

Instruction Manual

Model 4800 series

VW Earth Pressure Cells

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1. INTRODUCTION

1.1 Theory of Operation

Earth Pressure Cells, sometimes called Total Pressure Cells or Total Stress Cells are designed to measure stresses in soil or the pressure of soil on structures. Cells will respond not only to soil pressures but also to ground water pressures or to pore water pressure, hence the term total pressure or total stress. A simultaneous measurement of pore water pressure (μ), using a piezometer, is necessary to separate the effective stress (σ') from the total stress (σ) as defined by Terzaghi's principle of effective stress where;

$$\sigma' = \sigma - \mu$$

These parameters coupled with the soil strength characteristics will determine soil behavior under loads.

Earth pressure cells of the type described here are the hydraulic type; two flat plates are welded together at their periphery and are separated by a small gap filled with a hydraulic fluid. The earth pressure acts to squeeze the two plates together thus building up a pressure inside the fluid. If the plates are flexible enough, i.e. if they are thin enough relative to their lateral extent, then at the center of the plate the supporting effect of the welded periphery is negligible and it can be stated that at the center of the cell the external soil pressure is exactly balanced by the internal fluid pressure.

This is true only if the deflection of the plates is kept to a minimum and thus it is important that the cell be stiff. This in a practical sense means that the fluid inside the cell should be as incompressible as possible and that the pressure transducer required to measure the fluid pressure should also be stiff having very little volume change under increasing pressure.

Tests conducted by various researchers (as reported by Dunicliff, 1988) have shown that the introduction of a flat stress cell into a soil mass will alter the stress field in a way dependent on the relative stiffness of the cell with respect to the soil and also with respect to the aspect ratio of the cell, i.e. the ratio of the width of the cell to its thickness. A thick cell will alter the stress more than a thin cell. Hence, for these reasons, a thin, stiff cell is best and studies have shown an aspect ratio of at least 20 to 1 to be desirable.

Ideally, the cell ought to be as stiff (compressible) as the soil. But in practice this is difficult to achieve. If the cell is stiffer (less compressible) than the soil then it will over-register the soil pressure because of a zone of soil immediately around the cell which is "sheltered" by the cell so that it does not experience the full soil pressure. This can be represented schematically as shown in Figure 1.

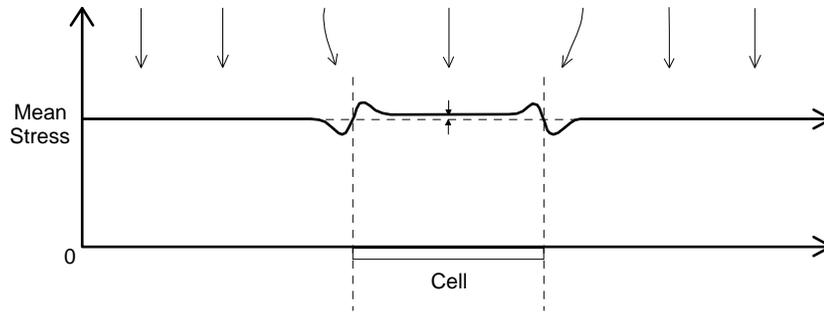


Figure 1 - Stress Redistribution, Weak Soil with Stiff Cell

As can be seen there is a stress concentration at the rigid rim but in the center of the cell the soil stress is only slightly higher than the mean soil stress, i.e. only slightly higher than the stress which would obtain were the cell not present.

In a stronger soil the de-stressed zone around the edge of the cell is more extensive and hence at the center of the cell the degree of *over-registration* of the mean stress is greater. This is represented schematically in Figure 2.

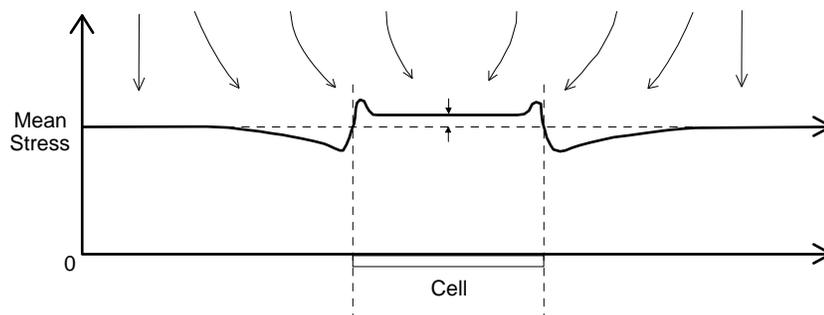


Figure 2 - Stress Redistribution, Strong Soil with Stiff Cell

In a stiff soil the cell may be less stiff (more compressible) than the soil, in which case the cell will *under-register* the mean soil stress as the stresses in the soil tend to "bridge" around the cell. This is represented schematically in Figure 3.

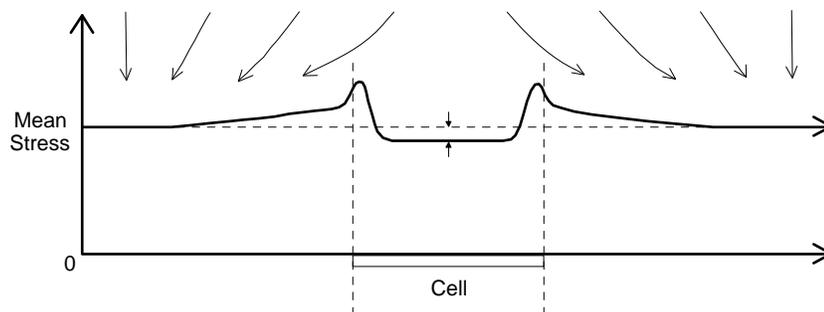


Figure 3 - Stress Redistribution, Stiff Soil with Weak Cell

Tests conducted at the University of Ohio (Ohio, USA) with several different soil types have shown that for Geokon cells the maximum degree of over or under-registration amounts to 15% of the mean soil stress.

Other factors should be kept in mind; the inherent variability of soil properties which give rise to varying soil stresses at different locations and a corresponding difficulty in getting a good sample of the mean stress from a limited number of cell locations. Also, the response of the cell to its immediate surroundings depends very largely on how closely the soil mass immediately around the cell has the same stiffness or compressibility or the same degree of compaction as the undisturbed soil mass. **Installation methods will need to pay particular attention to this detail.**

1.2 Earth Pressure Cell Design

Earth Pressure Cells are constructed from two stainless steel plates welded together around the periphery so as to leave a narrow space between them. This space is completely filled with de-aired hydraulic oil which is connected hydraulically to a pressure transducer where the oil pressure is converted to an electrical signal which is transmitted through a signal cable to the readout location.

In general Geokon Earth Pressure Cells use an all welded construction so that the space confining the oil is entirely metal not requiring 'O' rings which tend to trap air and reduce the cell stiffness. The oil is de-aired using a Nold DeAerator™ which materially improves the fluid stiffness and the performance of the cell. The pressure transducer normally employed is the Geokon Model 4500H which is available in several different pressure ranges (see Table 3). The cable is attached to the transducer in a sealed, waterproof manner. For earth pressure cells located inside a soil mass the cable may be armored and provided with strain relief at the cell to reduce the likelihood of pull-out.

Located inside the vibrating wire pressure transducer housing is a thermistor for the measurement of temperature at the cell location. In addition, a tripolar plasma surge arrester inside the transducer housing protects the vibrating wire pluck and read coils from electrical transients such as may be induced by direct or indirect lightning strikes.

Alternative pressure transducers with voltage (0-100 mV, 0-5 VDC, 0-10 VDC) or current (4-20 mA) output are also available for dynamic readout capability. Consult the factory for additional information.

1.3 Earth Pressure Cell Construction

Major components of the Model 4800 (rectangular and circular), 4810, 4815 and 4820 Earth Pressure Cells are shown in Figure 4 through Figure 8.

The Model 4800 Earth Pressure Cells may be rectangular or circular in shape. The standard size for the rectangular Model 4800 is 150 mm × 250 mm (6" × 10"), for the circular it is 230 mm (9") in diameter. Standard thickness for both styles is 6 mm (aspect ratio ≈ 40). For laboratory tests smaller, thinner cells can be manufactured. Contact the factory for additional information.

