Patents and Techniques of Contact Pressure Measurement in Geotechnical Engineering

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Abstract: Measuring the contact pressure between a structure and the surrounding ground is essential for the analysis and design of different geotechnical engineering systems (e.g. foundations, underground tunnels, buried pipes, vertical shafts and retaining walls). Several devices and techniques have been recently developed to facilitate the measurement and monitoring of contact soil pressure. These devices range from stiff pressure cells that measure the soil pressure against a structure at specific locations to flexible tactile sensors that can track the pressure changes continuously over a large contact area. This paper presents a review of selected devices and techniques commonly used to measure contact pressure in different soil-structure interaction problems. Selected US and international patents of relevance to contact pressure measurement in geotechnical engineering are referenced. A comparison between the different measurement techniques with respect to their applicability and limitations is also presented.

Keywords: Soil pressure cell, contact pressure transducer, recent patents, pneumatic pressure devices, tactile sensors, fiber optic sensors.

1. INTRODUCTION

Pressure measurements in soils fall into two basic categories: measurements within the soil mass and measurements at the interface between a structural element and the surrounding soil. Conventionally, embedded load cells have been used to determine the magnitude and distribution of in-situ stress within embankments and backfill material. Applications of contact earth pressure cells include measurement of pressure against retaining walls, culverts, piles and shallow foundations. The main reasons of using earth pressure cells are to confirm design assumptions and to provide feedback to improve future design.

The field of soil instrumentation is complex and rapidly evolving, and has been covered in detail by many authors. Carlson [1] is considered to be among the first who measured compressive stresses in concrete using load cells and showed that a cell stiffer than the surrounding material would indicate a higher stress state. Later studies by Taylor [2], Monfore [3], Peattie and Sparrows [4] investigated the effects of shape and internal construction of the gage on the measured pressure. A comprehensive survey of the use of pressure cells to measure stress states in soil has been made by Selig [5], Hanna [6] and Dunnicliff [7]. These studies aimed at developing a better understanding of the behaviour of large pressure cells when placed “in concrete” or “in soil” structures. An important criterion required for earth pressure measuring instrument is that it should be capable of determining a required parameter, such as pressure, or displacement, without leading to a change in that parameter as a result of the presence of the instrument in the soil.

This study, however, deals only with those types of instrument used to measure contact pressure acting on subsurface structures. Lazebnik and Tsinker [8] reviewed the different monitoring techniques used in soil-structure interaction problems focusing on the practical approaches of developing, calibrating and installing soil pressure measuring devices. This particular application requires a device that is rigid enough such that the sensing surface is not deformable during the loading process. It was concluded [8] based on several field studies that the best results can be achieved when pressure cells are installed in groups of three to four or covered by rigid plate flush-mounted with the underside of footings or the backside of the retaining structure. This was found to average out the soil reaction or lateral pressure and local discontinuities in the soil over the larger contact area of the plate.

The above studies among others contributed significantly to the state of knowledge in the field of instrumentation and provided engineers and researchers with guidelines as to the suitability of different devices to a given project. However, the evolving technology over the past decade has lead to the introduction of more techniques that have been adapted from other industries to suit geotechnical engineering applications.

The objective of this paper is to provide a review of contact pressures measurement techniques with a focus on the recent advances that have been successfully implemented in geotechnical engineering. A brief overview of the conventional contact pressure devices will also be provided. The concept and background of each device along with examples demonstrating its application will be presented.

2. LOAD CELLS

A load cell is a transducer that converts force into a measurable electrical output. Load cells have been widely

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used for measuring contact soil pressures in different geotechnical engineering applications including foundations, retaining walls, pavements, buried pipes and tunnels. The main advantage of using load cells is the extensive experience in different types of geotechnical projects accumulating over more than 70 years. In addition, there are various types of commercially available transducers with application-specific documentation and installation procedure. Load cells consist mainly of a disc of certain stiffness connected to a transducer. This disc is then placed atop of the surface where soil pressure is to be measured. Once the deformable face is pressed, a signal is sent to the transducer and converted into an equivalent earth pressure reading using a data acquisition system.

Load cells are often distinguished according to the type of output signal generated (hydraulic, pneumatic, electric, etc.), a brief description of the commonly used types is given below.

Hydraulic load cells are force-balance devices measuring the change in pressure of the internal filling fluid [9]. The applied pressure is usually transferred to a piston that in turn compresses the filling fluid confined in a diaphragm chamber as shown in Fig. (**1**). Since this sensor has no electric components, it is ideal for use in hazardous areas. Pneumatic load cells also operate on the force-balance principle. They contain no fluids that might contaminate the surrounding medium if the diaphragm ruptures. The resonant-wire pressure transducer was introduced in the late 1970s [10, 11]. A wire is gripped by a static member at one end, and by the sensing diaphragm at the other as shown in Fig. (**2**). An oscillator circuit causes the wire to oscillate at its resonant frequency. A change in pressure changes the wire tension, which in turn changes the resonant frequency of the wire. Because this change in frequency can be detected quite precisely, this type of transducer can be used for low differential pressure applications.

