of interest to the U.S. Army. For example, a modular ballistic protection system was recently developed and tested under blast loads (University of Maine, 2007). The blast test subjected the structure to non-uniform pressures that varied rapidly as a function of time. The Tactilus® sensor may be a valuable tool for recording the stresses that are applied to a structure under blast loads since it is capable of recording the non-uniform stress distribution at a frequency of up to 1000 Hz.

Modeling – The Tactilus® sensor is very well suited to providing data for the purpose of calibrating or validating finite element models. The Tactilus® sensor has the potential to provide a 64x64 matrix of spatially varying stress data (over 4000 data points), which may represent full-field stress data in many situations. This nicely complements a finite element model that is also capable of predicting spatially varying stresses. This may have significant implications in many applications since it may lead to a better understanding of the mechanics of the system being modeled.

Geotechnical Applications

Bridge abutments – Hartt (2005) installed earth pressure cells to monitor the stresses on the abutments of an integral abutment bridge. Abutments are the primary supporting element of the bridge superstructure, so it is critical to quantify the earth pressures acting on the abutment when analyzing the structure as a whole. This is especially true in the case of integral abutment bridges, since the abutments are cast integrally with the girders that form the bridge superstructure, but is also true for the case of traditional bridge construction with expansion joints. The Tactilus® sensor has great potential in this application since it is capable of measuring stresses at over 4000 points and can also conform to the non-planar shape of some abutments.

Retaining walls – Retaining structures such as sheet pile walls or gravity walls are structures that are designed to resist the stresses that are applied by backfill which often consists of earth or other material. Sheet pile walls are constructed by driving prefabricated sections into the ground. Soil conditions may allow for the sections to be vibrated into ground instead of it being hammer driven. The full wall is formed by connecting the joints of adjacent sheet pile sections in sequential installation. Sheet pile walls provide structural resistance by utilizing the full section. Steel sheet piles are most commonly used in deep excavations, although reinforced concrete sheet piles have also being used successfully (Deep Excavation LLC, 2009). The success of the structure is often governed by its ability to resist the overturning moment applied by the backfill material. Typical design procedures are generally very conservative and the stresses acting on the retaining structure are therefore likely over-predicted. The Tactilus® sensor can be utilized to measure the actual stresses applied by the backfill and therefore the actual applied overturning moment can be calculated. The factor of safety could then be determined and the retaining wall design could be evaluated in terms of cost effectiveness and safety. This may be especially useful when investigating alternative backfill materials such geofoam or tire derived aggregate. The

Tactilus® sensor also has the advantage of being able to conform to non-planar surfaces such as the typical corrugated shape of sheet piles.

Shallow foundations – A shallow foundation is considered to be any foundation that is supported by the soil lying immediately beneath the structure (Lambe and Whitman, 1969). Individual footings, usually rectangular in plan view, are the most common shallow foundation for columns, whereas strip footings are used to support walls. The selection of a foundation is often guided by tables of allowable bearing stresses. Most building codes contain such tables, based upon general experience with soils in the area to which the code applies. These allowable stresses usually lead to conservative designs for low buildings supported on spread footings. Stresses can be predicted using elastic theory. Alternatively, the Tactilus® sensor can be implemented to measure the actual bearing stresses and thus more accurately evaluate the engineering design.

Geofoam and other lightweight fill applications – Geofoam is a lightweight, rigid foam plastic that has been used around the world as a fill for more than 30 years, according to FHWA (2009). Geofoam is approximately 100 times lighter than most soils. This extreme difference in unit weight compared to other materials makes Geofoam an attractive fill material. It can be used to reduce loads on underlying soils or to build highways quickly without staged construction. It can also be used to repair slope failures, reduce lateral loads behind retaining structures, and minimize differential settlement at bridge abutments. The potential benefits of lightweight fills make them an attractive choice for engineers, but direct measurements of benefit (i.e. reduction of stresses) such as can obtained with the Tactilus® sensor may be necessary in order to determine the cost effectiveness of the product in particular scenarios.

