Field Installation of an Earth Pressure Cell

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An earth pressure cell (EPC) is a device designed to provide an estimate of normal stress in soil. The practice of designing and manufacturing stress-measurement devices revolves around the study of the interaction between the measuring device and the host material. However, distribution of normal stress is not necessarily uniform across a given surface. Consequently, output from an EPC may be different under soil-loading conditions than under fluid pressure. In addition, depending on the design, as the cell deflects, an arching-type phenomenon may develop. A study was conducted to devise a scheme for calibration of EPCs and to recommend a procedure for field installation. A new testing device was designed to permit the application of uniaxial soil pressure to the EPC by using various types of soil and load configurations. Sensitivities computed from soil calibrations varied from those determined from fluid calibrations by as much as 30 percent. A field installation procedure was developed from model tests. In the laboratory, a thin-walled steel cylinder with a geotextile bottom was filled with uniform silastic sand in a medium-dense state, and the EPC was placed within the sand. The entire apparatus (EPC, cylinder, and sand) was carried into the field and installed in the desired locations. The steel cylinder was then removed, leaving the cell, sand, and geotextile behind. Preliminary field data indicate that the soil calibration and placement procedure provide reasonably accurate measurements of the change in vertical stress.

A primary concern in pavement engineering is the evaluation of pavement performance under traffic loads. Knowledge of how a pavement responds to actual traffic is essential for advancing pavement design. Current practice in the United States is based on technology developed from the 1930s through the early 1960s. The design methods are derived from empirical performance data and material characterization, which are a function of the available traffic and other conditions that existed some 40 years ago. However, heavy trucks, considered to be the major consumer of pavement life, have increased in traffic frequency, speed, size, and weight since then. Therefore, assessing the pavement behavior under current truck traffic becomes an important factor in moving from empirical to mechanistic-empirical pavement design.

The Minnesota Department of Transportation is developing a mechanistic-empirical design method for future pavement design through the Minnesota Road Research Project (MnROAD). The knowledge of in situ stress of subgrade soil is important in predicting the pavement performance and the development of such a design method. For example, Hardy and Cebon (1, 2) proposed a model to evaluate continuous pavement response under a moving vehicle. They modeled the pavement system as an elastic beam resting on an elastic foundation, which requires input of a spring constant (k). If the subgrade soil is viewed as the elastic foundation, then its k value and its change with vehicle speed must be known to accurately model the pavement performance. However, an accurate k value can be established only through field experiments. To obtain measurements of subgrade soil stress, several earth pressure cells (EPCs) have been placed in the subgrade soils at MnROAD.

**BACKGROUND**

Taylor was one of the first to consider the interaction between an EPC and soil (3). Taylor’s method fell under the mantle of the indentation analogy. This approach consisted of estimating the difference between soil and cell deformations, or the indentation, and then computing the corresponding over- and underregistrations of the cell that would produce the same indentation (4).

Taylor considered an EPC at a depth, H, below the free soil surface with diameter, D, and thickness, 2H (30). The cell and soil were subjected to a uniaxial stress change acting perpendicular to the face of the cell. Assuming symmetry of deformations of the cell and soil, the indentation of each side (face) of the cell is given by \( \delta_i = \delta_s - \delta_c \), where \( \delta_i \) and \( \delta_c \) are the deformations of the soil and cell, respectively. For the material parameters \( M_s \) and \( M_c \), which represent the moduli of the soil and cell, \( \delta_c \) may be expressed as

\[
\delta_c = \frac{H}{2} \left( \frac{\sigma_c - \sigma_s}{M_c} \right) \tag{1}
\]

where \( \sigma_c \) and \( \sigma_s \) are the average stresses of the soil and cell, respectively. The difference, \( \delta_s \), is similar to the indentation of a circular plate or punch into an elastic solid under the load

\[
\sigma_s = \sigma_i - \sigma_c \tag{2}
\]

and \( \delta_i \) is then given by

\[
\delta_i = D \frac{\sigma_s}{N_f} \tag{3}
\]

The parameter \( N_f \) is an indentation coefficient that is a function of the deformation characteristics of the soil. Manipulation of the equations yields the relation (Equation 4) for the cell-soil registration ratio, \( \sigma_i/\sigma_s \). The coefficient \( K_i \) was defined as \( K_i = N_f/M_c \).

\[
\frac{\sigma_i}{\sigma_s} = \frac{D + N_f}{B + K_i} \tag{4}
\]

The coefficients \( N_f \) and \( K_i \) may be theoretically determined by employing the theories of Boussinesq, assuming that the soil acts as an elastic solid. Taylor suggested that \( N_f \) was approximately equivalent to \( M_c \), so that \( K_i \) approached unity. This assumption also was
used by Peattie and Sparrow (5). Hvorslev emphasized that the equations and parameters from the indentation analogy were theoretical and were only rough approximations of the actual stresses and deformations (4).

