INSTRUCTION MANUAL

FIBER-OPTIC PRESSURE TRANSDUCER

FOP Series

This product should be installed and operated only by qualified personnel. Its misuse is potentially dangerous. The Company makes no warranty as to the information furnished in this manual and assumes no liability for damages resulting from the installation or use of this product. The information herein is subject to change without notification.

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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 gage is delivered with a calibration data sheet, which includes a gage 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 availables, please consult Roctest website for details.

1.1 GAGE 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 gage 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.

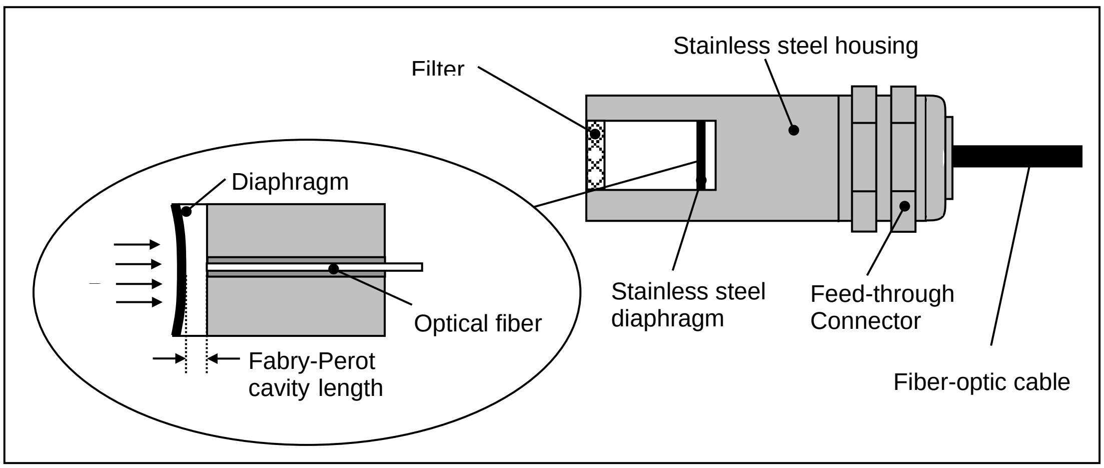

Figure 1: Schematic view of a FOP sensor

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: gage, absolute or differential type. In the case of gage 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 gage 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 gage, lists the following:

- Serial number
- Gage 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
Material:	17-4 PH Stainless steel			
Outside diameter in mm:	19	33.4	19	25.4
Filter:	50 micron low air entry sintered stainless steel filters(standard) or 1.6 micron high air entry ceramic filters (optional)			

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	± 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)

2 DATA READING AND ANALYSIS

2.1 FOP Preparation for initial reading

Gage readings should be taken as soon as the gages are received to ensure they have not been damaged during shipment. All gage transducers are individually calibrated before shipment and a gage factor (7-digit number) and the gage zero obtained at factory, in internal unit of Fabry-Perot cavity length, are supplied with each gage. Before using a transducer with the Universal fiber-optic readout unit from Roctest and Fiso Technologies, its gage factor must first be saved in the readout memory and selected. The calibration factor is already recorded in the transducer's gage 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 gage. Please review the operating manual of the readout unit before proceeding with readings.

First the gage must be connected in a channel number and the appropriate gage 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 gage 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. **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 gage zero (value between 14000 and 24000) when doing a zero adjustment. Knowing it is possible to re-enter the initial gage 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 gage 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.

Steps before taking a reading

1. Save gage factor into the readout memory
2. Connect each gage to one of the channel input connectors
3. Associate appropriate gage factor to the measuring channel
4. Null gages and ***record the gage 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 filter removed at a stabilized temperature and at a known barometric pressure. 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 for 2 to 3 hours to stabilize the temperature.

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.

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:

Gage 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 gage 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 gage factor 0001000 for all gages. 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.

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 gage factor 0001000 for all gages. 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 gage factor 0001000 you should have a reading between 10000 and 20000. Then this reading (L) must be inserted in the equation as described in section 2.6 to convert the value 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

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, 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)

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

where:

where:	P_{corr}	=	corrected pressure in psi
	P_{rec}	=	recorded pressure in psi
	CT	=	temperature correction factor in psi/°F
	T_o T_1	=	initial (at installation) and current temperature readings (°F)
	B_o 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_o	=	65°F
T_1	=	80°F
B_o	=	29.8 in. Hg
B_1	=	29.4 in. Hg
P_{corr}	=	22.25 - 0.01879 (80 - 65) - 0.491 (29.4 - 29.8)
P_{corr}	=	22.25 - 0.282 + 0.196 = 22.16 psi

SI units (bar)

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

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

Example:

P_{rec}	=	4.500 bar
CT	=	0.00143 bar/°C
T_o	=	20°C
T_1	=	25°C
B_o	=	1.013 bar
B_1	=	1.002 bar
P_{corr}	=	4.500 - 0.00143 (25 - 20) – (1.002 – 1.013)
P_{corr}	=	4.500 - 0.007 + 0.011 = 4.504 bar

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 gage factor 0001000 for all gages. 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:

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

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 gage factor 0001000 inside the readout unit
	Lc (center)	=	Mean reading in nm (see value identified center on the calibration data sheet.