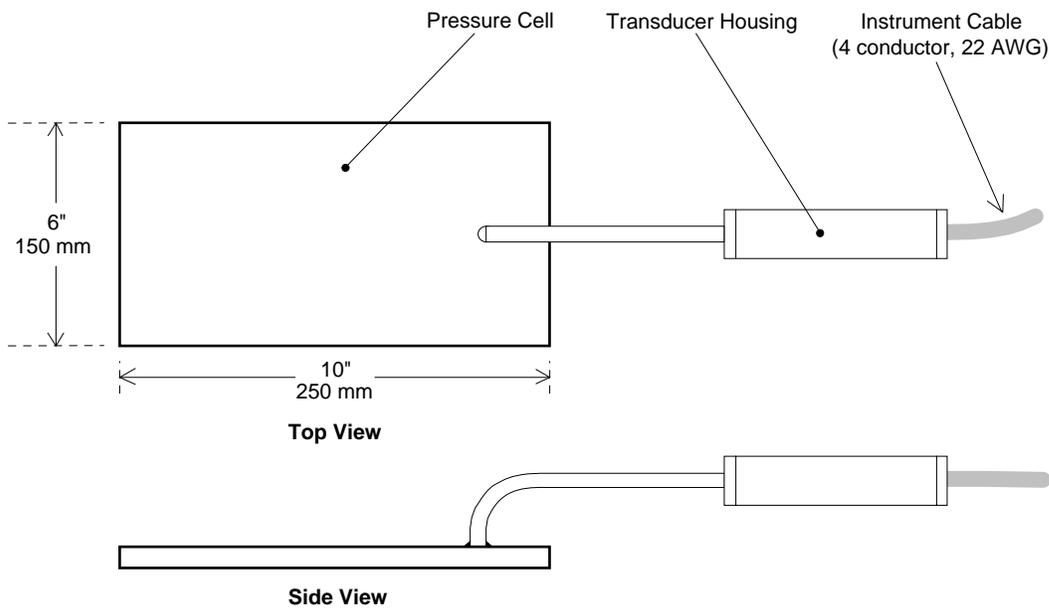


Figure 4 - Model 4800 Rectangular Earth Pressure Cell

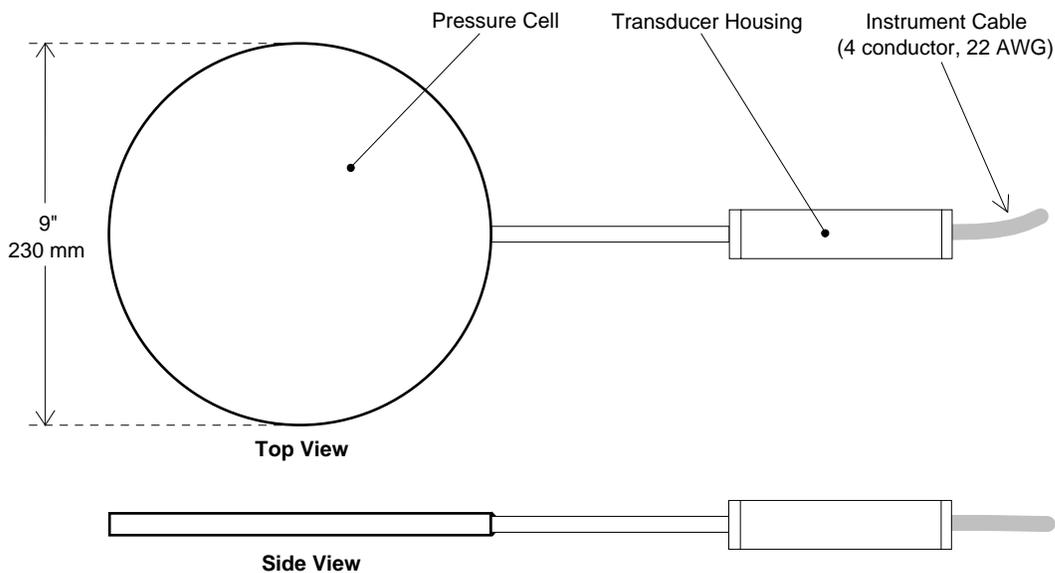


Figure 5 - Model 4800 Circular Earth Pressure Cell

The Model 4810 Earth Pressure Cell, or "contact" cell is designed for measuring soil pressures on structures. One of the plates is thick and designed to bear against the external surface of the structure in a way that will prevent flexure of the cell. The other plate is thin and reacts to the soil pressure.

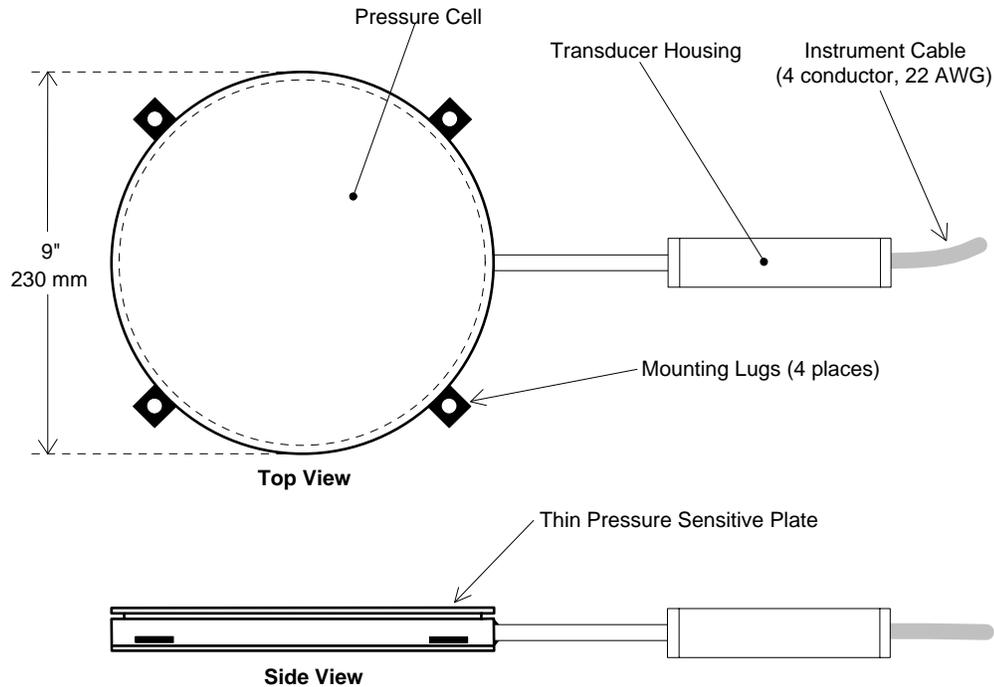


Figure 6 - Model 4810 Contact Pressure Cell

The Model 4815 Hydraulic Load Cell has been used for the measurement of loads in piles. And for the measurement of concentrated loads on tunnel linings. The pressure transducer housing is connected directly and perpendicular to the thick back plate.

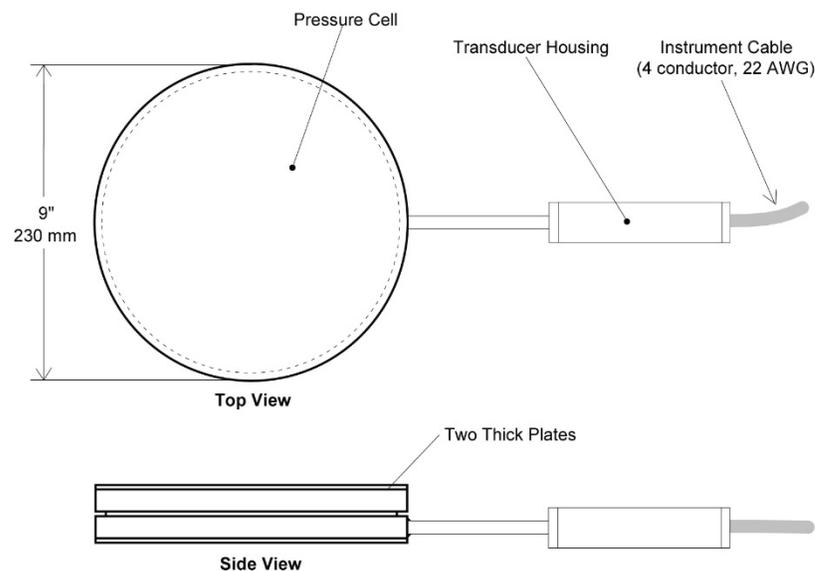


Figure 7 - Model 4815 Hydraulic Load Cell

The **Model 4820 Earth Pressure Cell** or "jack-out" cell is designed specifically for the measurement of soil pressures on the back side of slurry walls. The pressure transducer housing is connected directly and perpendicular to the thick back plate.

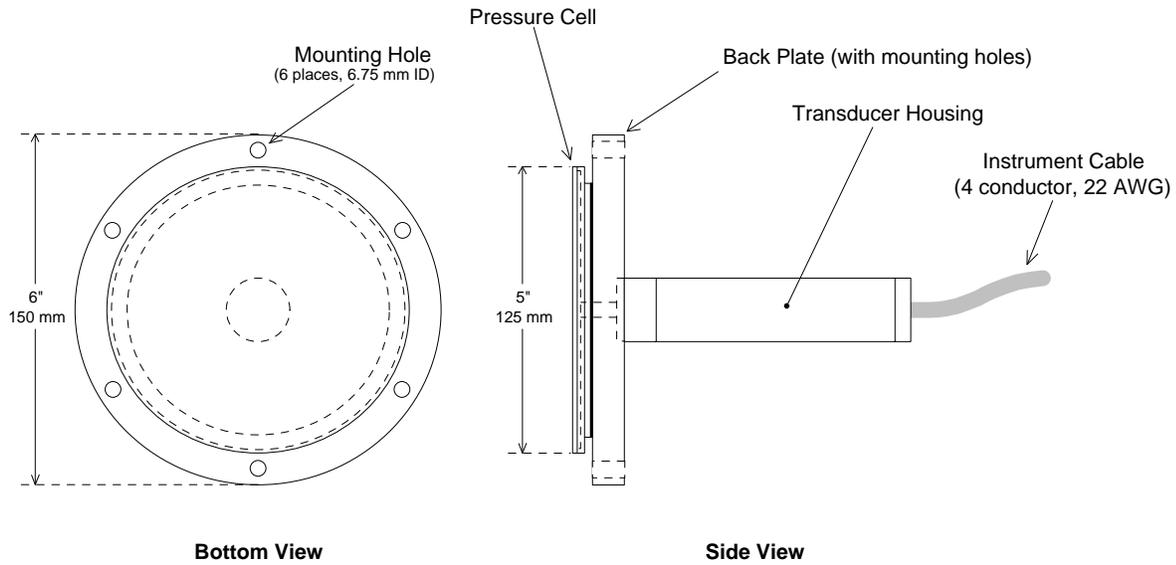


Figure 8 - Model 4820 Jack-Out Pressure Cell

2. INSTALLATION

2.1 Preliminary Tests

It is always wise, before installation commences, to check the cells for proper functioning. Each cell is supplied with a calibration sheet (Figure 17) which shows the relationship between readout digits and pressure and also shows the initial no load zero reading. The cell electrical leads (usually the red and black leads) are connected to a readout box (see Section 3) and the zero reading given on the sheet is now compared to a current zero reading. The two readings should not differ by more than ≈ 50 digits after due regard to corrections made for different temperatures, barometric pressures and height above sea level and actual cell position (whether standing up or laying down).

By pressing on the cell it should be possible to change the readout digits, **causing them to fall as the pressure is increased.**

Checks of electrical continuity can also be made using an ohmmeter. Resistance between the gage leads should be approximately 180 ohms, $\pm 5\%$. Remember to add cable resistance when checking (22 AWG stranded copper leads are approximately $14.7\Omega/1000'$ or $48.5\Omega/\text{km}$, multiply by 2 for both directions). Between the green and white should be approximately 3000 ohms at 25° (see Table 4), and between any conductor and the shield should exceed 20 megohms.

2.2 Pressure Cell Installation

2.2.1 Installation of Model 4800 Earth Pressure Cells Inside Fills & Embankments

Earth pressure cells are normally installed with the flat surfaces horizontal to measure vertical stresses. However, they can be placed at other orientations, inside the fill, to measure stresses in other directions i.e. a cell placed with the flat surfaces vertical will measure horizontal stresses in a direction perpendicular to the plates of the cell. They are sometimes placed at angles of 45 degrees.

Experience has shown that attempts to measure earth pressures in fills frequently meets with failure. The problem is twofold: First, the stress distribution in the fill can be inherently variable due to varying properties of the ground and varying degrees of compaction of the ground. Thus the soil stress at one location may not be typical of the surrounding locations. Secondly, a cell installed directly in the fill could result in the creation of an anomalous zone immediately around the cell where there may be a different, more fine-grained material, under a lesser degree of compaction. (The material around the cell may be poorly compacted because of the need to avoid damage to the cell.)