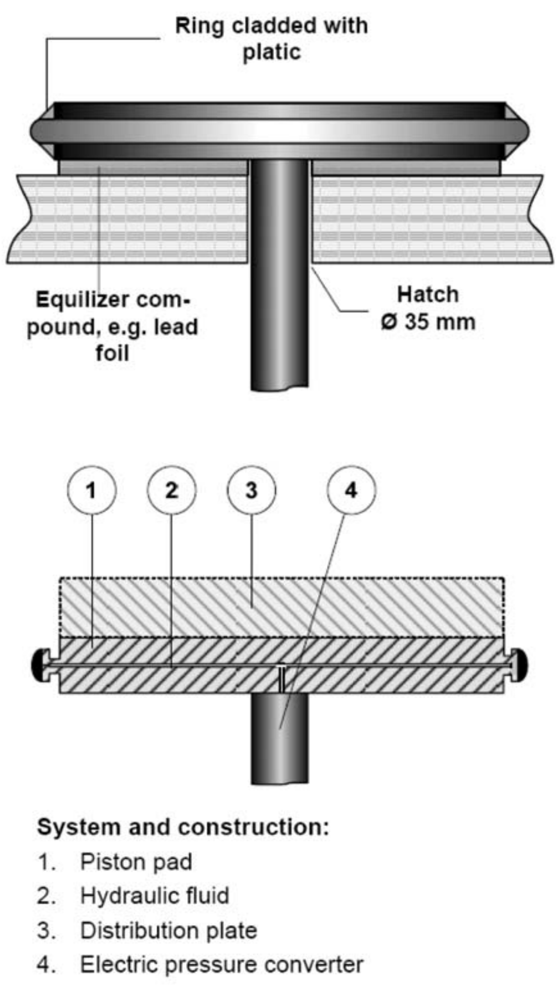

Fig. (1). Hydraulic load cell (Glotzl [9]).

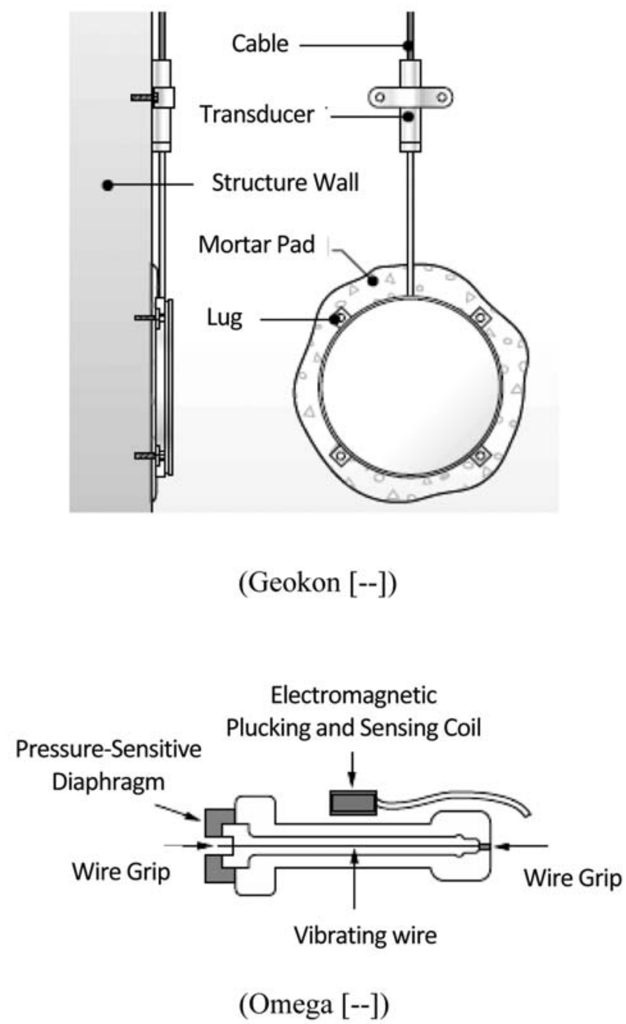

Fig. (2). Side and front views of a vibrating wire load cell.

One of the most commonly used pressure measuring tools is the strain gauge type load cells. They basically convert the load into electrical signals. The strain gauges are bonded onto a structural member that deforms when load is applied as shown in Fig. (**3**). In most cases, four strain gages are used to obtain maximum sensitivity and temperature com-pensation. Lazebnik and Chernysheva [12] highlighted that contact pressure cells need to have the same rigidity as

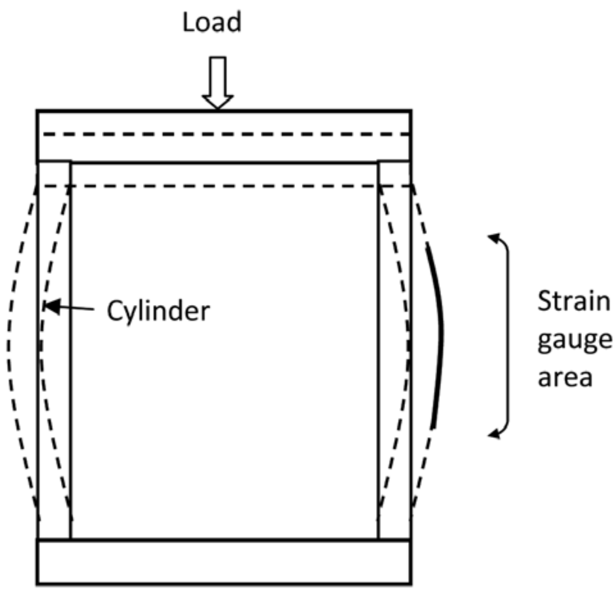

Fig. (3). Cylindrical load cell with bonded strain gage.

