



INSTRUCTION MANUAL

FIBER-OPTIC PRESSURE TRANSDUCER

FOP Series

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1 PRODUCT

The FOP Fiber optic piezometer is a stable, robust pressure transducer, designed to allow remote measurements of piezometric level and pore pressure over long periods of time. It can be installed in boreholes (model **FOP**, **FOP-microPZ**, **FOP-PZ**), driven into soft ground (model **FOP-P**), laid in trenches prior to fill replacement, or buried in concrete (models **FOP** and **FOP-F**). It can also be threaded to hydraulic or pneumatic lines (model **FOP-C**).

Each gauge is delivered with a calibration data sheet, which includes a gauge factor and/or calibration factors and a temperature correction factor except for the FOP-microPZ and FOP-PZ. These factors are determined through factory calibration.

Complete data logging systems are available, please consult Roctest website for details.

1.1 GAUGE CONSTRUCTION of FOP

The design of the pressure sensor is based on a non-contact measurement of the deflection of a stainless steel diaphragm, as opposed to the more conventional measuring of the diaphragm's deformation. When the gauge is under pressure, there is a variation of the Fabry-Perot cavity length made by the inner surfaces of the stainless steel diaphragm on one side and the tip of an optical fiber on the other side as illustrated in Figure 1. The geometry and material of the transducer are selected in order to obtain a linear relationship between the deflection of the diaphragm and the applied pressure.

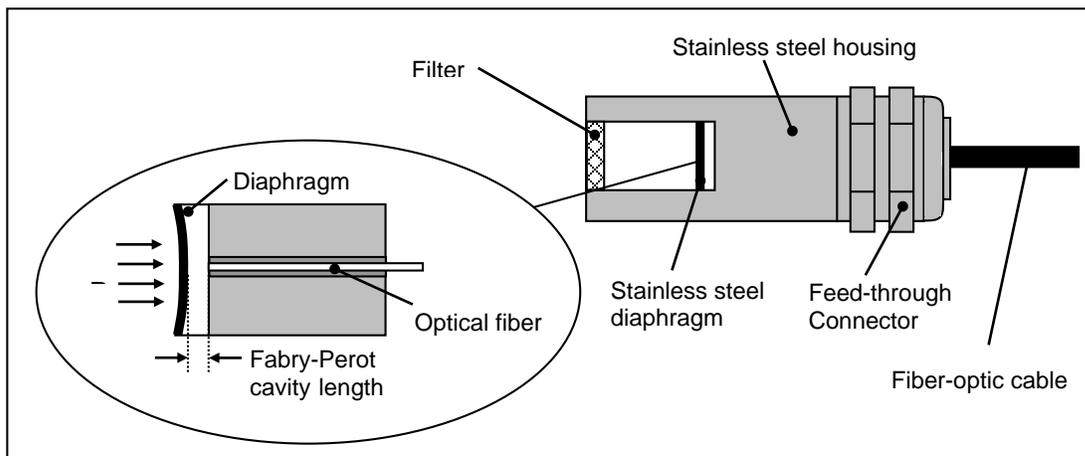


Figure 1: Schematic view of a FOP sensor

The mechanical robustness of the sensor is assured by the all welded stainless steel construction, with no epoxy, sealing rubber, or other sort of polymeric materials.

The pressure transducer comes in three different types: gauge, absolute or differential type. In the case of gauge type, the transducer comes with a vented cable, which keeps the cavity at ambient atmospheric pressure. In the case of absolute transducer, the cavity length is sealed under vacuum. Finally in the case of differential sensor, the cavity is to an arbitrary pressure and comes with a vent connection. The pressure value displayed by the

universal readout unit from Roctest is directly in engineering units either in imperial (psi) or SI (bar) system.

1.1.1 Models FOP and FOP-C

The model FOP piezometer is designed to be embedded in earth fills and concrete, or inserted into boreholes and pipes as small as 19 mm (3/4"). One end is fitted with an insert that holds a micrometric high air or low air entry filter. The opposite end contains the cable entry, fitted with watertight feed-through connector. All parts are made of stainless steel.

The filter is set in the front end of the piezometer and sealed with an o-ring. With the filter in place, the diaphragm is protected from solid particles, and senses only the fluid pressure to be measured. The filter housing easily removable for calibration and saturation can also be replaced with a female or male pipe thread adapter to use the gauge as a pressure transducer (Model FOP-C).

1.1.2 Model FOP-P

The model FOP-P piezometer is designed to be driven into unconsolidated fine grain materials such as sand, silt, or clay. The external housing is a thick walled cylinder fitted with a pointed shoe at one end, and a male thread adapter at the cable entry, fitting "EW" standard drill rods. Four port holes above the point hold micrometric filters. The cable passes through the threaded end, and can be fed through push rods leading to the surface. The cable entry is fitted with watertight feed-through connector. Both high and low air entry filters are available.

1.1.3 Model FOP-F

The model FOP-F piezometer is a thick wall version of the FOP piezometer with an outside diameter of 25.4mm.

1.1.4 Model FOP-MicroPZ and FOP-PZ

The model FOP-MicroPZ and FOP-PZ piezometers are based on non-contact deflection measurement of a miniature MOMS (Micro Optical Mechanical System) pressure sensor manufactured using photolithographic techniques. The pressure transducer has a flexible diaphragm assembled on top of a sealed vacuumed cavity, and the pressure measurement is based on Fabry-Perot white-light interferometry. Pressure creates a variation in the length of a Fabry-Perot cavity consisting of the inner surface of the flexible diaphragm on one side and a reference optical surface attached to the lead optical fiber on the other side.

The mechanical robustness for the FOP-microPZ is assured by the stainless protection sleeve and a porous stainless steel filter which protects the sensing element from solid particles, allowing the piezometer to sense only the fluid pressure to be measured. The total diameter of the sensor, including the housing, is only 4.8 mm and its total length is only 54 mm.

The MOMS pressure sensor is mass-produced in batches on glass and silicon wafers using well established photolithographic technologies derived from the semiconductor industry.

The model FOP-PZ is composed of the same miniature MOMS pressure sensor but this one is protected inside a PVC housing of 15.9mm of diameter. The fiber optic cable passed through a plastic cable gland on one side and at the pressure entry there is a porex HDP filter. The

advantage of this model is his ability to be protected against all forms of corrosion as there is no metallic part on the sensor.