In an earth fill, this zone of poor compaction would not be expected to be a problem since the earth above might be expected to simply move downwards to fill the voids and consolidate the ground. However, under the influence of rain water and vibration, any spaces in the soil immediately around the cell may grow so that the cell becomes completely de-coupled from the soil around it. In such a situation the internal soil stresses simply go around the cell instead of through it. The cell will then register only a very low pressure which does not change as the loads increase. This situation occurs frequently.

The best way to avoid the problem is to cast the cell inside a weak grout

A method used successfully in South Africa, by Oosthuizen et al, essentially uses the techniques similar to the one described in Section 2.2.5. Installation of the cells begins when the fill has reached a height of 1 meter above the instrument level. The Instrument location and the cable trenches are excavated 1 meter deep, the instrument pocket, with 45° sloping sides, (See Figure 9)

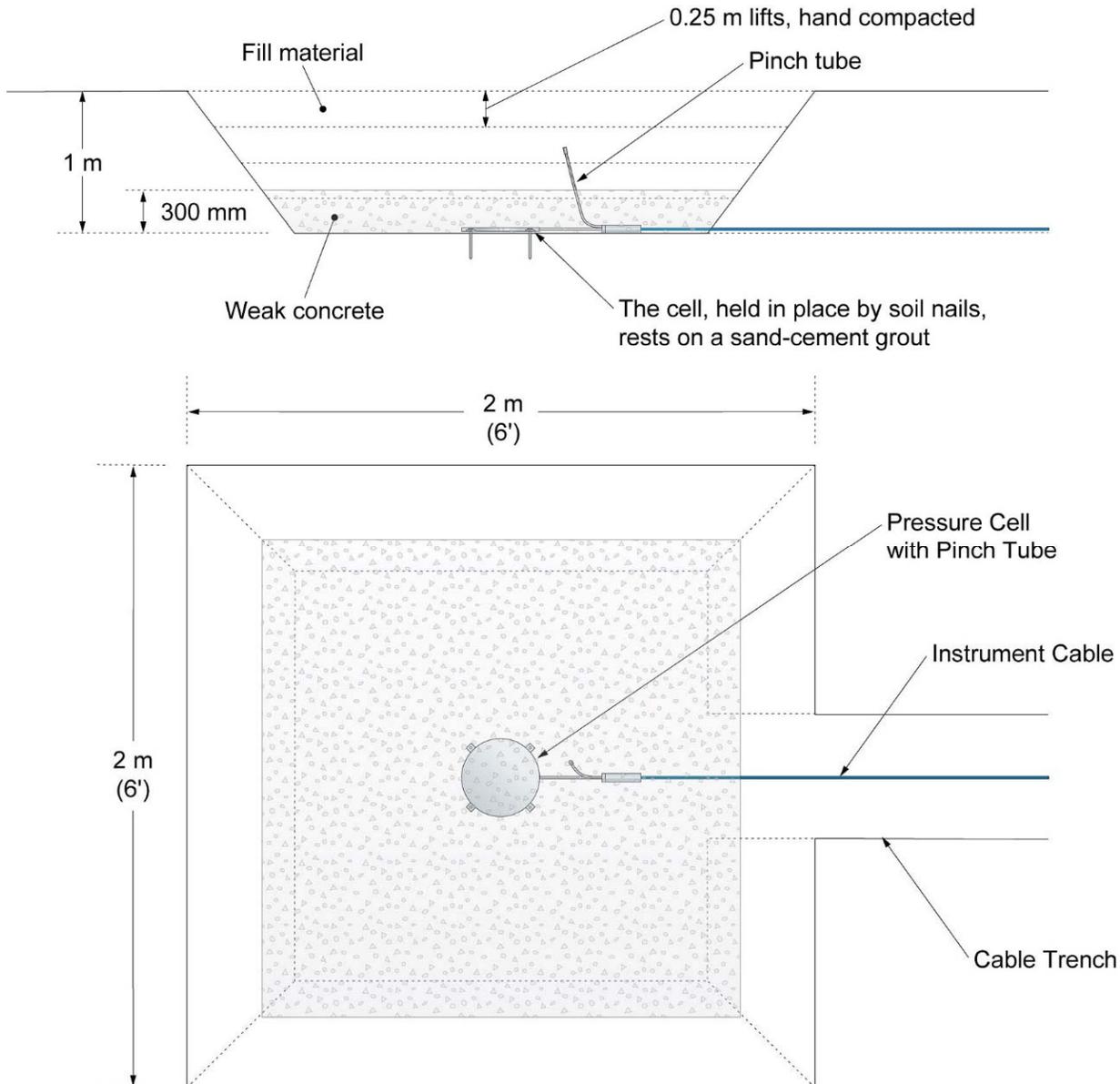


Figure 9 - Model 4800 Earth Pressure Cell Installation

The cells, (Model 4800-1-1P, complete with pinch tubes and lugs), are positioned on a thin layer of non-shrink sand-cement grout and are nailed in position using the lugs on the cells provided for this purpose. The excavated pocket is then backfilled to a depth of 300mm with a weak concrete in 100mm layers, vibrated with a poker vibrator. After 24 hours the cells are pressurized, by pinching the pinch tubes until the pressure in the cell, displayed on a connected Readout Box, starts to change.

The instrument location containing the grouted cells and the cable trench is then backfilled in 250mm layers, using the same material as the main fill placed by hand and compacted with pneumatic or gasoline backfill tampers, or vibratory trench rollers. After this, standard construction filling and compaction practices can continue.

Earth Pressure Cells clusters, placed according to the methods outlined above, may be installed either in trenches, below the temporary embankment grade, or in ramps above the temporary embankment grade. In dams, for example, it is usually convenient to install in trenches in the impervious rolled fill core, and in ramps in the filter zones and compacted rockfill shell zones. In earth embankments it is convenient to install in trenches. By so doing, adequate degrees of compaction of the backfill can be more easily obtained without damage to the cell clusters or cable arrays. As the cells are being covered and compacted, repeated readings should be taken to ensure that the cells are continuing to function properly.

See Section 2.3 for cable installation and protection.

Application	Grout for Medium to Hard Soils		Grout for Soft Soils	
	Weight	Ratio by Weight	Weight	Ratio by Weight
Water	30 gallons	2.5	75 gallons	6.6
Portland Cement	94 lbs. (1 sack)	1	94 lbs. (1 sack)	1
Bentonite	25 lbs. (as required)	0.3	39 lbs. (as required)	0.4
Notes	The 28 day compressive strength of this mix is about 50 psi, similar to very stiff to hard clay. The modulus is about 10,000 psi		The 28 day strength of this mix is about 4psi, similar to very soft clay.	

Table 1 - Cement/bentonite/water ratios for two grout mixes.

2.2.2 Installation of Model 4810 Contact ("fat-back") Pressure Cell

This section details installation instructions for the Model 4810 Earth Pressure Cells which are used for the measurement of earth pressures on structures. In backfills for piers, piles, bridge abutments, retaining walls, culverts and other structures the cells may be installed either inside a concrete structure being poured or directly on the surface of an existing structure. For slurry walls the Model 4820 Earth Pressure Cell is used as described in Section 2.2.4.

Installation in Poured Concrete

When pouring concrete the cells can be held to the forms using nails and the lugs welded to the edge of the cell (see Figure 5). Position the cell so that the thin pressure sensitive plate is directly against the concrete form (see Figure 10). Nail the plates to the form lightly in such a manner that they engage the concrete sufficiently so that they do not pull

out of the concrete when the forms are removed. Route the cable inside the concrete to a convenient readout location or to a block out inside where excess cable can be coiled. Protect the cable from damage during concrete placement and vibration, by tying it to adjacent rebars.

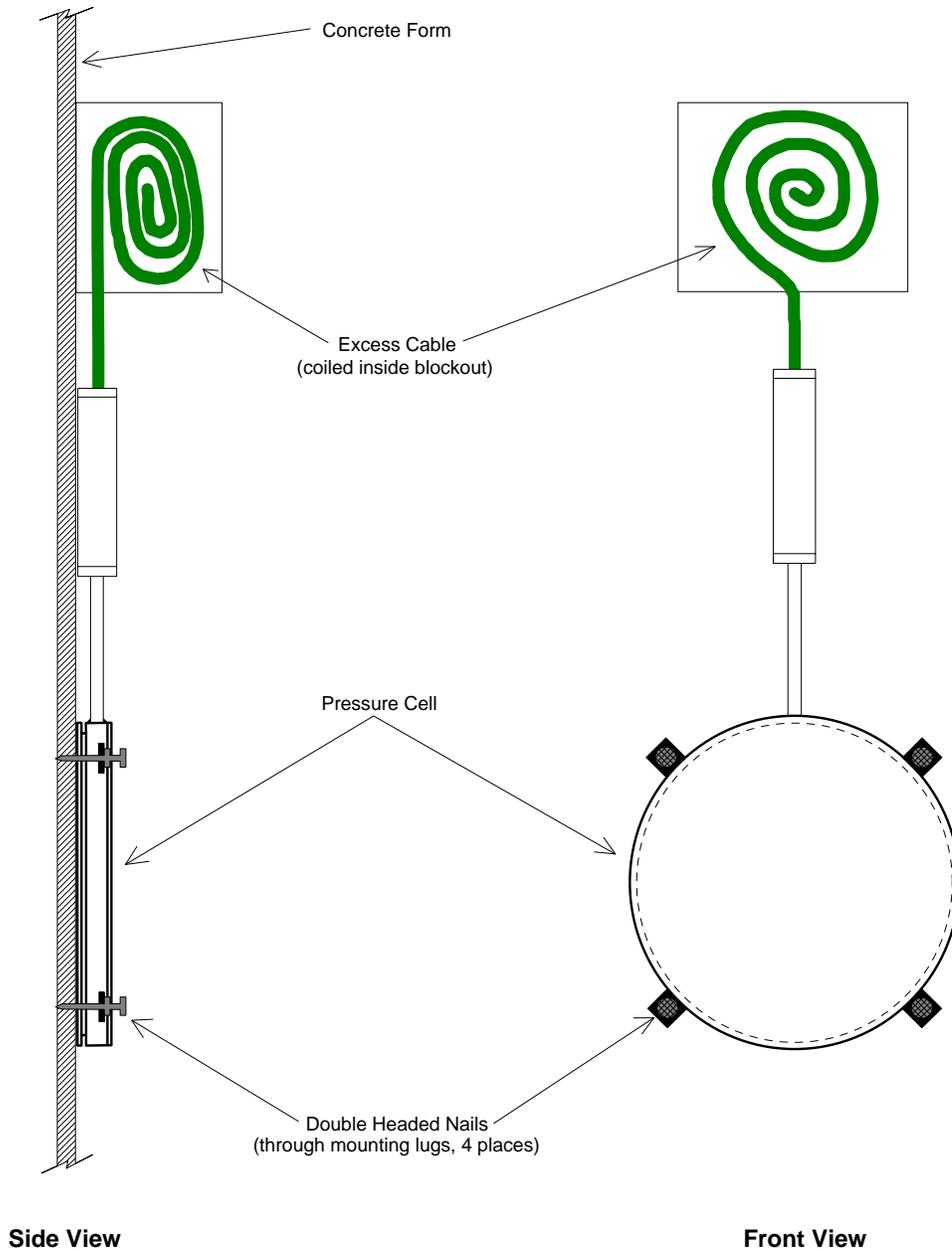


Figure 10 - Attachment of Model 4810 to Concrete Form

Installation on Existing Structures

Again the lugs welded to the edge of the cell can be used to hold the cell against the structure using nails, lag bolts, tie wire, etc. Even if the surface is smooth, but especially where the surface is rough or irregular a mortar pad between the cell and the structure is required. See Figure 11.