that of the monitored structure (retaining wall, pipe, etc.). Lazebnik *et al.* [13] conducted a comparison between different types of pressure cells made between the 1962 and 1971 and recommended a soil-cell stiffness ratio of 7 in order to reach a percentage error of less than 2%.

The concept of null pressure cells was introduced by Jennings and Burlan [14]. The chamber deflection under loading is consistently measured and an equivalent pressure is applied to the cell to bring the deflection to zero. Margason and Irwin [15] used the null pressure concept in earth pressure cells to measure soil pressure below road embankments. The cell was 7 inch in diameter and 1.125 inch in thickness. An electrical circuit was placed inside the fluid filled cell with diaphragm surface. Once the diaphragm displaces a distance of 0.0015 the circuit is closed and a signal is sent to increase fluid pressure until the diaphragm surface is back into position. Talesnick [16] developed a similar transducer based on the work of Deobelin [17]. The transducer, Fig. (**4**) consists mainly of a steel chamber that is air pressurized with sensing elements that have bonded strain gauges. When the elements deform due to soil pressure the strain gauges would detect the membrane strain and the air pressure system would null the soil pressure and bring the membrane back to the original position. Talesnick *et al.* [18] successfully applied the null pressure cells to measure contact pressure acting on buried structures.

In conclusion, wide varieties of earth pressure cells are available for the measurement of contact pressure on buried structures. Most of the available earth pressure cells are rigid in nature and therefore are considered suitable for measuring earth pressure at the interface between a rigid structure and the surrounding ground. Minimum movement of the cell surface should be allowed during loading to avoid significant relaxation of stresses and consequently deviation from the actual pressure. Among the above reviewed load cells, the null pressure sensors are able to minimize cell deflection and therefore can provide the best performance among the above reviewed load cells. A major limitation of the load cells is the need for installing several cells at different locations to capture the pressure distribution across a given surface. In addition and due to the rigidity of the load cells, they are not suitable for pressure measurement on flexible structures.

3. FIBER OPTIC SENSORS

The principle of operation of a fiber optic sensor (FOS) is having a sensing element that alters some parameters of the optical beam (intensity, wave length, polarization, phase, etc.) which gives rise to a change in the characteristics of the

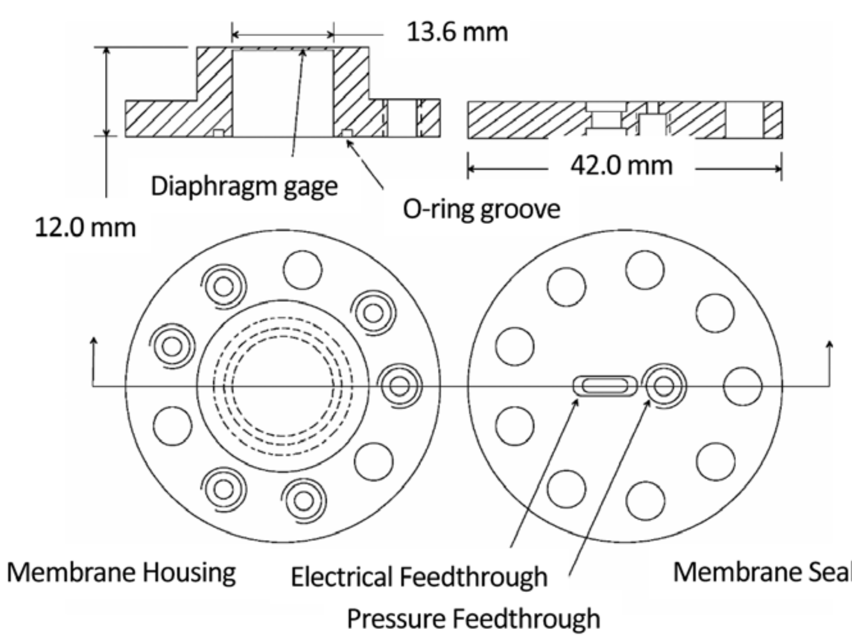

Fig. (4). Null soil pressure sensor [16].

optical signal received at the detector. The application of optical fibers as a sensing tool started about 30 years ago [19].

Fiber optic sensors have been used in different applications [20] including medicine [21], navigation [22], temperature measurement [23] and water treatment applications [24]. In addition, fiber optic sensors have been used in various civil engineering applications including the monitoring of bridges, dams and tunnels [25, 26]. In geotechnical engineering FOSs are used to measure moisture content and chemical concentration in soils [27, 28] and strains along pipelines [29].