The standard analysis considers uniaxial stress applied perpendicular to the face of the cell. What is missing, however, is the influence of arching through the soil caused by displacement of the cell itself. The cell registers the stress on the face, but this value may be different from the applied stress because of an arching effect (6, pp. 66–76). Thus, it is imperative that a calibration method be devised to account for the reduction in stress caused by the action of the cell.

LABORATORY STUDIES

Earth pressure cells (EPC) typically are calibrated by using fluid pressure to determine a sensitivity, which then can be used to transform a cell’s recorded electrical output into a pertinent estimate of earth pressure. It is implicitly assumed from such a calibration procedure that the response of the EPC under uniform fluid pressure would be equivalent to the earth pressure experienced under field conditions. However, that assumption does not acknowledge the potential for arching to occur in the soil and how that affects the net earth pressure acting on the EPC. It may become necessary to adjust the EPC sensitivity so that the cell reflects more closely the field value. A new method for calibration was proposed, whereby an EPC was evaluated by applying pressure on a soil column (7). A device was designed to allow loading to the sensitive face of the EPC through soil.

Uniaxial Calibration Device

To conduct uniaxial calibration tests on an individual EPC, a special loading apparatus was devised. A schematic cross section of the device is shown in Figure 1. The apparatus was designed to allow uniaxial loading on only the sensitive face of an EPC.

The uniaxial calibration device was used to observe the EPC’s response to simple uniaxial loading conditions through soil. Loading of the EPC was initiated as fluid pressure (hydraulic oil) was applied to a rubber membrane, which was inserted between the capping and center plates of the device. The rubber membrane isolated the oil from a soil column, which was in contact with the cell’s sensing face. Fluid pressure applied to the membrane subsequently was applied to the surface of the soil column and was transferred through the column to the face of the EPC. The plastic sleeves, which housed the soil column, were composed of a low-friction material. Because they could be inserted in and removed from the device, the sleeves also allowed certain soil column parameters, such as column height and column diameter, to be varied.

Calibration sensitivities pertaining to the two soil types (Ottawa 20-30 and 50-70 sand) at two different heights are presented graphically in Figure 2. The curves shown are typical for their respective calibration condition. The fluid sensitivity is given for comparison purposes. All soil sensitivities were less than the fluid sensitivity. Although the soil sensitivity was not seen to differ significantly between the two soil types (calibration values from both soils fell within ±10 percent of each other), the EPC sensitivity was observed to increase when the soil height was increased. One explanation for this decreasing trend stems from the arching effect. As the height of the soil column increases, the greater the resisting shear that develops. Furthermore, at some value of H, one would expect no additional decrease in the sensitivity because the critical distance where arching no longer contributes has been reached (8).

Universal Calibration Chamber

A universal calibration chamber was devised to test the EPCs in a three-dimensional soil environment subjected to an axial load (9, pp. 165–183, 10). For convenience, a 55-gal (208-L) drum was used to construct the chamber; a schematic is shown in Figure 3. The diameter, $D$, of the drum was 572 mm (22.5 in.), and the height, $H$, was cut down to 584 mm (23 in.). Sand was filled into the bottom third of the drum. A fluid-filled rubber bladder was placed on top of the sand. A second layer of soil was filled into the middle third of the drum. The EPC was placed in the center of the chamber within the second soil.

![Figure 1: Uniaxial calibration device, configured for soil loading.](image)
**FIGURE 2** Soil calibration for two types of silica sand at two column heights.

**FIGURE 3** Universal calibration components.
layer. A second fluid-filled rubber bladder was placed on top of the middle soil layer. Finally, a third layer of soil was poured on top of the second rubber bladder. The bottom soil layer acted as a buffer between the load frame and the upper rubber bladder. The purpose of the upper bladder was to develop a boundary condition of uniform pressure within the soil. The lower bladder was used to evaluate frictional effects along the inside walls of the drum. The frictional effects were observed to be minimal; the pressure in the lower bladder was only slightly smaller (about 1 percent) than that in the upper bladder. The response of the bladders to loading matched well with the expected stresses calculated by dividing the load cell signal by the circular area of the barrel.

Universal calibration tests were conducted with the middle layer of the chamber made up of clay. The response of the EPC, when placed within the clay layer, revealed highly scattered data (Figures 4 and 5) due to the low signal-to-noise ratio.

**Sand Pocket**

To improve the resolution of the EPC data within clay, a configuration was devised wherein the cell was placed within a pocket of dry sand. Loading would thus be transferred through the sand and applied to the cell. The sand’s density was set equal to the uniaxial calibration value (1.66 g/cm³). The expectation was that the EPC would respond in much the same manner within the sand pocket as it had when placed exclusively in dry sand.