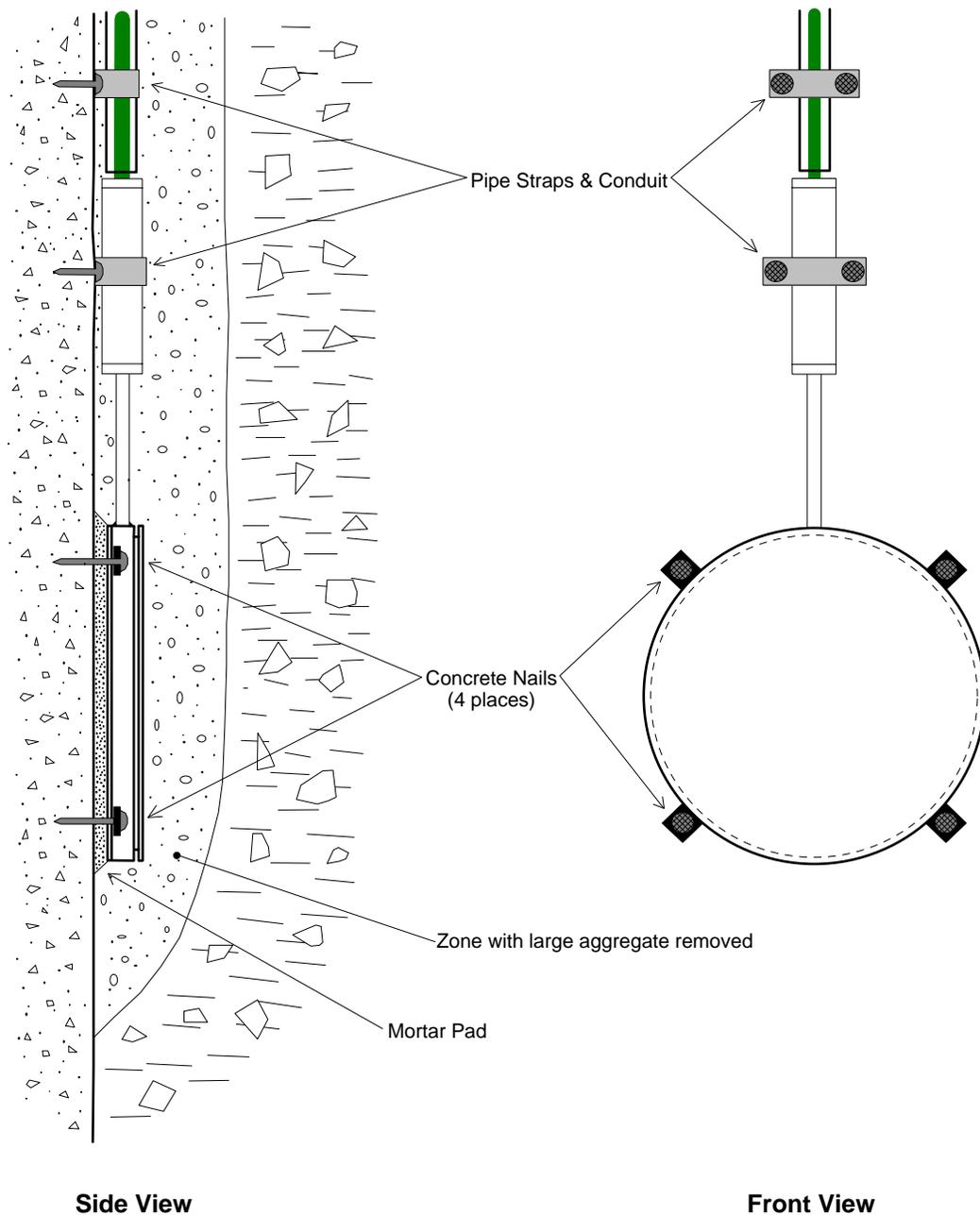


Figure 11 - Model 4810 Contact Pressure Cell Installation

Use the lugs on the cell as a template to locate the position for drilling holes for the installation of expanding anchors or install the anchors nearby and use wire to hold the cells in place. Alternately the cell may be nailed in place using the lugs as a guide. First mix up some quick setting cement mortar or epoxy cement. Trowel this onto the surface then push the cell into the cement so that the excess cement extrudes out of the edges of the cell. Hold the cell in place while the cement sets up, then complete the installation by adding the lag bolts (using the expansion anchors) and tightening or nailing the cell in place. Protect the cell, transducer housing and cable from direct contact with large chunks of rock by covering them with fine grained fill material from which all pieces larger than about 10 mm (0.5") have been removed. This fine material is kept next to the cell and cable as the fill is placed. Additional cable protection can be achieved by using metal conduit strapped to the surface of the structure

2.2.3 Installation of Model 4815 Hydraulic Load Cell.

A particular installation, shown in Figure 12, used the Model 4815 Hydraulic Load Cell to measure the concentrated load on a tunnel lining from an existing wooden pile (supporting a building above) that had been cut short by the tunnel excavation in frozen ground. The load cell was designed to measure any increase of load on the tunnel lining that might occur when, at the end of tunnel construction, the ground was allowed to thaw out. The load cell was positioned below the bottom of the pile and temporarily held in place with lugs and a mortar pad until the shotcrete tunnel lining was sprayed.

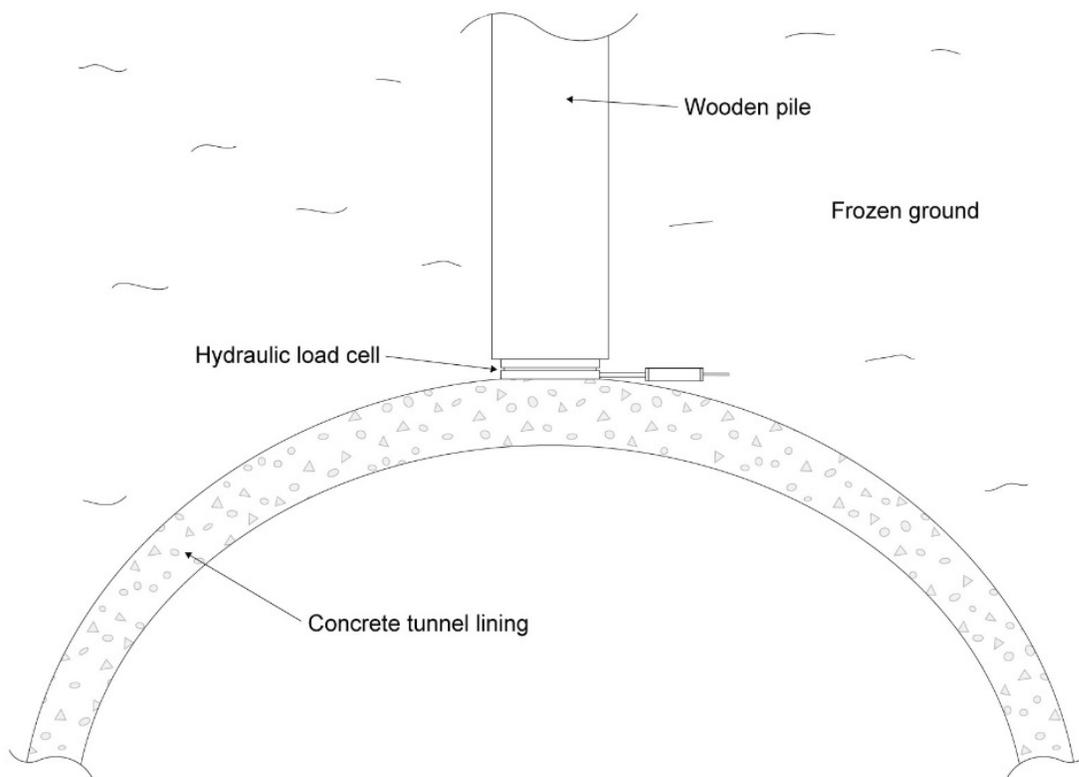


Figure 12 - Model 4815 Hydraulic Load Cell Measuring Loads on a Tunnel Lining

2.2.4 Installation of Model 4820 Jack-Out Pressure Cell in Slurry Trenches.

The Jack-Out Pressure first needs to be assembled into the jack-out frame. The assembly is shown in Figure 13. The support plate has a circular hole cut in it and bolt holes to fit the Jack-Out Pressure Cell (JOPC), and is connected to one end of a double-acting hydraulic jack by means of steel struts. The support plate and reaction plate are cambered top and bottom to prevent them from snagging on the sides of the slurry trench. The reaction plate is attached to the other side of the double-acting hydraulic jack. The jack is attached firmly to the rebar cable and arranged so that the plates are free to move outwards. The hydraulic line and signal cable are tied off to one of the rebars at intervals of 1 meter (3 feet).

When the rebar cage has been lowered to its proper depth, the jack is activated, forcing the two plates out against the trench walls.