In general, there are three types of FOSs commonly used in geotechnical applications: Fabry-Pérot Interferometric Sensors (FPI), Fiber Bragg Grating Sensors (FBG), and Distributed Brillouin/Raman Scattering Sensors. FPI and FBG sensors are the ones mostly used in local strain measurement applications by civil engineers while the third is used mainly for health monitoring of large structures (up to several kilometres) over long period of time with lower accuracy [30]. The main difference between FPI and FBG is in the technique used for altering the light properties. The FPI consists of two mirrors of reflectance separated by a gap, which represents the gauge length Fig. (**5**). The Fiber Brag Grating sensor is manufactured by altering the optical fiber core through exposing it to Ultraviolet (UV) light at certain locations. This causes a grating period to be formed. The input light passes through the fibers except for the component that has resonance with the grating period as shown in Fig. (**6**). Through a spectrum analyzer this wave can be detected. The grating period is the gauge length. When the gauge length changes due to straining of the grating pitch, the phase of the reflected wavelength shifts. The resonance value, λ_B, for the Fiber Bragg Grating can be expressed by [31].

$$\lambda_B = 2\ \eta_{ref}\ \Lambda \qquad (1)$$

Where η_{eff} is the refractive index of the fiber material and Λ is the grating pitch (see Fig. (**7**)).

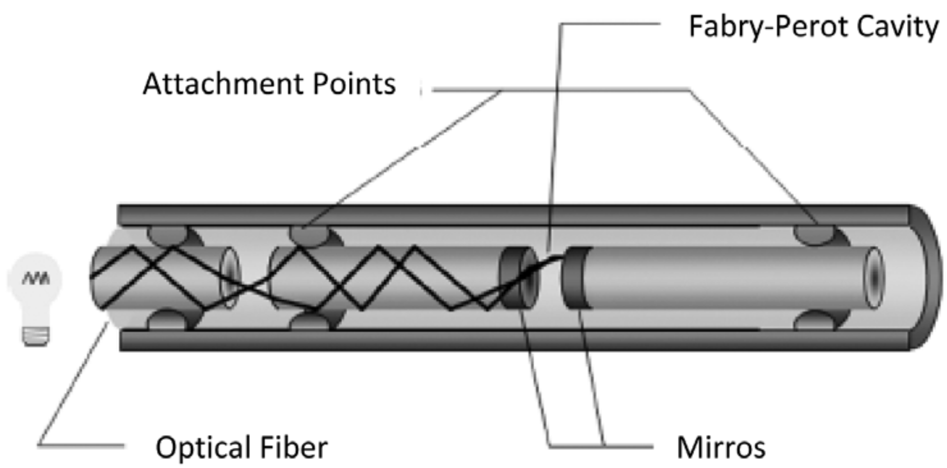

Fig. (5). Fabry-Perot Interferometer Sensor [30].

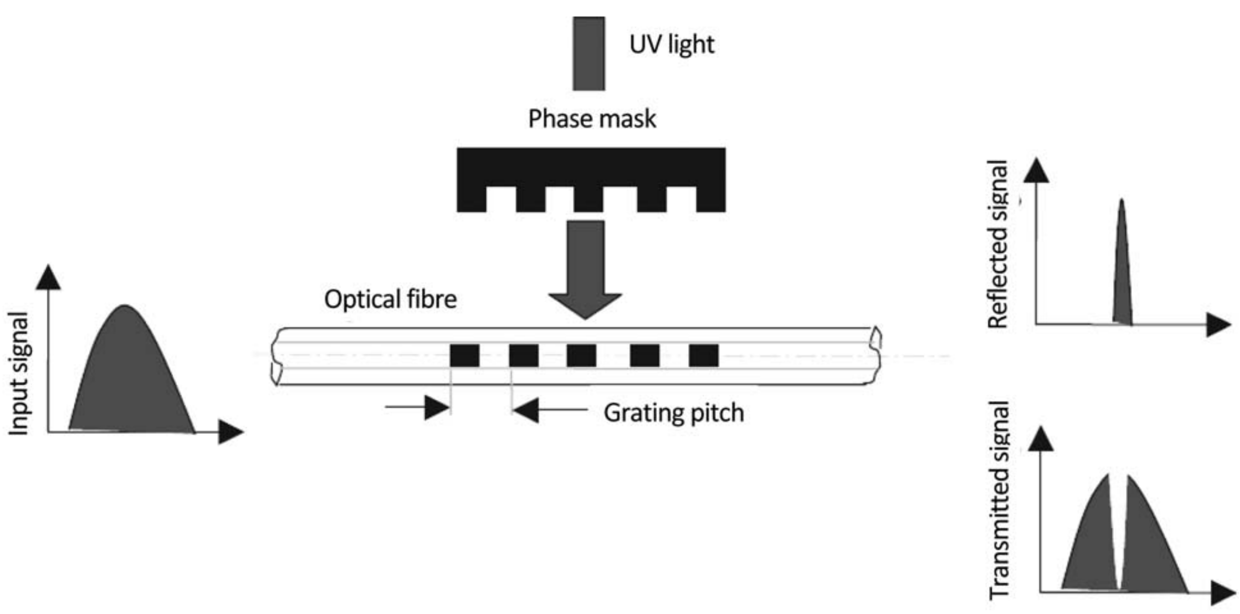

Fig. (6). Fiber Bragg Grating Sensor [25].