1.2 CALIBRATION

All piezometers are individually calibrated before shipment. Each piezometer is tested over its working pressure range and they are tested in temperature (except FOP micro-PZ and FOP-PZ).

A calibration data sheet supplied with each gauge, lists the following:

- Serial number
- Gauge factor and/or calibration factors
- Working pressure (in bar or psi)
- Temperature at time of factory calibration
- Barometric pressure at time of factory calibration
- Fiber optic cable type and length.
-

1.3 FOP SPECIFICATIONS

PERFORMANCE	
Models:	FOP, FOP-C, FOP-F, FOP-P
Pressure range:	200, 350, 500, 750, 1000, 1500, 2000, 3000, 5000, 7000 kPa ⁽¹⁾ 25, 50, 75, 100, 150, 250, 300, 500, 750, 1000 psi ⁽¹⁾
Resolution:	0.025% Full Scale
Accuracy:	+/-0.25% Full Scale
EMI / RMI susceptibility:	Intrinsic immunity
Proof pressure:	1.5x of rated pressure

(1) Other ranges available upon request.

CONSTRUCTION				
Model:	FOP	FOP-P	FOP-C	FOP-F
Housing:	Miniature	Push-in point with EW thread	Threaded (1/4-18NPT female standard)	Thick wall
Diaphragm Material:	17-4 PH Stainless steel			
Outside diameter in mm:	19	33.4	19	25.4
Cable diameter:	3 or 7mm			

1.3.1 Filter types

Two types of filters are available: high air entry ceramic or low air entry sintered stainless steel filters.

The table below summarizes the main differences between the two filter models.

<i>Stainless steel filter</i> <i>low air pressure entry</i> <i>pore diameter: ~50 μm</i>	<i>Ceramic filter</i> <i>high air pressure entry</i> <i>pore diameter: ~1 μm</i>
Filter generally used.	Filter usually installed for use in unsaturated fine grain material.
Does not allow suction measurements. If water level drops below the piezometer and that a suction builds up, the filter can de-saturate. But as soon as the water level comes up, it will re-saturate easily.	Allow measuring suction to -100 kPa. If negative pressure is more important, the filter will de-saturate and readings will become incorrect.
Air entry pressure: ~10 kPa	Air entry pressure: ~450 kPa
Small time lag.	More important time lag.
Easy to saturate and install.	Need to be saturated under vacuum.
Allows fine grain infiltration.	Helps prevent fine grain infiltration.

1.4 FOP-MicroPZ SPECIFICATIONS

Range	100, 200, 350 (standard range), 500, 750, 1000 kPa
Accuracy	± 0.5% F.S.
Resolution	0.065% F.S.
Overload	1.5x F.S.
Outer diameter	4.8 mm
Length	54 mm
Body material	Stainless steel 316
Cable	PVC 3 mm outside diameter
Filter	Stainless steel 316 (porosity 40 µm)

1.5 FOP-PZ SPECIFICATIONS

Range	100, 200, 350 (standard range), 500, 750, 1000 kPa
Accuracy ¹	± 0.5% F.S.
Resolution	0.065% F.S.
Overload	1.5x F.S.
Outer diameter	15.9 mm
Length	57 mm (without cable gland)
Body material	PVC
Cable	PVC 3 mm outside diameter
Filter	Porex HDP (porosity 70 µm)

¹Accuracy of ± 0.25% F.S can be achieved with a FPI-HR readout unit using a polynomial regression of 3rd degree.

2 DATA READING AND ANALYSIS

2.1 FOP Preparation for initial reading

Gauge readings and diagnostic signal (see section 5) should be taken as soon as the gauges are received to ensure they have not been damaged during shipment. All gauge transducers are individually calibrated before shipment and a gauge factor (7-digit number) and the gauge zero obtained at factory, in internal unit of Fabry-Perot cavity length, are supplied with each gauge. Before using a transducer with the Universal fiber-optic readout unit from Roctest and Fiso Technologies, its gauge factor must first be saved in the readout memory and selected. The calibration factor is already recorded in the transducer's gauge factor, which is registered on a label installed on the cable close to the fiber-optic connector and you can also find it on the calibration sheet of the gauge. See section 4 for relation between gauge factor and calibration factor. Please review the operating manual of the readout unit before proceeding with readings.

First the gauge must be connected in a channel number and the appropriate gauge factor must be assigned. **Fiber-optic pressure transducers must be nulled at least once to adjust the zero before taken an initial reading.** For nulling your transducer follow the instructions given in the operating manual of your readout. After nulling your transducer with the appropriate gauge factor pre-selected, the reading will indicate 0 or a very small value. Obviously, the transducer should not be submitted to pressure for a true zero reading and should be stabilized in temperature (see below for more information about initial reading). **The zero adjustment of the transducer is necessary when using for the first time a pressure transducer. It is also necessary to take note of the current value at installation of the gauge zero (value between 11000 and 23000) when doing a zero adjustment. Knowing it is possible to re-enter the initial gauge zero at installation could be useful in the case the readout is reset or its memory content is lost. For more information about zero adjustment and taking note of the gauge zero see the operating manual of your readout.**

You can also select the Imperial system of unit (in this case the reading will be displayed in psi) or the Metric system of unit (reading will be displayed in bars). See the operating manual of your readout for more information about the system of units.

Summary steps before taking a reading

1. Save gauge factor into the readout memory
2. Connect each gauge to one of the channel input connectors
3. Associate appropriate gauge factor to the measuring channel
4. Null gauges and **record the gauge zero in internal unit of Fabry-Perot cavity length**
5. Select appropriate system of units
6. Take your initial reading in engineering unit

2.2 Pre-installation initial reading

Before installing the sensor, it is necessary to take an initial reading. The procedure for taking an initial reading is the following:

Take a pre-initial reading in air with the stainless steel filter removed at a stabilized temperature and at a known barometric pressure (for ceramic filter see section 3.1.2 and 3.2). Record the reading, the temperature reading and the barometric pressure reading. *Do not touch the transducer body with your hand because you will change the temperature of the transducer and you can see a variation of the reading.*

Assemble the saturated porous element in a bucket filled with water onto the sensor. The sensor must be held tip up to ensure that no air bubbles are entrapped behind the filter. For lower pressure range transducers and for high air entry filters, monitor the pressure acting on the diaphragm to ensure it does not exceed 125 percent of the operating range of the piezometer. Leave the instrument in water at room temperature for 2 to 3 hours to stabilize the temperature of the sensor. See section 3 for more detail information about filter saturation.