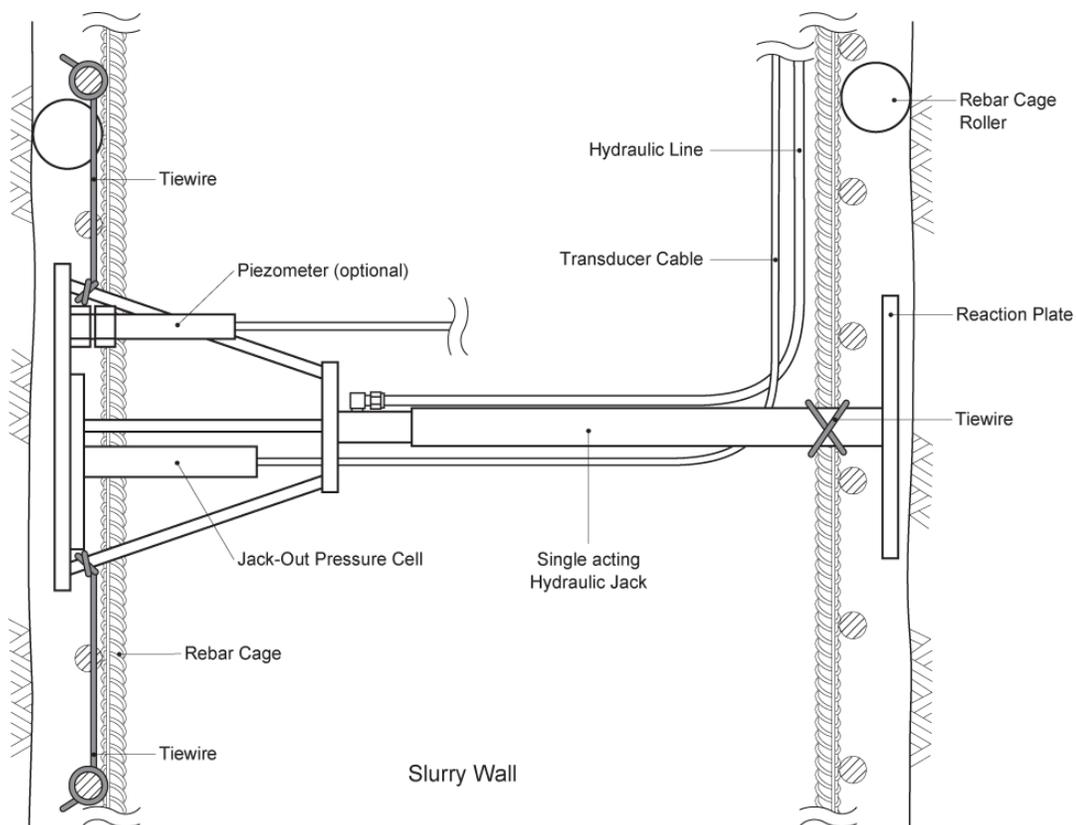


Figure 13 - Model 4820 Jack-Out Pressure Cell Installation

Observation of the pressure indicated by the JOPC (see Section 3 for readout instructions) will indicate when the cell has made contact with the wall. Pump up the jack until the JOPC reading indicates a pressure roughly 70KPa (10psi) greater than the slurry pressure at JOPC depth. This ensures that the cell is bearing against the walls of the trench and that the concrete grout pressure will not close the jack and allow the reaction plates to move away from the trench walls. Check the JOPC reading from time to time because the pressure might bleed away if the walls of the trench are soft and yielding. Repressurise as needed. Leave the jack pressurized until the grout has set up.

2.2.5 Installation of Cells to Measure Earth Pressure at the Base of Footings, Floor Slabs, Pavements, Etc.

Experience has shown that attempts to measure contact earth pressures on the base of footings, floor slabs, pavements, etc., frequently meets with failure. The problem is twofold: First, the contact stress distribution can be inherently variable due to varying properties of the ground and varying degrees of compaction of the ground. Thus the contact stress at one location may not be typical of the surrounding locations. Secondly, a cell installed as described in Section 2.2.1 could result in the creation of an anomalous zone immediately around the cell where there may be a different, finer grained material, under a lesser degree of compaction. (The material around the cell may be poorly compacted because of the need to avoid damage to the cell.)

In an earth fill, this zone of poor compaction would not be a problem, since the earth above would simply move downwards to fill the voids and consolidate the ground. However, where there is a concrete slab immediately above the cell this consolidation may not take place and in fact, under the influence of rain water and vibration, the spaces around the cell may grow so that the cell becomes completely de-coupled from the concrete above. In such a situation the concrete slab bridges over the gap and the loads in the concrete simply go around the cell instead of through it. The cell registers only a very low pressure which does not change as the loads increase.

The best way to avoid the problem, if at all possible, is to cast the cell inside the concrete. This can often be done when the initial concrete bonding layer is spread over the surface of the ground. At this time a Model 4800-1-1P Earth Pressure Cell with a pinch tube, is pressed into the bonding layer so that it rests against the ground below. A weighted tripod can be used to hold the stress cell in place until the concrete hardens. The pinch tube is arranged to protrude above the bonding layer and, when the concrete has hardened, it is used to pressurize the cell and ensure good contact between the cell and the surrounding concrete. See Figure 14.

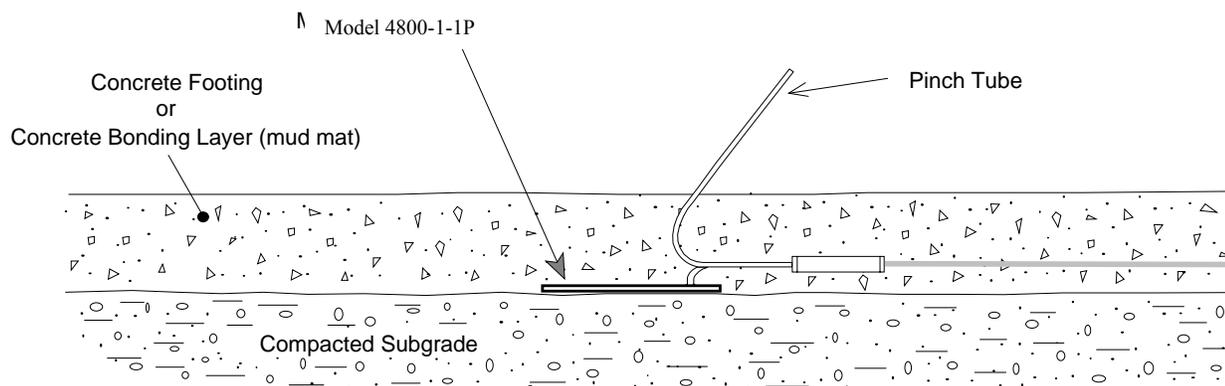


Figure 14 - Model 4800-1-1P Earth Pressure Cell Installation

The advantage of this method lies in its simplicity and in that it permits the ground below the concrete to be completely compacted in the normal way.

2.2.6 Installation of Push-in Pressure Cells to Measure lateral Earth Pressures.

The Model 4830 is designed to be pushed into soft soils using available drill rods, usually AW. Unless the ground is very soft it is recommended that a borehole be drilled to within about 2ft of the desired location and then push the cell the rest of the way.

A few things to note and be aware of:

1) Temperature effects:

This pressure cell is relatively stiff due to the geometry and the need for a robust construction for pushing into the ground. It is always advisable to obtain the pre-installation zero pressure readings in the borehole at the borehole temperature. It may take a significant amount of time for the sensor to come to thermal equilibrium but this is an important measurement and if it is not possible to take this reading in the borehole it may be possible to take the reading in a bucket of water that is at the ground temperature.

2) Piezometer Saturation:

The piezometer filter and sensor are saturated at the factory and sealed with Mylar tape. Do not remove the tape until just before the sensor is installed in the ground. The filter is saturated by drawing a vacuum on the sensor and then allowing water to flow into the sensor when the vacuum is released. If the sensor is to be installed and then removed and reused at other sites the saturation process should be performed at each installation. Geokon can supply the necessary portable equipment to accomplish this.

3) Overpressure:

When pushing the cell into the ground it is possible that pressures in excess of the sensors full scale range can be generated causing the sensor to experience a zero shift or even permanent damage. To prevent this, readings should be taken as the sensor is pushed. When the indicated pressure approaches 150% of full scale the pushing operation should be terminated until the sensor output comes back within its calibrated range.

2.3 Cable Installation

Cable placement procedures vary with individual installations. In general, however, all installations have in common the requirements that; 1) the cable must be protected from damage by angular particles of the material in which the cable is embedded, 2) the cable must be protected from damage by compaction equipment, 3) in earth and rock embankments and backfills, the cable must be protected from stretching as a result of differential compaction of the embankment, 4) in concrete structures, the cable must be protected from damage during placement and vibration of the concrete.

In embankments, cables may be embedded in a protective covering of sand or selected fine embankment materials. A typical installation might, for example, comprise the positioning of a series of cables on a prepared layer consisting of not less than 200 mm (8") of compacted selected fine material. In order to establish an acceptable grade without undue interference with construction operations, the prepared layer may be located either in a trench or on an exposed ramp. In rockfill dams with earth fill cores, for example, it is frequently convenient to install cable in trenches in the core and fine filter zones, and in ramps in the coarse filter and compacted rockfill shell zones. Individual cables should be spaced not less than 12 mm (0.5") apart, and no cable should be closer than 150 mm (6") to the edge of the prepared layer. In instances in which cables must cross each other, or in which more than one layer of cables must be placed in a given array, the cables should be separated from each other by a vertical interval of not less than 50 mm (2") of hand-compacted sand or selected fine embankment material. Since the elongation capability of electrical cable is quite substantial, it is not necessary to place the cable with "S" shaped meanders, which in any case serve no purpose.

During the backfill of trenches in earth dams, a plug, approximately 0.5 meter (2 feet) in width, made of a mixture of 5% bentonite (by volume) from an approved source and exhibiting a free swell factor of approximately 600%, and 95% embankment material, can be placed in the trenches at intervals of not greater than 20 meters (50 feet). The purpose of the bentonite plugs is to reduce the possibility of water seepage through the embankment core along the backfilled trenches.

The cable may be marked by using a mylar cable labels. For an individual cable the identification number should be taped near the end of the cable. Additional cable labels might be specified at regular intervals along the cable to aid in identification if cables need to dug up for splicing, etc.

Cables may be spliced, without affecting gage readings, nevertheless splicing should be avoided wherever possible. If necessary, waterproof the splice completely, preferably using an epoxy based splice kit such the 3M Scotchcast™, model 82-A1. These kits are available from the factory.