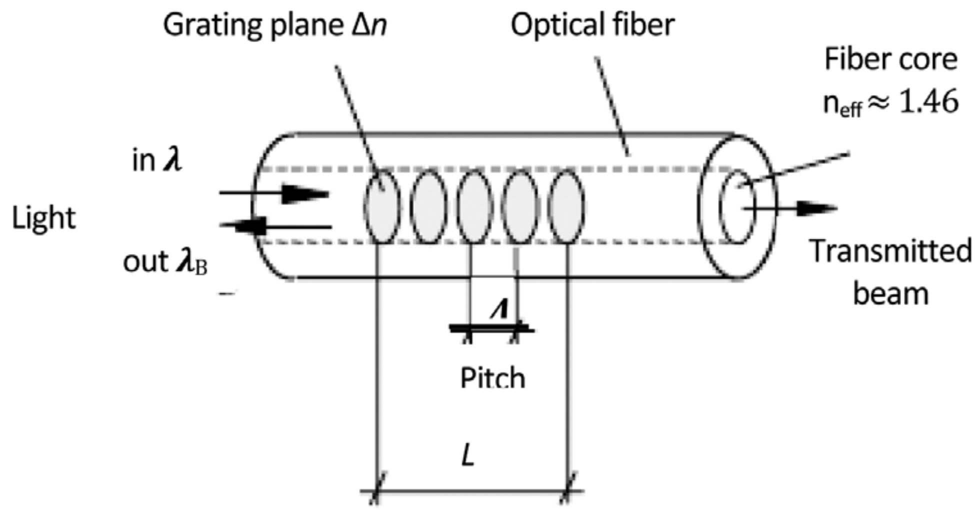

Fig. (7). Fiber Brag Grating principle [31].

An interesting example that demonstrates the application of FBG in contact pressure measurement is the work of Legge *et al.* [32]. The fibre Bragg grating stress cell was made by encapsulating the FBG sensor in a silicon casing. When the cell was exposed to a lateral pressure it experienced longitudinal strains. The silicon, having a high Poisson's ratio, enhances the longitudinal sensitivity of the sensor. The longitudinal response of the system was calibrated with respect to lateral pressures in the laboratory. The developed cell served several problems encountered by traditional load cells, such as sensitivity to water ingress, short life range and fragility. FBG sensors allow for multiplexing which is having several sensors (gratings) over one optical fiber as shown in Fig. (**8**). Each grating has its resonance value that reflects a specific wavelength among the light spectrum. This is considered an advantage as it saves on the wiring time and additional installation of sensors.

Dore *et al.* [33] presented a patent for fiber optic sensors that is capable of measuring horizontal strains at the interface between asphalt pavement and base layer. This was based on the work of Duplain and Van-Neste [34]. Duplain [35] made further improvement to the previous patent by minimizing the dispersion effect of the measurand. This yielded less distorted readings by eliminating other physical changes, hence enhancing the sensor sensitivity to the measurand.

4. TACTILE SENSORS

Adapted from the robotic industry, the basic principle of tactile sensors is the change of electrical resistance with pressure of a material placed between two electrodes or in touch with two electrodes placed at one side of the material [36]. Conductive elastomer cords or pads laid in a grid pattern are usually employed with the resistance measurements being taken at the points of intersection (sensels). Fig. (**9**) shows a 3 x 3 array of resistive sensels and the circuitry that can be used to implement a tactile transducer [37].

The first tactile sensor patent was credited to Krivopal [38]. The sensor is used in several applications for measuring soil pressures in granular materials. Paikowsky and Hajduk [39] and Paikowsky *et al.* [40] used tactile sensor technology to measure pressure distribution under rigid footings supported by sandy soil. Results indicated good agreement between the measured pressures and the theoretical prediction using the Bearing Capacity theories. Springman *et*

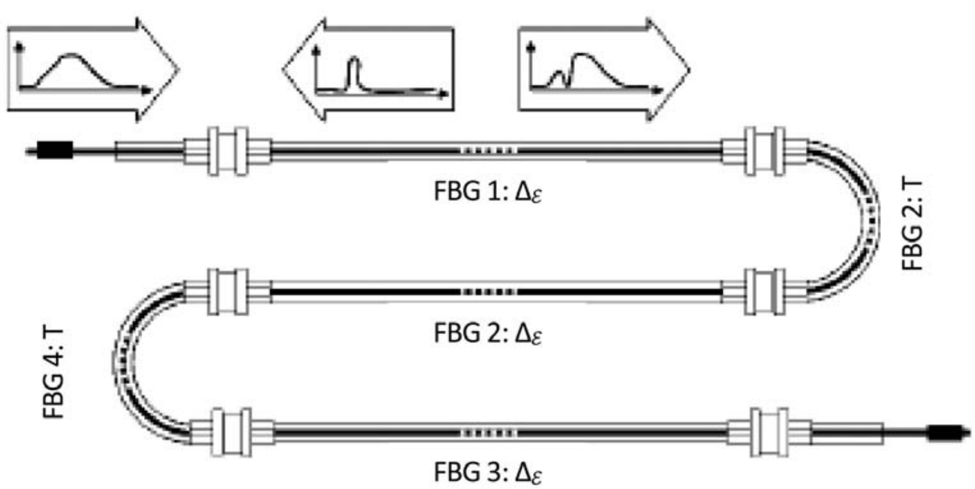

Fig. (8). Multiplexing of FBG sensors [30].