It is even preferable to leave it overnight provided that arrangements are made to keep the water at more or less uniform temperature. The instrument is temperature stabilized if the water temperature (ambient) is uniform. All sudden changes of temperature must be avoided.

With the water temperature and ambient temperature in equilibrium raise the sensor by the cable until it is out of the water and take a second reading. Record the stabilized value. Monitor three successive readings to ensure a stable value is recorded. This is the initial reading. Record ambient and water temperature, barometric pressure and the initial reading and diagnostic value of the sensor. See section 3 for advice about initial reading after installation.

2.3 FOP-MicroPZ and FOP-PZ initial reading

For piezometers FOP-MicroPZ and FOP-PZ there is two possibilities of calibration data sheet. You can have a calibration sheet with linear or polynomial regression.

If you have a calibration data sheet with linear regression you will have these parameters as example:

Gauge factor: 6013141

Calibration factor (CF) in psi/nm: -0.031835

If you want to get the output reading in engineering unit (bar or psi) directly on the display of the readout unit then you must save the gauge factor number inside the memory of the readout unit and follow the same steps as described in section 2.1 for the initial reading measurement.

Or if you have many piezometers that you want to read with the raw data in nanometer and convert it later using the calibration factor then you must assign the gauge factor 0001000 for all gauges. In this case you do not do any zero adjustment or nulling to adjust the zero. You should follow the same step as described in section 2.2 for initial reading without removing the filter however. To convert raw data in engineering unit you should then follow instructions as explained in section 2.7. See section 4 for relation between gauge factor and calibration factor.

However, if you have a calibration data sheet with a polynomial regression of third degree then you do not need to follow all steps as described in section 2.1. In this case you should

assign the gauge factor 0001000 for all gauges. Do not do any zero adjustment or nulling to adjust the zero. You should follow the same step as described in section 2.2 for initial reading without removing the filter however.

After selecting gauge factor 0001000 you should have a reading between 10000 and 23000. Then this reading (L) must be inserted in the equation as described in section 2.6 to convert the raw value in nanometer in engineering unit.

2.4 ON-SITE FUNCTION CHECK (OPTIONAL)

Piezometers are calibrated in factory with high precision calibrators having accuracy at least four times better than the accuracy of the piezometer. However, it is tempting for the user to make function/calibration checks.

The preferred method for an on site function check is to carry out the readings in a water filled pipe at uniform temperature. Variables that otherwise may be present if the piezometer is checked in an open borehole (i.e. temperature gradients, flow, unknown density variations) and that were not present at time of factory calibration are eliminated.

The function check can be made relative to barometric pressure or to a difference of piezometric head in the pipe. In both cases, barometric pressure should be measured and recorded along with the readings. A protected function check pipe may be installed in a borehole or in a building.

2.5 PRESSURE EQUATIONS for standard FOP Piezometers using unique gauge factor

The fiber-optic pressure transducer measures absolute pressure and must be corrected for barometric pressure changes. The sensors are supplied with a temperature correction factor (CT), which is used to correct the pressure reading for significant variations in temperature.

To convert changes in readings to changes in pressure corrected for barometric pressure and temperature changes, use the following equation:

Imperial units (psi)

$$P_{\text{corr}} = P_{\text{rec}} - CT (T_1 - T_0) - 0.491 (B_1 - B_0)$$

where:

- P_{corr} = corrected pressure in psi
- P_{rec} = recorded pressure in psi
- CT = temperature correction factor in psi/°F
- T_0 T_1 = initial (at installation) and current temperature readings (°F)
- B_0 B_1 = initial (at installation) and current barometric pressure in in. of Hg
- 0.491 = constant for all sensors in psi/in. of Hg.

Example:

- P_{rec} = 22.25 psi
- CT = 0.01879 psi/°F
- T_0 = 65°F

$$\begin{aligned}
 T_1 &= 80^\circ\text{F} \\
 B_0 &= 29.8 \text{ in. Hg} \\
 B_1 &= 29.4 \text{ in. Hg} \\
 P_{\text{corr}} &= 22.25 - 0.01879 (80 - 65) - 0.491 (29.4 - 29.8) \\
 P_{\text{corr}} &= 22.25 - 0.282 + 0.196 = 22.16 \text{ psi}
 \end{aligned}$$

SI units (bar)

$$P_{\text{corr}} = P_{\text{rec}} - CT (T_1 - T_0) - (B_1 - B_0)$$

where: P_{corr} = corrected pressure in bar
 P_{rec} = recorded pressure in bar
 CT = temperature correction factor in bar/°C
 T_0, T_1 = Initial (at installation) and current temperature readings (°C)
 B_0, B_1 = Initial (at installation) and current barometric pressure in bar.

Example:

$$\begin{aligned}
 P_{\text{rec}} &= 4.500 \text{ bar} \\
 CT &= 0.00143 \text{ bar/}^\circ\text{C} \\
 T_0 &= 20^\circ\text{C} \\
 T_1 &= 25^\circ\text{C} \\
 B_0 &= 1.013 \text{ bar} \\
 B_1 &= 1.002 \text{ bar} \\
 P_{\text{corr}} &= 4.500 - 0.00143 (25 - 20) - (1.002 - 1.013) \\
 P_{\text{corr}} &= 4.500 - 0.007 + 0.011 = 4.504 \text{ bar}
 \end{aligned}$$

2.6 POLYNOMIAL PRESSURE EQUATIONS for FOP-MicroPZ and FOP-PZ Piezometers

For piezometers FOP-MicroPZ and FOP-PZ with polynomial equation you should assign the gauge factor 0001000 for all gauges. The calibration factors are obtained using a polynomial regression of 3rd degree. Then to convert changes in readings (internal unit in nm) to changes in pressure use the following equation:

$$P_{\text{rec}} = c3 (L-Lc)^3 + c2 (L-Lc)^2 + c1 (L-Lc) + c0$$

where: P_{rec} = Pressure in bar, kPa or psi
 $c0, c1, c2, c3$: = Calibration factors (see on calibration data sheets)
 L = Current reading in nm using gauge factor 0001000 inside the readout unit
 Lc (center) = Mean reading in nm (see value identified center on the calibration data sheet.