2.4 Electrical Noise

Care should be exercised when installing instrument cables to keep them as far away as possible from sources of electrical interference such as power lines, generators, motors, transformers, arc welders, etc. Cables should never be buried or run with AC power lines. The instrument cables will pick up the 50 or 60 Hz (or other frequency) noise from the power cable and this will likely cause a problem obtaining a stable reading. Contact the factory concerning filtering options available for use with the Geokon dataloggers and readouts should difficulties arise.

2.5 Initial Readings

Initial readings must be taken and carefully recorded along with the barometric pressure and temperature at the time of installation. Take the initial readings while the cell is in position, just prior to it being covered by fill and pouring of concrete. ***Again, it is imperative that initial readings at zero load are taken!***

3. TAKING READINGS

3.1 GK-404 Readout Box

The GK404 is a palm sized readout box which displays the vibrating wire value and the temperature in degrees centigrade.

3.1.1 Operating the GK-404

Before use, attach the flying leads to the GK-404 by aligning the red circle on the silver “Lemo” connector of the flying leads with the red line on the top of the GK-404 (Figure 15). Insert the Lemo connector into the GK-404 until it locks into place.



Figure 15 - Lemo Connector to GK-404

Connect each of the clips on the leads to the matching colors of the sensor conductors, with blue representing the shield (bare).

To turn the GK-404 on, press the “ON/OFF” button on the front panel of the unit. The initial startup screen will display:

Geokon Inc.
GK-404 verX.XX

After approximately one second, the GK-404 will start taking readings and display them based on the settings of the POS and MODE buttons.

The unit display (from left to right) is as follows:

- The current Position: Set by the **POS** button. Displayed as a letter A through F.
- The current Reading: Set by the **MODE** button. Displayed as a numeric value followed by the unit of measure.
- Temperature reading of the attached gage in degrees Celsius.

Use the **POS** button to select position **B** and the **MODE** button to select **Dg** (digits). (Other functions can be selected as described in the GK404 Manual.)

The GK-404 will continue to take measurements and display readings until the unit is turned off, either manually, or if enabled, by the Auto-Off timer. If the no reading displays or the reading is unstable see Section 5 for troubleshooting suggestions.

For further details information the GK-404 manual.

3.2 GK-405 Readout Box

The GK-405 Vibrating Wire Readout is made up of two components: The Readout Unit, consisting of a Windows Mobile handheld PC running the GK-405 Vibrating Wire Readout Application; and the GK-405 Remote Module, which is housed in a weatherproof enclosure and connects to the vibrating wire gage to be measured. The two components communicate wirelessly using Bluetooth[®], a reliable digital communications protocol. The Readout Unit can operate from the cradle of the Remote Module, or, if more convenient, can be removed and operated up to 20 meters from the Remote Module.

3.2.1 Connecting Sensors

Connecting Sensors with 10-pin Bulkhead Connectors Attached:

Align the grooves on the sensor connector (male), with the appropriate connector on the readout (female connector labeled sensor or load cell). Push the connector into place, and then twist the outer ring of the male connector until it locks into place.

Connecting Sensors with Bare Leads:

Attach the GK-403-2 flying leads to the bare leads of a Geokon vibrating wire sensor by connecting each of the clips on the leads to the matching colors of the sensor conductors, with blue representing the shield (bare).

3.2.2 Operating the GK-405

Press the button labeled “POWER ON (BLUETOOTH)”. A blue light will begin blinking, signifying that the Remote Module is waiting to connect to the handheld unit. Launch the GK-405 VWRA program by tapping on “Start” from the handheld PC’s main window, then “Programs” then the GK-405 VWRA icon. After a few seconds, the blue light on the Remote Module should stop flashing and remain lit. The Live Readings Window will be displayed on the handheld PC. Choose display mode “B”. Figure 16 shows a typical vibrating wire output in digits and thermistor output in degrees Celsius. If no reading displays or the reading is unstable see Section 5 for troubleshooting suggestions. For further information consult the GK405 Instruction Manual.

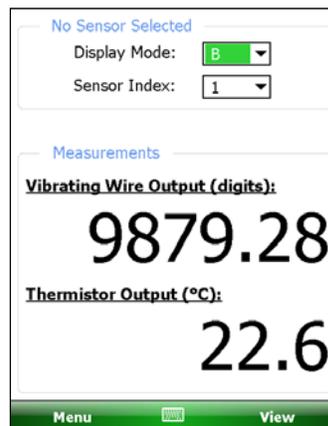


Figure 16 - Live Readings – Raw Readings

3.3 GK-403 Readout Box (Obsolete Model)

The GK-403 can store gage readings and also apply calibration factors to convert readings to engineering units. The following instructions explain taking gage measurements using Mode "B" (similar to the GK-401 switch positions "B"). Consult the GK-403 Instruction Manual for additional information.

3.3.1 Connecting Sensors

Connecting Sensors with 10-pin Bulkhead Connectors Attached:

Align the grooves on the sensor connector (male), with the appropriate connector on the readout (female connector labeled sensor or load cell). Push the connector into place, and then twist the outer ring of the male connector until it locks into place.

Connecting Sensors with Bare Leads:

Attach the GK-403-2 flying leads to the bare leads of a Geokon vibrating wire sensor by connecting each of the clips on the leads to the matching colors of the sensor conductors, with blue representing the shield (bare).

3.3.2 Operating the GK-403

- 1) Turn the display selector to position "B".
- 2) Turn the unit on.
- 3) The readout will display the vibrating wire output in digits (See Equation 1 in Section 4.1.) The last digit may change one or two digits while reading.
- 4) The thermistor reading will be displayed above the gage reading in degrees centigrade.
- 5) Press the "Store" button to record the value displayed.

If the no reading displays or the reading is unstable see Section 5 for troubleshooting suggestions.

The unit will automatically turn itself off after approximately two minutes to conserve power.

3.4. Measuring Temperatures

Each Vibrating Wire Pressure Cell is equipped with a thermistor for reading temperature. The thermistor gives a varying resistance output as the temperature changes. Usually the white and green leads are connected to the internal thermistor.

- 1) Connect the ohmmeter to the two thermistor leads coming from the stress cell. (Since the resistance changes with temperature are so large, the effect of cable resistance is usually insignificant.)
- 2) Look up the temperature for the measured resistance in Table 4 (Appendix B). Alternately the temperature could be calculated using Equation 4 (Appendix B). For example, a resistance of 3400 ohms equivalent to 22° C. When long cables are used the cable resistance may need to be taken into account. Standard 22 AWG stranded copper lead cable is approximately 14.7 Ω /1000' or 48.5 Ω /km, multiply by 2 for both directions.

Note: Geokon readout boxes will read the thermistor and display temperature in °C automatically.

4. DATA REDUCTION

4.1 Pressure Calculation

The basic units utilized by Geokon for measurement and reduction of data from Vibrating Wire Earth Pressure Cells are "digits". Geokon Readouts display "digits" in the Earth Pressure Cell reading position. Calculation of digits is based on the following equation;

$$\text{Digits} = \left(\frac{1}{\text{Period}} \right)^2 \times 10^{-3} \text{ or } \text{Digits} = \frac{\text{Hz}^2}{1000}$$

Equation 1 - Digits Calculation

To convert digits to pressure the following equation applies;

$$\text{Pressure} = (\text{Current Reading} - \text{Initial Reading}) \times \text{Calibration Factor}$$

or

$$P = (R_1 - R_0) \times G$$

Equation 2 - Convert Digits to Pressure

The Initial Reading (R_0) is normally obtained during installation (usually the zero reading). The Calibration Factor (G , usually in terms of psi or kPa per digit) comes from the supplied Calibration Sheet (a **typical** calibration sheet is shown in Figure 17). To convert the output to other engineering units, multiply the Calibration Factor by the conversion multiplier listed in Table 2.

From → To ↓	psi	"H ₂ O	'H ₂ O	mm H ₂ O	m H ₂ O	"HG	mm HG	atm	mbar	bar	kPa	MPa
psi	1	.036127	.43275	.0014223	1.4223	.49116	.019337	14.696	.014503	14.5039	.14503	145.03
"H ₂ O	27.730	1	12	.039372	39.372	13.596	.53525	406.78	.40147	401.47	4.0147	4016.1
'H ₂ O	2.3108	.08333	1	.003281	3.281	1.133	.044604	33.8983	.033456	33.4558	.3346	334.6
mm H ₂ O	704.32	25.399	304.788	1	1000	345.32	13.595	10332	10.197	10197	101.97	101970
m H ₂ O	.70432	.025399	.304788	.001	1	.34532	.013595	10.332	.010197	10.197	.10197	101.97
"HG	2.036	.073552	.882624	.0028959	2.8959	1	.03937	29.920	.029529	29.529	.2953	295.3
mm HG	51.706	1.8683	22.4196	.073558	73.558	25.4	1	760	.75008	750.08	7.5008	7500.8
atm	.06805	.0024583	.0294996	.0000968	.0968	.03342	.0013158	1	.0009869	.98692	.009869	9.869
mbar	68.947	2.4908	29.8896	.098068	98.068	33.863	1.3332	1013.2	1	1000	10	10000
bar	.068947	.0024908	.0298896	.0000981	.098068	.033863	.001333	1.0132	.001	1	.01	10
kPa	6.8947	.24908	2.98896	.0098068	9.8068	3.3863	.13332	101.320	.1	100	1	1000
MPa	.006895	.000249	.002988	.0000981	.009807	.003386	.000133	.101320	.0001	.1	.001	1

Table 2 - Engineering Units Multiplication Factors

For example, assume an initial reading of $R_0 = 9101$, a present reading of, $R_1 = 7390$ and a Calibration Factor of -0.1192 kPa/digit. The calculated pressure is;

$$204 \text{ kPa} = (7390 - 9101) \times -0.1192$$

[Appendix D shows how a second order polynomial can be used to improve accuracy]

4.2 Temperature Correction

The vibrating wire earth pressure cell is quite sensitive to temperature fluctuations but often temperature changes in the ground are minor and can be ignored. Corrections for temperature effects on the transducer alone can be made using the Thermal Factor (K) supplied on the calibration sheet (see Figure 13) along with an equation for its proper use. See Equation 3.

Temperature Correction = (Current Temperature - Initial Temperature) × Thermal Factor

or

$$P_{\text{corrected}} = (R_0 - R_1)G + (T_1 - T_0)K$$

Equation 3- Temperature Correction for the Transducer Only.