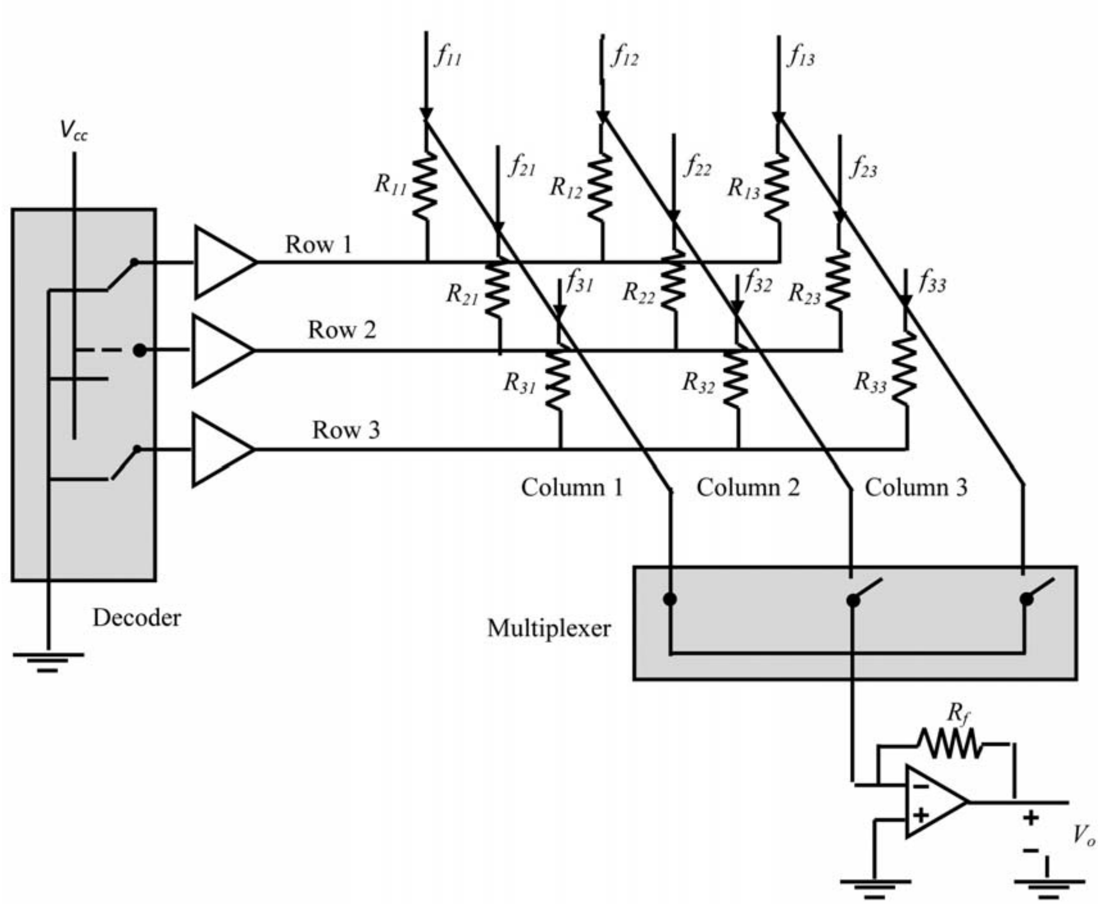

Fig. (9). Resistive tactile transducer [37].

al. [41] used tactile sensors in geotechnical centrifuge to predict the load distribution due to rock falls on protection structures.

In another geotechnical application, tactile sensors have been used to measure earth pressure acting on buried pipes. Choo *et al.* [42] and Abdoun *et al.* [43] measured the radial pressure acting on a pipeline as shown in Fig. (**10**). O'Rourke *et al.* [44] used tactile sensors to measure the lateral earth pressure on pipes (Fig. **11**) and recommended covering the sensors with two layers of Teflon to minimize shear stresses on the sensors. Weidlich *et al.* [45] estimated pressures on pipes under cyclic axial loading.

Tachi *et al.* [46] managed to transform the pressure measured using tactile sensors into forces in three-dimensional space. The developed Optical Tactile Sensor involves photographing sensels using charge coupled device (CCD) cameras. The sensels consisted of colored circular markers arranged in different layers forming a grid. Images were taken and analyzed through color coding technology to represent different pressure intensities.