Standard piezometers are sealed and unvented. Consequently they respond to barometric changes. However this response will vary depending how they are installed. If they are buried or installed in a sealed borehole, it is likely that full effect of the barometric changes will not be felt immediately. It can be significantly attenuated. On the contrary, if the piezometers are installed in a standpipe or a well open to atmosphere, barometric changes will directly be felt. In that case, a systematic barometric correction is recommended following the formula given below. In situations where the effects of barometric changes on measurements are not clear, it is suggested to independently record barometric and piezometric changes and correlate them to arrive at a correction factor.

It is suggested to use a barometer on site for measuring changes in atmospheric pressures.

Use the following relation to apply barometric corrections:

$$P_{\text{corr}} = P_{\text{rec}} - (B_1 - B_0)$$

Where

- P_{corr} = Corrected pressure in kPa
 P_{rec} = Pressure previously calculated in kPa (see above)
 B_0 B_1 = Initial (at installation) and current barometric pressure in kPa.

2.6.1 Equation with temperature compensation

Temperature variations will slightly affect readings for piezometers FOP-MicroPZ and FOP-PZ. For this reason, we do not provide normally a temperature correction factor. However, if you want it you should request it at the time of the order and a thermal test will be done during manufacturing. If you have a temperature correction factor, then the equation should be:

$$P_{\text{corr}} = (P_{\text{rec1}} - P_{\text{rec0}}) - CT (T_1 - T_0) - (B_1 - B_0)$$

- where: P_{corr} = Corrected pressure in kPa
 P_{rec1} = Recorded pressure in kPa (see formula above)
 P_{rec0} = Initial recorded pressure in kPa
 CT = Temperature correction factor in kPa/°C
 T_0 T_1 = Initial (at installation) and current temperature readings (°C)
 B_0 B_1 = Initial (at installation) and current barometric pressure in kPa

Example with sensor FOP-PZ serial number: 1019101001

Information from the calibration data sheets (see bottom of the first page)

Lc=Center	14598
C0	88.16139984
C1	-0.0328627713

C2	7.978174494E-07
C3	-1.267945332E-10
Pressure unit	psi

Considering the following initial condition without any pressure applied on the sensor at the atmospheric pressure.

L ₀	= 16924 nm
T ₀	= 20°C
B ₀	= 100.2 kPa

Then first we must compute the initial recorded pressure P_{rec0}

$$P_{rec0} = c3 (L_0 - L_c)^3 + c2 (L_0 - L_c)^2 + c1 (L_0 - L_c) + c0$$

$$P_{rec0} = -1.267945332E-10 (16924 - 14598)^3 + 7.978174494E-07 (16924 - 14598)^2 - 0.0328627713 (16924 - 14598) + 88.16139984$$

$$P_{rec0} = 14.44 \text{ psi}$$

Be aware of the unit. To convert the pressure from psi to kPa multiply by 6.8948

$$P_{rec0} = 99.56 \text{ kPa}$$

Note that the calibration in factory is done compared to the zero absolute, that explains the initial value of 14.44 psi although there is no pressure applied to the sensor. This value should be similar to the barometric pressure. You should consider this value as your initial value.

Here is a series of value after the installation and reading stabilization.

L ₁	= 15015 nm
T ₁	= 25°C
B ₁	= 101.3 kPa
CT	= -0.0422 kPa/°C

Then we must compute the actual recorded pressure P_{rec1}

$$P_{rec1} = c3 (L_1 - L_c)^3 + c2 (L_1 - L_c)^2 + c1 (L_1 - L_c) + c0$$

$$P_{rec1} = -1.267945332E-10 (15015 - 14598)^3 + 7.978174494E-07 (15015 - 14598)^2 - 0.0328627713 (15015 - 14598) + 88.16139984$$

$$P_{rec1} = 74.59 \text{ psi}$$

Be aware of the unit. To convert the pressure from psi to kPa multiply by 6.8948

$$P_{rec1} = 514.28 \text{ kPa}$$

Now I can compute the corrected pressure using the formula.

$$P_{\text{corr}} = (P_{\text{rec1}} - P_{\text{rec0}}) - CT (T_1 - T_0) - (B_1 - B_0)$$

$$P_{\text{corr}} = (514.28 - 99.56) - (-0.0422) (25 - 20) - (101.3 - 100.2)$$

$$P_{\text{corr}} = 414.72 + 0.211 - 1.1$$

$$P_{\text{corr}} = 413.831 \text{ kPa}$$

2.7 Linear pressure equation for piezometers with gauge factor 0001000

For piezometers with linear equation you can assign the gauge factor 0001000 and convert the reading using the equation below. With this method also you assign always the same gauge factor in the readout unit and you record always the reading in raw units in nanometers (nm).

The calibration factor (CF) is obtained using a linear regression. Then to convert changes in readings (internal unit in nm) to changes in pressure use the following equation:

SI units (kPa)

$$P_{\text{rec}} = CF \times (L_1 - L_0)$$

And

$$P_{\text{corr}} = P_{\text{rec}} - CT (T_1 - T_0) - (B_1 - B_0)$$

where:

- P_{corr} = corrected pressure in kPa
- P_{rec} = recorded pressure in kPa
- L_0 L_1 = Initial (at installation) and current readings (nm)
- B_0 B_1 = Initial (at installation) and current barometric pressure in kPa.
- CF = Calibration factor in kPa/nm
- CT = Temperature correction factor in kPa/°C
- T_0 T_1 = Initial (at installation) and current temperature readings (°C)

CF and CT are defined on the calibration data sheet provided with each sensor.

3 INSTALLATION

Fiber optic piezometers can be installed in various ways to suit each individual application. Specific guidelines for the installation of piezometers have been set for piezometer installation by various agencies and specialists. A list of references is given in appendix.

The following instructions summarize the generally accepted practice for:

- filter saturation,
- initial reading after installation
- cable identification,
- piezometers installed in clay fill, granular material or boreholes,
- piezometers driven into soft soil,
- cable routing.