The Temperature Correction value is then added to the pressure calculated using Equation 2. For example, assume an initial temperature of 25° C, a temperature at the time of measurement of 12° C and a Thermal Factor of +0.03852 kPa/° C. The thermally corrected pressure is;

$$203.5 \text{ kPa} = 204 + (12 - 25) \times 0.03852$$

Note that this correction for temperature applies only to the pressure transducer itself and not to the entire cell surrounded by soil or soil and concrete each with its own (different) temperature coefficient of expansion. Commercially it is not practical to measure this effect without incurring huge expenses. Suffice to say that the effect is usually small at depths where the temperature is fairly constant. But where temperatures do vary the effect can be quite large. For more information see Appendix D which gives a theoretical treatment.

In practice the best way to compensate for temperatures is to derive a factor from simultaneous measurements of pressure and temperature at times when the temperature is changing and when it can be safely assumed that the applied load is not changing.

4.3 Barometric Correction

The pressure transducer used in Geokon Vibrating Wire Earth Pressure Cells is evacuated and hermetically sealed and will respond to barometric pressure fluctuation. If a correction for these fluctuations is required then it is necessary to record the initial barometric pressure, S_0 , and the barometric pressure at the time of each reading, S_1 , and subtract the change ($S_1 - S_0$) from the calculated pressure reading.

Barometric Pressure: 1008.1 mbar

Technician: Stewart Kinnip

Applied Pressure (kPa)	Gage Reading 1st Cycle	Gage Reading 2nd Cycle	Average Gage Reading	Calculated Pressure (Linear)	Error Linear (%FS)	Calculated Pressure (Polynomial)	Error Polynomial (%FS)
0.0	8980	8981	8981	0.298	0.09	-0.059	-0.02
70.0	8395	8395	8395	70.06	0.02	70.13	0.04
140.0	7811	7811	7811	139.7	-0.10	139.9	-0.02
210.0	7223	7223	7223	209.7	-0.08	210.0	0.00
280.0	6634	6634	6634	279.9	-0.03	280.0	-0.01
350.0	6042	6043	6043	350.4	0.11	350.0	0.01

(kPa) Linear Gage Factor (G): -0.1192 (kPa/ digit) Regression Zero: 8983

Polynomial Gage factors: A: -3.082E-07 B: -0.1145 C: _____

Thermal Factor (K): 0.03852 (kPa/ °C)

Calculate C by setting P=0 and R₁ = initial field zero reading into the polynomial equation

(psi) Linear Gage Factor (G): -0.01728 (psi/ digit)

Polynomial Gage Factors: A: -4.47E-08 B: -0.01661 C: _____

Thermal Factor (K): 0.005586 (psi/ °C)

Calculate C by setting P=0 and R₁ = initial field zero reading into the polynomial equation

Calculated Pressures: Linear, $P = G(R_1 - R_0) + K(T_1 - T_0) - (S_1 - S_0)^2$

Polynomial, $P = AR_1^2 + BR_1 + C + K(T_1 - T_0) - (S_1 - S_0)^2$

*Barometric pressures expressed in kPa or psi. Barometric compensation is not required with vented transducers.

The above instrument was found to be in tolerance in all operating ranges.
 The above named instrument has been calibrated by comparison with standards traceable to the NIST, in compliance with ANSI Z540-1.

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Figure 17 - Sample Model 4800 Calibration Sheet

5. TROUBLESHOOTING

Maintenance and troubleshooting of Vibrating Wire Pressure Cells is confined to periodic checks of cable connections. Once installed, the cells are usually inaccessible and remedial action is limited. Consult the following list of problems and possible solutions should difficulties arise. Consult the factory for additional troubleshooting help.

Symptom: Pressure Cell Readings are Unstable

- ✓ Is the readout box position set correctly? If using a datalogger to record readings automatically are the swept frequency excitation settings correct? Try reading the cell on a different readout position. For instance, channel A of the GK-401 and GK-403 might be able to read the pressure cells. To convert the Channel A period display to digits use Equation 1.
- ✓ Is there a source of electrical noise nearby? Most probable sources of electrical noise are motors, generators, transformers, arc welders and antennas. Make sure the shield drain wire is connected to ground whether using a portable readout or datalogger. If using the GK-401 Readout connect the clip with the green boot to the bare shield drain wire of the pressure cell cable. If using the GK-403 connect the clip with the blue boot to the shield drain wire.
- ✓ Does the readout work with another pressure cell? If not, the readout may have a low battery or be malfunctioning. Consult the appropriate readout manual for charging or troubleshooting directions.

Symptom: Pressure Cell Fails to Read

- ✓ Is the cable cut or crushed? This can be checked with an ohmmeter. Nominal resistance between the two gage leads (usually red and black leads) is 180Ω , +/- 5%. Remember to add cable resistance when checking (22 AWG stranded copper leads are approximately 14.7Ω /1000' or 48.5Ω /km, multiply by 2 for both directions). If the resistance reads infinite, or very high (megohms), a cut wire must be suspected. If the resistance reads very low ($<100\Omega$) a short in the cable is likely.
- ✓ Does the readout or datalogger work with another pressure cell? If not, the readout or datalogger may be malfunctioning. Consult the readout or datalogger manual for further direction.

APPENDIX A. SPECIFICATIONS

A.1 Earth Pressure Cells

Model:	4800 Earth Pressure Cell (rectangular)	4800 Earth Pressure Cell (circular)	4810 Contact Pressure Cell	4820 Jack-Out Pressure Cell
Ranges: ¹	70kPa (10psi) 170kPa (25psi) 350 kPa (50 psi) 700 kPa (100 psi) 1MPa (150 psi) 2Mpa (300psi) 3 MPa (435 psi) 5 MPa (750 psi) 7.5 MPa (1100 psi) 20 MPa (3000 psi)	70kPa (10psi) 170kPa (25psi) 350 kPa (50 psi) 700 kPa (100 psi) 1MPa (150 psi) 2Mpa (300psi) 3 MPa (435 psi) 5 MPa (750 psi) 7.5 MPa (1100 psi) 20 MPa (3000 psi)	350kPa (50psi) 700kPa (100psi) 1Mpa (150psi) 2 MPa (300 psi) 3 MPa (500 psi) 5 MPa (750 psi)	350kPa (50psi) 700kPa (100psi) 1Mpa (150psi) 2 MPa (300 psi) 3 MPa (500 psi) 5 MPa (750 psi)
Resolution:	±0.025% FSR			
Accuracy: ⁴	±0.5% FSR (±0.1% FSR with a polynomial expression)			
Linearity:	±0.5% FSR (standard), ±0.1% FSR (optional)			
Overrange:	150% FSR			
Operating Temperature:	-20 to +80° C			
Excitation Frequency Range	1400-3500Hz			
Output Frequency Range	2000-3000Hz			
Cell Dimensions: ² (active area)	150 × 250 mm 6 × 10"	230 mm OD 9" OD	230 mm OD 9" OD	125 mm OD 5" OD
Coil Resistance:	150 Ω			
Material:	316 Stainless Steel			
Weight:	2.3 kg. (5 lbs.)	2.3 kg. (5 lbs.)	4.7 kg. (10.3 lbs.)	2.7 kg. (6 lbs.)
Electrical Cable: ³	2 twisted pair (4 stranded conductor), 22 AWG Foil shield (with drain wire), PVC jacket, nominal OD=6.3 mm (0.250")			

Table 3 - Earth Pressure Cell Specifications

Notes:

¹ Consult the factory for other ranges available

² Consult the factory for other sizes available.

³ Consult the factory for alternate cable types.

⁴ The stated accuracy is the accuracy of the pressure transducer itself. The system accuracy depends on many factors as discussed in Section 1.1 of the manual

A.2 Thermistor (see Appendix B also)

Range: -80 to +150° C

Accuracy: ±0.5° C

APPENDIX B. THERMISTOR TEMPERATURE DERIVATION

Thermistor Type: YSI 44005, Dale #1C3001-B3, Alpha #13A3001-B3
 Resistance to Temperature Equation:

$$T = \frac{1}{A + B(\ln R) + C(\ln R)^3} - 273.2$$

Equation 4 - Resistance to Temperature

Where;

T = Temperature in °C.

LnR = Natural Log of Thermistor Resistance.

A = 1.4051×10^{-3} (coefficients calculated over the -50 to +150° C. span)

B = 2.369×10^{-4}

C = 1.019×10^{-7}

Ohms	Temp	Ohms	Temp	Ohms	Temp	Ohms	Temp	Ohms	Temp
201.1K	-50	16.60K	-10	2417	+30	525.4	+70	153.2	+110
187.3K	-49	15.72K	-9	2317	31	507.8	71	149.0	111
174.5K	-48	14.90K	-8	2221	32	490.9	72	145.0	112
162.7K	-47	14.12K	-7	2130	33	474.7	73	141.1	113
151.7K	-46	13.39K	-6	2042	34	459.0	74	137.2	114
141.6K	-45	12.70K	-5	1959	35	444.0	75	133.6	115
132.2K	-44	12.05K	-4	1880	36	429.5	76	130.0	116
123.5K	-43	11.44K	-3	1805	37	415.6	77	126.5	117
115.4K	-42	10.86K	-2	1733	38	402.2	78	123.2	118
107.9K	-41	10.31K	-1	1664	39	389.3	79	119.9	119
101.0K	-40	9796	0	1598	40	376.9	80	116.8	120
94.48K	-39	9310	+1	1535	41	364.9	81	113.8	121
88.46K	-38	8851	2	1475	42	353.4	82	110.8	122
82.87K	-37	8417	3	1418	43	342.2	83	107.9	123
77.66K	-36	8006	4	1363	44	331.5	84	105.2	124
72.81K	-35	7618	5	1310	45	321.2	85	102.5	125
68.30K	-34	7252	6	1260	46	311.3	86	99.9	126
64.09K	-33	6905	7	1212	47	301.7	87	97.3	127
60.17K	-32	6576	8	1167	48	292.4	88	94.9	128
56.51K	-31	6265	9	1123	49	283.5	89	92.5	129
53.10K	-30	5971	10	1081	50	274.9	90	90.2	130
49.91K	-29	5692	11	1040	51	266.6	91	87.9	131
46.94K	-28	5427	12	1002	52	258.6	92	85.7	132
44.16K	-27	5177	13	965.0	53	250.9	93	83.6	133
41.56K	-26	4939	14	929.6	54	243.4	94	81.6	134
39.13K	-25	4714	15	895.8	55	236.2	95	79.6	135
36.86K	-24	4500	16	863.3	56	229.3	96	77.6	136
34.73K	-23	4297	17	832.2	57	222.6	97	75.8	137
32.74K	-22	4105	18	802.3	58	216.1	98	73.9	138
30.87K	-21	3922	19	773.7	59	209.8	99	72.2	139
29.13K	-20	3748	20	746.3	60	203.8	100	70.4	140
27.49K	-19	3583	21	719.9	61	197.9	101	68.8	141
25.95K	-18	3426	22	694.7	62	192.2	102	67.1	142
24.51K	-17	3277	23	670.4	63	186.8	103	65.5	143
23.16K	-16	3135	24	647.1	64	181.5	104	64.0	144
21.89K	-15	3000	25	624.7	65	176.4	105	62.5	145
20.70K	-14	2872	26	603.3	66	171.4	106	61.1	146
19.58K	-13	2750	27	582.6	67	166.7	107	59.6	147
18.52K	-12	2633	28	562.8	68	162.0	108	58.3	148
17.53K	-11	2523	29	543.7	69	157.6	109	56.8	149
								55.6	150

Table 4 - Thermistor Resistance versus Temperature

APPENDIX C. Temperature Effect on Earth Pressure and Concrete Stress Cells – Some Theoretical Considerations

The following theoretical treatment is by no means rigorous - there are some questionable assumptions and approximations – but it should give some idea of the magnitude of the thermal effect to be expected on hydraulic earth pressure cells, buried in soil, or installed at the contact between soil and structure, and on concrete stress cells embedded in concrete.