The EPC demonstrated excellent response to both static and rapid loading within the sand pocket. Results of universal calibration tests with the EPC–sand pocket configuration are given in Figures 6 and 7. The EPC output was very similar to results from tests conducted with dense, dry sand. As before, when the soil sensitivity was applied, the cell output agreed well with respect to the pressure measured in the bladder.

Sand pocket universal calibration tests also were conducted, wherein Class 6 gravel was placed in the top soil layer. Class 6 gravel is a coarse-grained material that is used in practical application as an aggregate overlying the subgrade soil underneath paved roads. The gravel was placed above the upper bladder. The EPC and sand pocket were installed as before. A circular piece of geotextile was placed between the gravel and the top of the upper bladder to help protect the bladder. The response of the EPC was excellent to both static and rapid loading through the gravel (Figures 8 and 9).

**FIELD INSTALLATION**

To provide an environment consistent with that used for calibration, a configuration was suggested wherein the cell was placed within a pocket of dry sand within a clay subgrade. Loading would thus be transferred through the sand and applied to the cell. The sand’s density was the same as the uniaxial calibration value (1.66 g/cm³).

Preparation of the sand pocket and placement of the EPC within it was carried out in a special container before installation of the entire arrangement within the clay. The sand pocket container (Figure 10) consisted of a thin-walled steel cylinder (diameter = 150 mm (6 in.), height = 125 mm (5 in.)) and a piece of geotextile, which acted as the bottom of the cylinder. The container was filled with Ottawa 20-30 silica sand at the density of 1.66 g/cm³. The EPC was carefully placed at a known position within the sand. A slot cut into the side of the cylinder allowed the lead wire from the EPC to extend outside the steel cylinder. The piece of geotextile was folded over one end of the
FIGURE 5  Universal calibration curve, rapid loading test, conducted in clay.

FIGURE 6  Universal calibration curve, static loading test, conducted in soil pocket of Ottawa 20-30 sand.
FIGURE 7 Universal calibration curve, rapid loading test, conducted in soil pocket of Ottawa 20-30 sand.

FIGURE 8 Universal calibration curve, static loading test, conducted in soil pocket of Ottawa 20-30 sand with overlying Class 6 gravel.
cylinder and clamped firmly around the outside of the cylinder with a hose clamp.

A hole with the approximate dimensions of the sand pocket container was dug in the clay. The depth of the hole was 102 mm (4 in.), or 25 mm (1 in.) smaller than the container height, and the hole diameter was 178 mm (7 in.), or 25 mm larger than the container diameter. The container was placed in the hole. The hose clamp was removed from the outside of the steel cylinder. Extra sand was poured into the gap between the edge of the hole and the side of the cylinder to a height that was even with the sand inside the container. The last step was to carefully pull the steel cylinder out from the pocket of dry sand. The unclamped geotextile was left buried. The cylinder's rubber slit allowed the EPC lead wire to remain in place so as not to disturb the orientation of the cell.

Three EPCs (Kulite gauges) were installed on the top of subgrade soil in a flexible pavement at the MnROAD project. Figure 11 shows the pavement structure and sensor locations. A truck test was conducted to evaluate the response of the cells. The truck passed over the cells at a speed of 64 km/h (40 mph). The truck was a five-axle tractor-trailer combination. The weights were calibrated and placed on the truck so that the total weight of the truck was approximately 354 kN (79.6 kips). The truck axle loads were as follows: steering axle = 53.4 kN (12.0 kips), front axle of tractor tandem = 75.2 kN (16.9 kips), back axle of tractor tandem = 73.9 kN (16.6 kips), front

![Figure 9: Universal calibration curve, rapid loading test, conducted in soil pocket of Ottawa 20-30 sand with overlying Class 6 gravel.](image-url)

![Figure 10: Sand pocket container.](image-url)

![Figure 11: (a) Section view of pavement structure and sensor location and (b) plan view of sensor location.](image-url)
FIGURE 12  Earth pressure cell response from moving truck.

axle of trailer tandem  = 69.4 kN (15.6 kips), back axle of trailer tandem  = 81.9 kN (18.4 kips).

Figure 12 shows a typical response of an EPC. The subgrade soil pressure ranged from about 20 to 28 kPa (3 to 4 psi), and the steering axle generated the smallest stress. A further study is being conducted to compare measured stress and calculated stress under falling weight deflectometer and truck loads.

RECOMMENDATIONS

An EPC should be calibrated in the lab with the uniaxial calibration device by using soil pressure. Silica sand at a column height of 25 mm is suitable for calibration purposes. Once the cell has been calibrated and its soil system sensitivity has been determined, it should be installed in the ground within a sand pocket. Whatever sand type was used for cell calibration should then be used to fill the sand pocket. It is suggested that the density of the sand pocket be the same as, or as close as possible to, the value used in calibration. At least 50 to 80 mm (2 to 3 in.) of sand cover should be above the face of the cell.

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REFERENCES


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