In a recent patent [47], Son and Parks used textile electrodes to form a cloth based tactile sensor. Several problems have been reported including the electrode wiring for large size grids (more than 10 by 20). To rectify the problem, an intermediate harness was introduced between

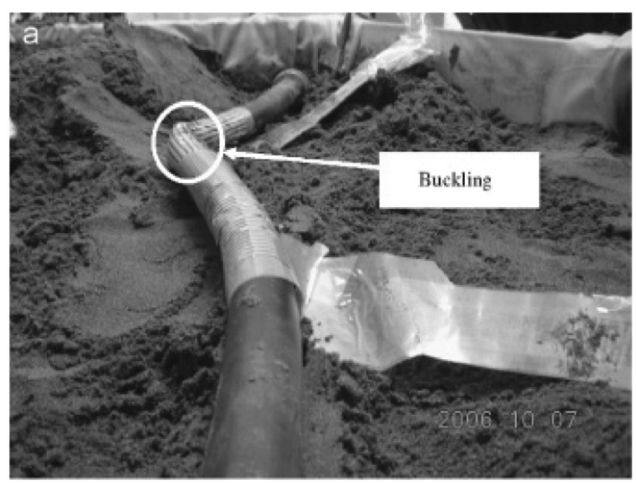

Fig. (10). Tactile sensing sheets around deformed pipelines [42].

the two layers that form the grid. All electrical connections are connected to the intermediate harness rather than directly to the electrodes.

The most recognizable advantage of using tactile sensors to measure soil pressure in geotechnical applications is the fact that each sensor contains many sensing points (sensels) which could reach up to 2016 points in one single sensor with 10 mm spacing [44]. This allows visualizing soil pressures across a given section. In addition, 3D images of the pressure distribution are produced over the monitored area with time.

The major disadvantage of tactile sensors is the extensive calibration required for each testing condition in order to obtain quantitative results. The calibration process accounts for the hysteretic behaviour, loading rate, unloading and interface conditions. In addition, the sensors are prone to moisture. In general, tactile sensors are promising and proven to be satisfactory for qualitative pressure measurements.

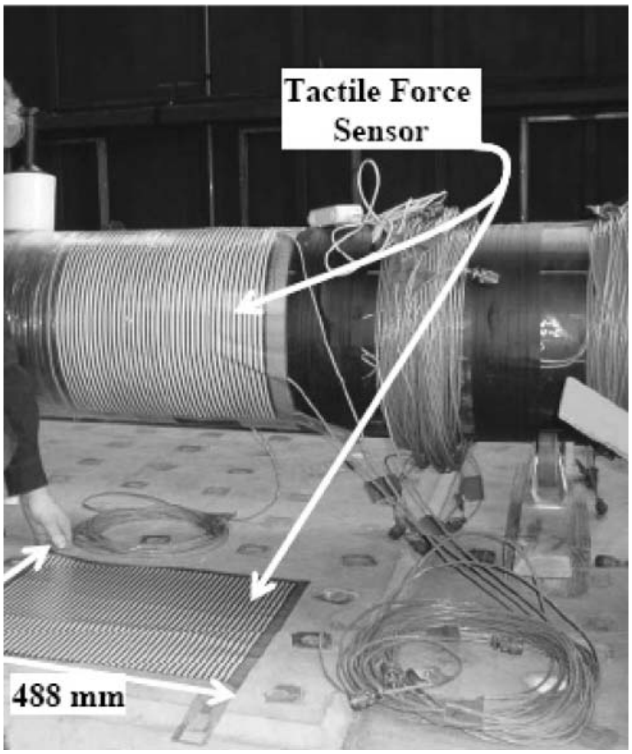

Fig. (11). Tactile sheets around a pipe in the lab [44].

5. OTHER TECHNIQUES

This section summarizes some of the recent developments reported by researchers to measure contact soil pressure for specific experiments. These include piezoresistive cells, normal and tangential earth pressure cells, mini sensors and integrated cantilever cells. A brief description of each is given below.

Piezoresistive Cells

Piezoresistive cells are based on the fact that piezoelectric materials generate electric current of certain frequency when subjected to pressure. Examples of such materials are polyvinylidene fluoride (PVdF) and monocrystalline silicone. The piezo-electric material is usually laid in a grid format inside a flexible sensor. When this sensor is pressed, electric current is generated relative to the amount of pressure applied. As opposed to tactile sensors which are limited to static loading, piezoresistive sensors are suitable for pressure measurement under dynamic loads [48].

Ilstad *et al.* [49] measured contact soil pressures due to explosive loadings. A gauge has been developed (contact area of 1 m^2) using 9 separate sensors (0.2 x 0.2 m) placed between an aluminum and steel plates. Further improvements were recommended to obtain a better calibration and improve the measured pressures.

Normal and Tangential Pressure Cells

Arnold *et al.* [50] developed a load cell that is capable of measuring normal and tangential earth pressure simultaneously. The cell had 6 strain gauge based transducers arranged to form a statically determinant truss structure. Three of the transducers measure the vertical forces whereas the other three measure the horizontal forces. The system was functional and reliable for investigating mobilization of passive earth pressure and cantilever retaining walls.

Soil Pressure Mini-Sensor

Xia and Xiaoke [51] used mini-sensor made of monocrystalline silicon to measure soil pressure. The most important feature of these sensors is the high accuracy at very low ranges of applied loads which guarantees the reliability of the soil pressure test in geotechnical engineering. The system proved successful for calibration with soil and had linear calibration curves.