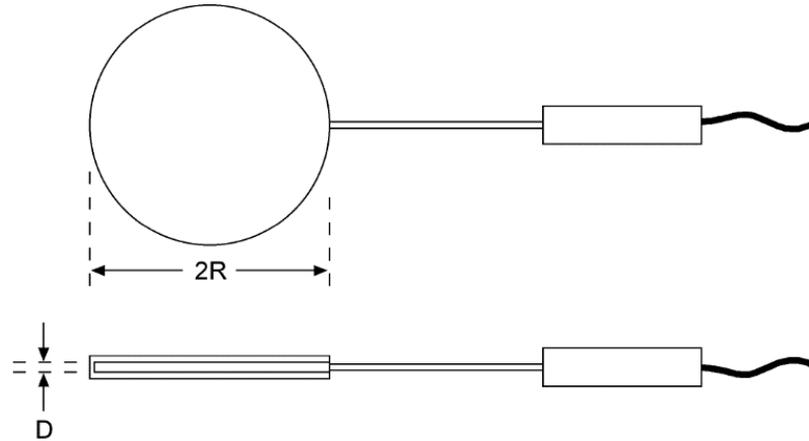


Figure 18 - Circular Cells, Radius and Thickness

Consider a circular cell of radius R containing a liquid film of thickness D , coefficient of thermal expansion K ppm/ $^{\circ}\text{C}$, and bulk modulus G .

For a temperature rise of 1°C the expansion, Y_T of the liquid film is given by the equation:

$$Y_T = KD \dots\dots\dots ①$$

Expansion of the liquid is resisted by the confinement of the surrounding medium (soil or concrete) and this causes a pressure rise, P , in the liquid and a compression of the liquid, Y_c , given by the equation:

$$Y_c = PD/G \dots\dots\dots ②$$

So that the net expansion, Y , of the cell is equal to:

$$Y = D (K - P/G) \dots\dots\dots ③$$

Liquid pressure inside the cell causes deformation of the surrounding medium. The amount of deformation can be quantified by modification of formulas found in [1], where the deformation, Y , produced by a uniform pressure, P , acting on a circular area, R radius, on the surface of a material with modulus of elasticity, E , and Poisson's ratio, ν , is given by:

$$Y = \frac{2 PR (1-v^2)}{E} \quad \text{at the center}$$

And
$$Y = \frac{4 PR (1-v^2)}{\pi E} \quad \text{at the edge}$$

And the difference is
$$\frac{PR (1-v^2)}{E} (2 - 4/\pi)$$

The above formulas apply to pressures acting on a free surface. However, in the confined case, Y, at the edge of the cell, can be assumed to be nearly zero and so Y, at the center, is assumed to be:

$$\frac{PR (1 - v^2)}{E} (2 - 4/\pi) \quad \text{i.e. the same difference as before.}$$

If the average Y, across the cell is assumed to be half this value and if the deformation of the medium on either side of the cell is assumed to be the same then the average total expansion of the cell is given by:

$$Y = 0.73 PR (1-v^2) \times 0.5 \times 2/E = 0.73 PR (1-v^2)/E \quad \text{..... ④}$$

Equating ③ & ④ gives:

$$P (D/G + 0.73 R (1 - v^2)/E) = KD \quad \text{..... ⑤}$$

If one side of the cell lies in contact with a rigid structure, e.g. a concrete retaining wall or a concrete bridge footing, then

$$Y = 0.73 \frac{PR (1-v^2)}{E} \times 0.5/E = 0.36 \frac{PR (1-v^2)}{E} \quad \text{..... ⑥}$$

And
$$P (D/G + 0.36 R (1-v^2)/E) = KD \quad \text{..... ⑦}$$

Where E pertains to the soil material.

Since these expressions are only approximate they can be simplified even further: for all $E < 10 \times 10^6$ psi the term D/G is negligible so long as the cell is designed and constructed properly, i.e., G is large, (no air trapped inside the cell), and D is small. Also, the term $(1-v^2)$ can be replaced by 0.91 since v usually lies between 0.25 and 0.35.

Hence, for total embedment:

$$P = 1.5 EKD/R \quad \text{psi / } ^\circ\text{C}$$

And, for contact pressure cells:

$$P = 3 EKD/R \quad \text{psi / } ^\circ\text{C}$$

Some typical values of the various parameters are:

Liquid	$K \times 10^{-6} / ^\circ\text{C}$	$G \times 10^6 \text{ psi}$
Oil	700	0.3
Mercury	180	3.6
Water	170	0.3
Glycol	650	
50/50 Glycol/Water	400	

Embedment Material	$E \times 10^6 \text{ psi}$	ν
Plastic Clay	0.003	
Soil	0.001 to 0.02 [Ref 2]	0.25 to 0.45
Sand	0.02 to 0.06 [Ref 3]	0.28 to 0.35
Compacted Ottawa Sand	0.2	
Weathered Rock	0.04 to 0.11 [Ref 4]	
Concrete	5.0	0.25

Examples:

For an oil-filled cell, 9 inches diameter and $D = 0.060$ inches, totally embedded in:

1. Plastic Clay, $E = 3000 \text{ psi}$, $\nu = 0.3$,..... $P = 0.042 \text{ psi} / ^\circ\text{C}$
2. Soil, medium stiffness, $E = 10000 \text{ psi}$, $\nu = 0.3$ $P = 0.138 \text{ psi} / ^\circ\text{C}$
3. Coarse Sand, $E = 50000 \text{ psi}$, $\nu = 0.3$ $P = 0.69 \text{ psi} / ^\circ\text{C}$

(For contact pressure cells, multiply the above values for P by 2.)

For a concrete stress cell, 9 inch diameter and $D = 0.020$ inches:

4. Concrete, $E = 5 \times 10^6 \text{ psi}$, $\nu = 0.25$ $P = 22.7 \text{ psi} / ^\circ\text{C}$

Same cell, embedded in concrete, filled with mercury instead of oil, $P = 5.8 \text{ psi} / ^\circ\text{C}$

For an oil-filled cell embedded in a completely rigid medium $P = 210 \text{ psi} / ^\circ\text{C}$

For a mercury-filled cell embedded in a completely rigid medium $P = 650 \text{ psi} / ^\circ\text{C}$

References:

[1] Roark, R.J. and Young, W.C. “ Formulas for Stress and Strain,” McGraw Hill, fifth edition, 1982, p 519.

[2] Weiler, W.A. and Kulhawy, F.H. “ Factors Affecting Stress Cell Measurement in Soil” J. Geotech. Eng. Div. ASCE . Vol. 108, No. GT12, Dec., pp1529-1548.

[3] Lazebnik, G.E., “Monitoring of Soil-Structure Interaction.” Chapman & Hall. pp 224

[4] Fujiyasu, Y. and Orihara, K. “Elastic Modulus of Weathered Rock.” Proc. of the 5th Intl. Symp. on Field Measurements in Geomechanics - Singapore 1999. p 183

APPENDIX D. NON LINEARITY AND THE USE OF A SECOND ORDER POLYNOMIAL TO IMPROVE THE ACCURACY OF THE CALCULATED PRESSURE

Most vibrating wire pressure transducers are sufficiently linear ($\pm 0.2\%$ FS) that use of the linear calibration factor satisfies normal requirements. However, it should be noted that the accuracy of the calibration data, which is dictated by the accuracy of the calibration apparatus, is always $\pm 0.1\%$ FS.

This level of accuracy can be recaptured, even where the transducer is non-linear, by the use of a second order polynomial expression which gives a better fit to the data than does a straight line. The polynomial expression has the form:

$$\text{pressure} = AR^2 + BR + C$$

where R is the reading (digits channel B) and A,B,C, are coefficients. Figure 17 shows a typical calibration sheet of a transducer which has a very little non-linearity. The figure under the “Linearity (%FS)” column is

$$\frac{\text{Calculated pressure} - \text{True pressure}}{\text{Full-scale Pressure}} \times 100\% = \frac{G(R_1 - R_0) - P}{F.S} \times 100\%$$

Note The linearity is calculated using the regression zero for R_0 shown on the sheet.

For example, from the typical sheet shown in Figure 17 when $P = 210$ kPa, $G(R_1 - R_0) = -0.1192(7223 - 8983)$, gives a calculated pressure of 209.8 kPa. The error is 0.2 kPa. Whereas the polynomial expression gives a calculated pressure of $A(7223)^2 + B(7223) + 1053 = 209.9$ kPa and the actual error is only 0.01 kPa. This is an insignificant improvement but where the non-linearity is higher, say $\pm 0.25\%$ FS the improvement could be significant.

Note. If the polynomial equation is used it is important that the value of C, in the polynomial equation, be taken in the field, following the procedures described in Section 2.5. The field value of C is calculated by inserting the initial field zero reading into the polynomial equation with the pressure, P, set to zero.

If the field zero reading is not available calculate C using the zero pressure reading on the calibration sheet. In the above example the value of C would be derived from the equation $0 = A(8981)^2 + B(8981)$ from which $C = +1053$.

It should be noted that where changes of earth pressures are being monitored it makes little difference whether the linear coefficient or the polynomial expression is used.