3.1 FILTER SATURATION FOR FOP PIEZOMETERS

Two types of filters are available; high air entry ceramic or low air entry sintered stainless steel filters. Saturation of the filter:

- reduces the possibility of filter clogging,
- decreases response time,
- ensures hydraulic continuity between the pore water and the piezometer diaphragm in unsaturated soils.

3.1.1 Low air entry sintered stainless steel filters

The filter on the FOP piezometer body is removed by holding the piezometer in one hand and pulling and twisting the filter housing with the other hand.

Saturate the filter by placing it in a receptacle of clean water for at least 15 minutes.

Immerse the piezometer housing with the filter removed in a water bath. With the diaphragm end pointing upwards and submerged, reassemble the filter. Tap piezometer housing lightly to remove any air bubbles present. As soon as the filter is saturated, it must stay submerged until ready to install.

3.1.2 High air entry ceramic filters

The ceramic filter is delivered cased in a bottle and pre-saturated in water. If the ceramic filter is not pre-saturated, install the filter in a receptacle of clean water and boil the porous ceramic filter for a minimum of two-hour period.

Final installation must be carried out under water to avoid any air intrusion.

- Connect the piezometer to a readout unit.
- Put the piezometer upside-down in a container filled with clean water. The piezometer tip should be up and completely submerged.

- With the piezometer submerged, firmly grasp the housing with both hands and push the filter assembly into its tip. Gradually increase the pushing force using thumbs until it is fully inserted. This step may take a while to be completed.

Some resistance will be met; it is normal and due to the small porosity of the ceramic filter. While pushing on the filter assembly, check the readings on the readout unit to avoid excessive pressure variations that could damage the piezometer. Refer to the calibration sheet for pressure range.

- The filter installation is now completed.
- Keep the piezometer underwater for at least 24 hours before proceeding with field installation. This will allow the pressure induced by the filter installation to decrease. When ready to be installed, the piezometer reading should be close to the one of acceptance test with the filter removed (see details in section 2.2).

3.2 Initial reading after installation

Before installing the piezometer in its final location on site, an initial reading has to be taken to correctly convert readings into pressure measurements when the piezometer is in operation. This process is also necessary to be able to apply later temperature and barometric corrections.

Leave the instrument in water for two or three hours to let the temperature stabilize. It is preferable to leave it overnight, provided that arrangements are made to keep the water at more or less uniform temperature. All sudden changes of temperature and direct exposure to the sun must be avoided.

With the water temperature, ambient temperature and piezometer temperature in equilibrium, raise the piezometer by the cable until it is out of the water about two centimetres. We recommend to take the initial reading in raw data in nanometer by assigning the gauge factor 0001000. If you want read directly the pressure in engineering unit with the readout unit then you will need to assign the appropriate gauge factor and complete a nulling to adjust the zero as explained in section 2.1.

We recommend to take three successive readings to ensure a stable value and record it. This is the initial reading (called L_0). Record ambient temperature (T_0) and barometric pressure (B_0). We recommend also to record the diagnostic function (**DIAG**), the signal and light voltage and compare value of the table on section 5.2.1. This is important for evaluating the performances for both the readout unit and the sensor.

However sometimes, it is very difficult to use the FOP readings just after installation for proving that the sensors are working properly or not since it is normal after installation to see slight variations in readings coming from temperature and barometric variations, and from short term disturbance of the water and/or air pore pressures induced by installation and construction activities. And the effects of these variations over the readings can be hard to quantify accurately. This applies for installation both in boreholes or fills.

In the case of installations made according to the 'fully grouted' method, the level of uncertainty is even higher because of the difficulty in making a grout perfectly adjusted to the surrounding soil. See article from Marefat, Contreras for more information about this technique of installation.

In non – or partially – saturated soils, one should not expect to read exactly 0 kPa after installation because of the above mentioned factors, and because of the potential suction in the soil and potential air infiltration in the piezometers in the case where these are fitted with low-air entry filters. But from our experience, as soon as water gets back in the soil, pressure increases to normal levels.

It is recommended after installation to take as many readings as possible and if possible to use a datalogger to record the readings every hour for a period that can be up to one week. This will greatly help assessing if the piezometers are responding normally or if there is any problem and to define a stable initial reading.

If the readings remain stable and within a certain range, from about -25 to +25 kPa (depending on the piezometers' range), we should assume that the piezometers are still working properly, unless other events lead us to believe otherwise. In such case, the best method to check consists in retrieving and calibrating the piezometers.

It should be kept in mind that these piezometers are designed for giving reliable relative readings, provided that temperature are stable and barometric pressures at the level of the piezometers are properly measured. Accurate absolute readings are slightly more difficult to obtain.

3.3 INSTALLATION IN FILL

3.3.1 Compacted clay

Excavate a trench or recess about 30 cm deep by about 0.8 m². Form a cylindrical hole in the side wall of the trench. The hole diameter should be slightly smaller than the piezometer body.

Push the piezometer into the side of the hole. Make sure that the piezometer filter is in direct contact with the host material. If necessary to ensure continuity with the saturated high air entry filter and the pore water, smear the filter with a thin paste of the saturated material.

Before backfilling, the cable must be laid with the utmost care. Loop the cable around the recess, making sure it rests on a bed of hand placed and compacted screened clay.

Make sure that the cable does not cross over itself or other cables in the same area.

Backfill the recess with screened clay containing no particles larger than 2.5 mm in diameter. The backfill should have a water content and density equal to that of the surrounding material.

Make sure that the cable is protected from potential damage caused by angular material, compacting equipment or stretching due to subsequent deformations during construction or fill placement.

3.3.2 Granular materials

Install the piezometer as described above in a recess excavated for this purpose. Place the piezometer within the trench, loop cable and backfill with screened material containing the same moisture content and compacted to the same density as the surrounding fill. In rock fill, it is necessary to place a graded filter around the piezometer. Use fine grain clean sand

around the instrument and increase the particle size as the backfill proceeds outwards to the rock fill. The sand placed in the recess around the instrument and cable should range in size from 0.5 mm to 2.5 mm in diameter.

3.4 INSTALLATION IN BOREHOLES

The method used to install a piezometer in a borehole depends on the particular conditions in which the installation must be carried out. Artesian conditions, borehole stability, available drilling equipment and sealing material are among the factors that will influence the method chosen. The method described below will cover most applications.