Integrated Strain Gauge Based Load Cells

Another technique for measuring contact soil pressures on rigid pipes, shafts and tunnels was developed by Meguid and Tobar [52]. Sensitive load cells were integrated into the physical models as shown in Fig. (**12**). The system has been used successfully to measure earth pressure on different subsurface structures.

CURRENT & FUTURE DEVELOPMENTS

Earth pressure cells can be used to measure stresses within embankments and subgrade pressure, and contact pressures on retaining walls, tunnel linings, railroad bases and bridge abutments. Load cells can be of the mechanical, hydraulic, vibrating wire, or electrical-resistant strain gauge type. They measure strains or displacements under the applied loads that are translated into loads through calibration. The pressure cells, properly installed in appropriate locations, can give good data on the stress distribution between a buried structure and the surrounding ground at specific locations. They should be installed in orthogonal sets of at least three for confirming that adequate stress levels are being achieved.

Over the past two decades, several developments have been made in the area of pressure sensors employing fiber-optics, tactile sheets and piezoresistive materials. Fiber-optic transducers bring to the measurement systems many of the advantages that optical-fiber technology has brought to communications systems. The very high bandwidth of optical fibers allows them to convey a large amount of measurand information through a single fiber; because optical fiber is a dielectric, it is not subject to interference from electromagnetic waves that might be present in the sensing environment. In addition, fiber-optic sensors can function

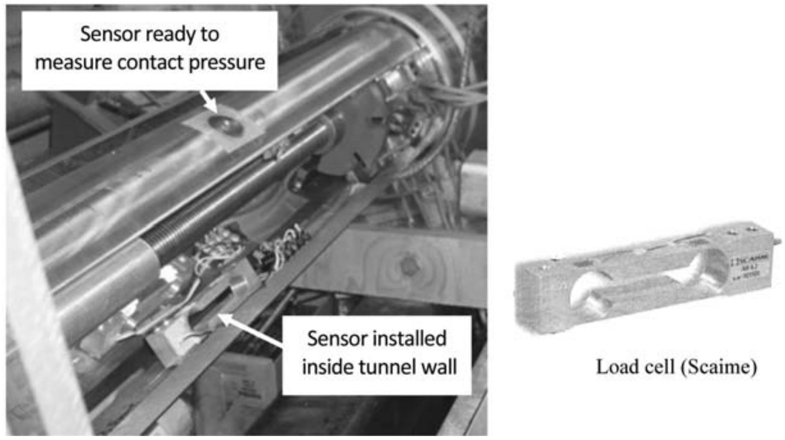

Fig. (12). Integrated strain gauge load cells to measure contact pressure on model tunnels [52].

Table 1. Comparison Between Selected Contact Pressure Measurement Techniques

Technique	Advantages	Disadvantages
Conventional Techniques	• Investigated over 70 years • All technical problems are known • Various suppliers available • General Familiarity	• Problems of strain gages • Geometry problems: aspect ratio, arching, point loading, lateral stress rotation • Single pressure value
Flexible Tactile Sensors	• Stress distribution over an area rather than a single pressure value • Visualizing soil pressure distribution in 3D • Very thin and flexible • Different sizes and shapes	• Qualitative measurements • Extensive calibration at each sensel if quantitive data required • Creep, shear stress, water ingress and insensitive to low stresses
Fiber Optic Sensors	• No electric current related problems • Water resistant system • Remote sensing (several kilometres) • Multiplexing (several sensors with one wire)	• Short gage length (about 25 mm) • Temperature sensitivity • Relatively new

Table 2. Selected Applications of Contact Pressure Measurement Cells

Sensor Type	Reported Applications
Null Pressure Sensors	Stresses on Buried structures in controlled pressure chambers [18].
Fiber Optic Sensors	One-dimensional stress in sand [32].
Tactile Sensors	Pressure distribution under rigid footings on sand. [39, 40]. Load distribution due to rock fall on protection structures [41]. Earth pressure acting on buried pipes [42, 43, 44, 45].
Piezoresistive cells	Contact pressure due to explosive loadings [49].
Normal and tangential pressure cells	Passive pressure mobilization on cantilever retaining walls [50].
Soil pressure mini-sensor	Contact pressure at low range with high accuracy [51].
Integrated strain gauge based load cells	Earth pressure acting on subsurface structures such as tunnels, pipes and shafts [52].

under adverse conditions of temperature, and toxic or corrosive atmospheres that can erode metal sensors. Adapted from the robotic industry, tactile sensors are devices which measure the parameters of a contact between the sensor and an object. The basic principle of this type of sensor is the measurement of the resistance of a conductive elastomer or foam between two points. A summary of the main types of sensors used in geotechnical engineering practice along with the advantages and disadvantages of each type is given in Table **1**. Table **2** presents a list of applications that utilized different contact pressure measurement techniques in geotechnical engineering.

With the advances in technology more patents and techniques will be introduced which are expected to broaden the application fields and enhance the accuracy of pressure measurement sensors. It should be noted that the present review is not intended to provide extensive coverage of all existing pressure measurement devices used in civil engineering; it rather provides a review of the different available techniques used to measure contact pressure between surface or subsurface structures and the surrounding ground.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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