Culverts and other buried pipe structures – According to Spangler (1958), the supporting strength of conduit culverts depends primarily on three factors: 1. the inherent strength of the conduit; 2. the distribution of the vertical load and bottom reaction; and, 3. the magnitude and distribution of lateral earth pressures which act against the sides of the structure. The same basic principles apply to buried pipe structures of any kind. The Tactilus® sensor can be utilized in the investigation of culvert or buried pipe design by directly measuring the distribution of stresses around a pipe since the Tactilus® sensor can conform to the circular shape of the culvert. This addresses the second and third factors suggested by Spangler (1958). This may be especially useful when investigating alternative fill materials. As an example, Sun et al. (2005) performed a numerical analysis to investigate the effect of geofoam backfill on the stresses acting on a culvert. They determined that the geofoam has a great effect in reducing vertical stresses above and below the culvert, but experimental data was not collected to verify these findings. The Tactilus® sensor is ideally suited to providing experimental data to compare with their numerical solutions or for other cases.

Effectiveness of soil mixing procedures – According to Deep Excavation LLC (2009), various methods of soil mixing have been used widely in Japan for about 20 years. Soil mixing has also been used for many temporary and permanent deep excavation projects including the Central Artery project in Boston. Many different methods exist to mix soil in different applications, each of which aims to provide the most efficient and economical method to mix cement with soil and transform soil to become more like a soft rock. The effectiveness of the soil mixing procedure (for example, at reducing lateral earth pressures acting on a structure) can be quantified by utilizing the Tactilus® sensor.

Earth dams – Earth dams are structures that are primarily comprised of soil with the purpose of retaining water. Earth dams are the largest earth structures and the most critical in terms of safety. Numerous earth dams have failed and substantial loss of life has been incurred (e.g. Malpasset Dam, 1959). Terzaghi et al. (1996) stated that the most important source of error in the effective stress stability analysis of earth dams is in the evaluation of the intensity and distribution of the pore pressures. Thus, the Tactilus® sensor has potential in earth dam applications since it can be utilized to measure in situ pressure distributions.

Pavement systems – Clapp (2007) reported the results of studies that utilized stress sensors embedded within the supporting layers of a flexible asphalt pavement system. The objective was to determine the effectiveness of geogrid reinforcing in the pavement base layer. Stresses and strains were measured in order to incorporate the findings into modifications to the current pavement design guide, NCHRP 1-37A, Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (http://www.trb.org/mepdg/). It is critical to quantify pavement improvement due to geogrid or other reinforcement in terms of stresses and strains. Thus, the Tactilus® sensor has great potential in the field of pavement engineering since mechanistic data (i.e. stresses) are required to conform to current design procedures.

Centrifuge testing – Centrifuge devices have been utilized to simulate the effects of earthquakes and landslides. These phenomena can cause surface faulting, seismic settlement, and lateral spreading due to soil liquefaction (Ha et al., 2008). Ha et al. (2008) utilized a centrifuge to investigate the effect of earthquakes on buried pipelines. Tactile sensors were successfully utilized to measure the stresses at the interface of the buried pipeline and surrounding soil. The Tactilus® sensor is well suited to measuring stresses in soils or at soil-structure interfaces in tests performed in centrifuge devices (i.e. to simulate earthquakes and landslides) because of its ability to collect stress distribution data at a high frequency.

Storage containers – A thorough understanding of the stress distribution within granular material and the pressure acting on the retaining storage structures (e.g. silos) are problems of practical importance to engineers (Liu and Yeung, 2008). The Tactilus® sensor may be utilized in this application for measuring vertical stresses at the bottom of the storage container and/or horizontal (radial) stresses acting on the sides of the retaining storage structure. These measurements may lead to a better understanding of the stresses that must be resisted by the structure and consequently a more efficient engineering design.

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