1. Drill the borehole below the required depth at which the piezometer is to be installed. Drive the casing thirty centimeters below the required piezometer elevation. Wash until the water (or biodegradable drilling mud) emerging from the borehole runs clear. This will prevent the backfill materials from sticking to and plugging the casing.
2. Raise the casing fifteen centimeters and pour sand below its bottom. Repeat the operation once and lower the piezometer to the top of the sand. Check the borehole depth after each operation.
3. While holding the instrument in place, repeat step 2 until thirty centimeters of sand are placed above the piezometer.
4. Raise the casing fifteen centimeters and pour compressed dry bentonite below its bottom. Repeat the operation until a seal of at least 1.2 m is in place. When pouring bentonite, keep the cable taut to prevent the bentonite from hooking up in the casing. Pour the bentonite slowly in the hole to avoid bridging. A brush or a thirty centimetre layer road salt can be used to unplug a blocked hole. Check the borehole depth after each operation.
5. Wait for the bentonite to set up. Two hours are generally enough. Refer to supplier's instructions for exact time. Keep the borehole filled with water. This will prevent the bentonite of drawing water from surrounding soil during its setting.
6. If only one piezometer is to be installed in the hole, backfill the casing with a bentonite/cement grout.

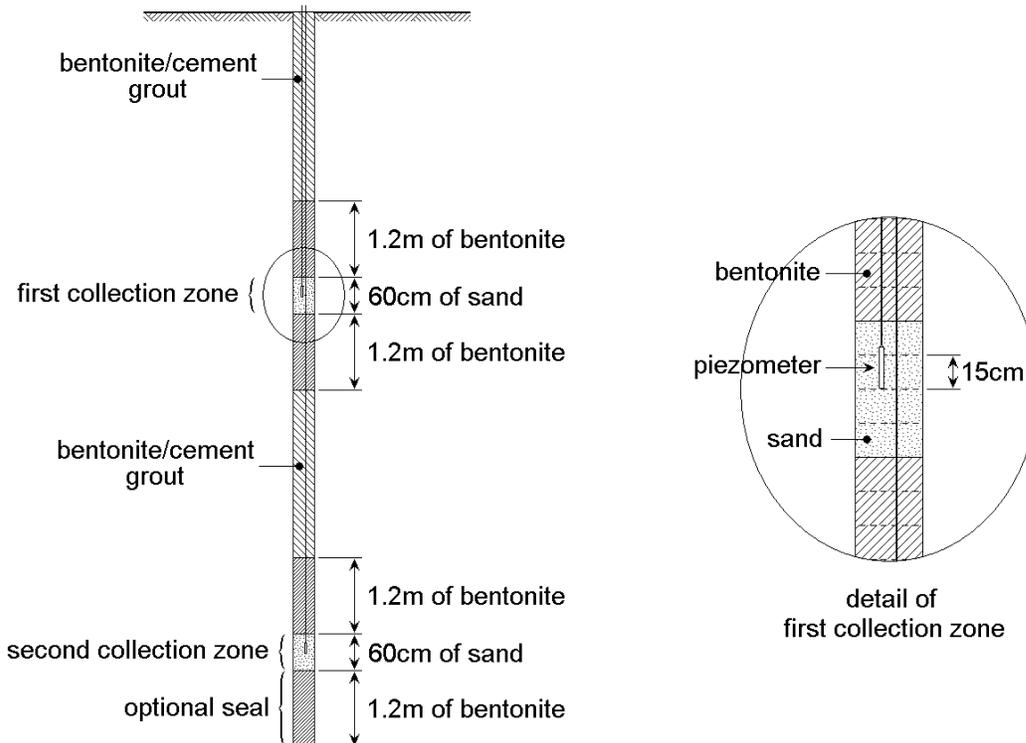
If more than one piezometer is to be installed in the borehole, backfill with a bentonite/cement grout to an elevation of a meter and a half below the second piezometer. Then use 1.2 m of bentonite. Repeat operations 1 to 5 for the second piezometer. When all instruments are installed, backfill with a bentonite/cement grout.

7. Pull the casing without rotating it during removal. Top off the borehole with grout.

If the deepest piezometer has for purpose to measure the pore water pressure in a specific horizon, it is necessary to drive the casing below the instrument and set a 1.2 m bentonite seal at the bottom of the borehole. Pull the casing as the bentonite is set in place. Proceed by stages of fifteen centimeters. Be very careful not to plug or allow bentonite to stick to the inside walls of the casing. This is accomplished by making sure the bentonite level is at all times below the casing and by slowly dropping bentonite in single file down the hole. Trying to feed bentonite too rapidly will result in bridging in the casing or borehole.

Tamping of compressed bentonite is not required. Prior to setting the sand in place, lower a cylindrical weight down the borehole to ensure that it is clear from any obstructions and, if necessary, rinse the borehole until clear water emerges.

Note: It is also possible to place the piezometer into a sand filled canvas bag. The bag then acts as a sand filled intake zone.



Typical installation of piezometers in a borehole

Note that an alternate way to install piezometers in boreholes is to fill the entire borehole with grout after having lowered the instruments. This method, known as the Fully Grouted Borehole Installation, is peculiar in that:

- Piezometers are installed with filter end upward.
- Proper care must be taken for preparing a grout mix that will mimic as well as possible the stiffness and permeability of the surrounding ground. This is achieved by selecting the proper water-cement ratio. Mixtures shown in the table below can be used as a starting point. The cement and water are mixed first. When proper ratio is reached, bentonite powder is slowly added until as heavy as feasible to pump.

Suggested Grout Mixes					
Material	Ratio by weight	Soil Hardness	Material	Ratio by weight	Soil Hardness
Portland Cement	1	Hard to Medium	Portland Cement	1	Soft
Bentonite	0.3	Hard to Medium	Bentonite	0.4	Soft
Water	2.5	Hard to Medium	Water	6.6	Soft

See article from Marefat, Contreras for more information about this technique of installation.

3.5 CABLE IDENTIFICATION

The cables are identified with the gauge factor that is labeled on the piezometer housing. The gauge factor is stamped on a tag that is fastened to the readout end of the cable. Should the cable be cut, we recommend the use of our cable splice kits.

3.6 CABLE ROUTING

3.6.1 Transition from vertical borehole to horizontal trench

The cable should be routed along a curved path as it goes from a vertical to the horizontal position. At the collar of the borehole, embed the cable along a large radius circular path within a cushion of screened sand and 5% bentonite mix, hand compacted to the surrounding fill density.

Piezometers installed to monitor rock contact zones are generally installed in shallow boreholes to protect them against concentrated loads or movements. Run cables emerging from these holes through the dam core and locate the vertical to horizontal cable transition zone above the rock surface. Do not lay the cable directly on rock.

3.6.2 Horizontal cable runs

Two methods are currently used to protect horizontal cable runs from damage. Embedment within selected materials on surface of the fill or in a trench within the fill. Only the latter is discussed here. Surface installations require continuous surveillance and protection from the earth moving equipment circulating on the fill. For a description of this method, please refer to Clements (1982), reference A-6 in Section 6.

Some of the more important considerations that must be given to horizontal cable runs are:

- Avoid traversing transition zones where large differential settlements could create excessive strain in the cable.
- Avoid cable splices - if necessary, use only our approved splice kits.
- Do not lay cables one on top of the other.
- Use horizontal snaking or vertical snaking of the cable within the trenches. For most materials, a pitch of 2 m with an amplitude of 0.4 m is suitable. In very wet clays increase the pitch to 1 m.

- Use a combination of horizontal and vertical snaking at transition zones.

The trench dimensions should be 25 cm wider than the laid out width of the cable. The trench should be a minimum of 60 cm deep. A 12 cm bedding layer of minus 0.8 mm sand is placed along the trench bottom. As required, bentonite must be added to the sand to form impervious sections or plugs.

The cable is then covered with one 15cm lift of minus 0.8 mm material.

Backfill the trench with selected material completely and compact the selected material with light hand operated machines.

During the cable routing, read the instruments at regular intervals to ensure continued proper functioning.

4 Relation between gauge factor and calibration factor

The Gauge Factor (GF) is specific for each pressure sensor and is written on the fiber optic cable near the connector. It gives the relationship between the deflection of the diaphragm and the applied pressure. The Gauge Factor is a 7-digit number, for example 6025192. The structure of the Gauge Factor is given below:

6	0	2	5	1	9	2
---	---	---	---	---	---	---

6	X	Y	Z	Z	Z	Z
---	---	---	---	---	---	---

The following table presents the meaning of each digit contained in the Gauge Factor.

6	This first digit is the same for every pressure sensor; this is an identifier indicating to the readout unit that it is a pressure sensor.
X	This digit is a sensor number. It is used if more than one sensor have the same calibration factor; generally, this value equals zero.
Y	This digit is an exponent used in the conversion calculations from cavity distance variation (nm) to pressure unit (psi).

- Z All these digits serve to calculate the relation from cavity length variation in nm to psi with the following equation:

$$-Z.ZZZ * 10^{2-Y} = \text{Slope in } nm/psi$$

4.1 Reading the FOP

Reading the pressure with the FOP is simply made by connecting the FOP, entering the gauge factor and performing a NULL GAUGE in a fiber optic readout unit such as DMI, UMI or FTI models. This will give directly the pressure in psi or bar depending of the Unit System used.

In some particular applications and also for sensor troubleshooting, it is useful to have the Fabry-Perot cavity distance in nanometers. To do so, the gauge factor 0001000, known as the Default Gauge Factor, must be enter in the readout unit instead of the sensor gauge factor (generally, it is already introduced in the readout unit and identified as FISO 1000).

4.2 Example

For a given FOP pressure sensor, the following readings can be taken.

- A) Using the sensor Gauge Factor

Entering the gauge factor 6025192 and performing a null gauge before applying any pressure leads to the following results:

Applied Pressure (psi)	Measured pressure (psi)
0	0
200	200

- B) Using the Default Gauge Factor 0001000

Using the gauge factor 0001000 leads to the following results:

Applied Pressure (psi)	Measured Cavity Length (nm)
0	18190.5
200	17152.0

From these results, the pressure in psi can be calculated back using the equation described in the previous section and the FOP gauge factor.

- Calibration factor determination

$$G.F. : 6025192 \Rightarrow -5.192 * 10^{2-2} = -5.192 \text{ nm/psi}$$

- Cavity length variation

$$17152.0 - 18190.5 = -1038.5 \text{ nm}$$

- Pressure calculation

$$\frac{-1038.5 \text{ nm}}{-5.192 \text{ nm/psi}} = 200.0 \text{ psi}$$

4.3 Determination of the Gauge Factor

Finally, it can be shown that the Gauge Factor can be determined from the Calibration Factor by the following equations:

$$-ZZZZ = C.F. * 10^{Y+1}$$

$$Y = \left[\text{INTEGER} \left(\text{LOG} \left(\frac{10000}{-C.F.} \right) \right) \right] - 1$$

Where C.F. is the Calibration Factor given in nm/psi. The values in the above example can be used to calculate $Y = 2$ and $ZZZZ = 5192$. Note that the Calibration Factor is determined in factory using a precisely calibrated pressure system.

5 TROUBLESHOOTING

5.1 Fiber optic readout unit

Maintenance of fiber optic readout unit is required. Periodically check battery status for portable readout unit, the quality of light and connector.

5.1.1 Battery charge and discharge cycles for portable readout unit

Extend your battery life, charge it constantly!

The battery lifespan* is directly related to the number of charge and discharge cycles it will be subjected to. One cycle corresponds to a charge followed by a discharge.

The following table shows the direct relationship between the discharge depth and the number of cycles. When you completely let your battery discharge every time (discharge depth of 100%), you reduce the remaining number of charge and discharge cycles of your battery.

Depth of discharge	Number of cycles
100 %	200 to 300
50 %	800 to 1000
25 %	> 1500
0 %	(4 to 5 years)

(When unit is constantly powered by power supply/ battery charger)

IMPORTANT WARNING:

- Waiting for a complete discharge is not recommended;
- Completely discharging the battery strongly reduces its lifespan*;
- Make sure to fully recharge the battery before storing the FTI-10 for a long period of time or when it is fully discharged and that it won't be used immediately;
- Even though you have fully recharged the battery before storing, you must do it every 6 months.

Notice: When the battery dies, contact Roctest to arrange the return of your equipment for battery replacement.

Battery life / runtime*: Time your FTI-10 will run before it must be recharged.

Lifespan*: Total amount of time your battery will last before it must be replaced.

5.1.2 Cleaning the connectors

Dirty connectors are one of the major problems in fiber optics, causing high connector loss, high reflectance, contaminating readout unit and causing the loss of sensor signal. For proper use of the fiber optic readout unit, the fiber optic connectors must be kept clean and free of dust at all times. Any dust may obstruct the light transmitted from one connector to the other, and reduce the signal-to-noise ratio to an unusable level. It is always

important to reinstall the dust cap on the tip of the connector after reading the sensor if it is not connected permanently to a fiber optic datalogger.

IT IS A GOOD PRACTICE TO ALWAYS CLEAN THE TRANSDUCER CONNECTOR BEFORE MATING IT TO THE READOUT UNIT.

Wiping the end with low lint tissue such as Kimwipes or lens cleaning tissues is a simple and easy way to clean transducer connectors. By keeping your transducer connectors clean you will also prevent the contamination of the input connector of the readout unit. However, we recommend cleaning the input connector of the readout unit also occasionally. Use the specially designed 2.5-mm Mini Foam Swab for cleaning the input connector. Contact Roctest if you need a cleaning kit.

We also recommend to do a visual inspection of the fiber optic connector using a portable optical microscope to inspect for dirt and damage (for more information see the following link <https://www.thefoa.org/tech/ref/testing/test/scope.html>).

5.2 Fiber optic piezometers troubleshooting

5.2.1 Diagnostic and error messages

When you take a reading with a fiber optic piezometers and a readout unit we recommend to complete also a diagnostic of the sensor using the diagnostic function.

With the diagnostic function (**DIAG**) the user can obtain useful information for evaluating the performances for both the readout unit and the sensor. The diagnostic information is: the light intensity (in Volts), the signal (in Volts), the battery remaining capacity (%), and the memory in use (%). By comparing the diagnostic information with the following evaluation table, the user can make a diagnosis of its setup measurement.

DIAGNOSTIC:	Defective	Poor	Normal
Light	< 0.4 V	0.4 – 1.0 V	> 1.0 V
Signal	< 0.3 V	0.3 – 1.5 V	> 1.5 V
Battery	If < 25 %, batteries need to be recharged		
Memory	0 - 100 % of memory in use		

The portable readout unit has an auto-diagnosis feature that informs the user in case of defective or noisy measurement conditions. Depending on the conditions, the readout will display different messages:

MESSAGE	TYPE AND DESCRIPTION	POSSIBLE CAUSE & REMEDIES
« MEMORY LOST »	ERROR The content of the RAM memory has been erased.	✓ The RAM memory has been corrupted so the conditioner is automatically reset with the factory default settings. Contact factory if that problem persists.
« L.Bat »	INFORMATION Battery remaining capacity	✓ Recharge the batteries.

	is below 25 % of its full capacity.	
« NO SIGNAL »	<p>ERROR</p> <p>The conditioner detects a low level signal or no signal.</p>	<ul style="list-style-type: none"> ✓ No transducer connected to the readout or improper connection. Verify connections or clean transducer connector and input connector. Check connector with a microscope. (see section 5.1.2). If you suspect the connector, cut it and replace it by a new one and test again if you get a signal value. ✓ Fiber optic extension cable is longer than the maximum length permitted. Use cable with shorter length. Maximum length permitted depend of the light intensity in the readout unit and the reflection of the light from the sensor. With over 600m of cable length, it is considered a long cable length with a portable readout unit equipped with ST connector. ✓ Cable is damaged. Verify if the cable is not damaged or cut. ✓ Check if the same troubles (No signal) occur with other instruments connected. If so, the readout unit may be suspected and the factory should be consulted. ✓ Readout unit is defective. ✓ Check the same sensor with a different readout unit to determine if you have also a No signal. If yes, sensor or cable is probably defective. ✓ Have you check the diagnostic signal? (see section 5.2.1)
« SYSTEM FAULT »	<p>ERROR</p> <p>The conditioner has detected a faulty condition.</p>	<ul style="list-style-type: none"> ✓ The conditioner has detected a faulty condition other than NO SIGNAL. Contact factory if that problem persists.
« SETTLING »	<p>INFORMATION OR ERROR</p> <p>The conditioner is settling its electronic.</p>	<ul style="list-style-type: none"> ✓ This is not a defective condition if the message normally disappears after 2 or 3 seconds. This message is displayed just after the conditioner is turned ON or just after a transducer is connected to the conditioner.
« WAIT AVRG »	INFORMATION	<ul style="list-style-type: none"> ✓ This message appears when the

	The conditioner is averaging the data readings of the transducer.	conditioner displays the first data measurement and the <i>Averaging Time</i> is greater than 2 s. Wait until the <i>Averaging Time</i> elapsed.
« WAITING FOR ACQUISITION »	INFORMATION During an <i>Acquisition Session</i> , the conditioner goes in Wait State between two successive data measurements.	✓ This message appears only during a delayed <i>Acquisition Session</i> . It is displayed between two successive data measurements and when the <i>Acquisition Rate</i> is larger than 23 seconds.
« WAITING FOR STARTING TIME »	INFORMATION The programmed mode of acquisition is activated and the conditioner goes in Wait State until the activation of the <i>Acquisition Programs</i> at the preset date and time.	✓ This message appears only when the programmed mode of acquisition is activated.

5.3 Other troubles

If pressure variations are suspicious, check if those variations are correlated with recorded temperature and barometric pressure. Check if corrections to raw pressure are applied correctly.

Try to perform a calibration on-site and contact Roctest with reading for evaluation.

6 MISCELLANEOUS

REFERENCES:

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- A-5 Hanna, T.H. *Foundation Instrumentation*, Trans. Tech. Publications, Ohio, USA, 1973. (Chapter 3 describes different types of piezometer tips, methods of installation, methods of recording and the protection of piezometers.)
- A-6 Clements, D. J., and A. C. Durney (1982), *Instrumentation Developments*, proceedings of the Autumn Conference on the British National Committee on Large Dams (BNCOLD) Keele University, Institution of Civil Engineers, London, pp. A5-55.
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