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

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, <u>it is suggested to independently record barometric and piezometric changes and correlate them to arrive at a correction factor.</u>

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

Use the following relation to apply barometric corrections:

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

Where

P_{corr}	=	Corrected pressure in kPa
Prec	=	Pressure previously calculated in kPa (see above)
CT	=	temperature correction factor in bar/°C (if applicable)
B_o B_1	=	Initial (at installation) and current barometric pressure in kPa.

2.7 LINEAR PRESSURE EQUATIONS for FOP-MicroPZ and FOP-PZ Piezometers

For piezometers FOP-MicroPZ and FOP-PZ with linear equation you can assign the gage factor 0001000 and convert the reading using the equation below. 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 (bar)

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

And

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

where:	P_{corr}	=	corrected pressure in bar
	P_{rec}	=	recorded pressure in bar
	$L_o\ L_1$	=	Initial (at installation) and current readings (nm)
	$B_o\ B_1$	=	Initial (at installation) and current barometric pressure in bar.
	CF	=	Calibration factor in bar/nm

Note:
If on the calibration data sheet you have a gage factor with 7 digits then you can enter this gage factor directly inside the memory of the readout unit using the step as described in section 2.1 and then you can apply directly the following equation to compensate for barometric pressure change.

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

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,
- 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.

Immerse the piezometer housing with the filter removed in a water bath. With the diaphragm end pointing upwards and submerged, reassemble the filter. Keep the piezometer submerged until ready to install.

3.1.2 High air entry ceramic filters

Follow the procedure described above. To saturate the filter, boil the porous ceramic filter for a minimum two-hour period.

Proceed as above to reassemble and store the piezometer.

3.2 INSTALLATION IN FILL

3.2.1 Compacted clay

Excavate a trench or recess about 30 cm deep by about 0.8 m^2. 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.

3.2.2 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.

3.3 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. The method described below will cover most applications. Artesian conditions, borehole stability, available drilling equipment and sealing materials are among the factors, which will influence the method, chosen. For a description of other methods, please consult the references listed in Section 4.

The casing is driven 30 cm below the required piezometer elevation. If the piezometer is to measure the pore water pressure in a specific horizon, it will be necessary to drive the casing 1 m below the piezometer elevation to enable the placement of a bentonite pellet (Peltonite) seal at the hole bottom.

After driving the casing, wash until the water emerging from the hole runs clear.

If required, set the two foot bentonite seal at the bottom of the borehole. Raise the casing 15 cm. Place the bentonite in six inch increments until the bentonite level is one foot below the piezometer elevation. Pull the casing as the bentonite is set in place. 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 the bentonite pellets in single file down the hole. Trying to feed the bentonite pellets too rapidly will result in bridging of the pellets in the casing or borehole. This will make it extremely difficult to complete the seal. Tamping of compressed bentonite pellets is not required.

Prior to setting the sand in place, lower a cylindrical weight down the hole to ensure that the hole is clear from any obstructions and if necessary, rinse the borehole until clear water emerges.

In the same manner, place 30 cm of fine, clean sand in 15 cm increments below the level of the piezometer tip. Pull the casing as the backfilling with the sand proceeds. Lower the piezometer into the hole. Take the initial readings as described above.

Pull the casing 15 cm and backfill with fine clean sand. Repeat until the sand and casing are 30 cm above the top of the piezometer. Take another reading on the piezometer.

Lift the casing in 15 cm increments and backfill with bentonite pellets until a minimum 1.3 m seal has been formed. During the bentonite pellet placement keep the cable taut to prevent the pellets from hooking up in the casing. Pour the pellets in the hole one at a time to avoid bridging. If only one piezometer is to be installed in the hole, backfill the casing with a cement/bentonite grout. If more than one piezometer is to be installed in the hole, backfill with host material or sand/bentonite mixture to an elevation of four feet below the second piezometer, then use 1 m of bentonite, 30 cm of sand, then the piezometer. Proceed as described above.

Pull the casing. Do not rotate the casing during removal.

Once all casing is removed, top off the borehole with grout.

3.4 CABLE IDENTIFICATION

The cables are identified with the gage factor that is labeled on the piezometer housing. The gage 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.

3.5 CABLE ROUTING

3.5.1 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.

3.5.2 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 4.

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 MISCELLANEOUS

REFERENCES:

A-1 Terzaghi, K., and R. B. Peck. *Soil Mechanics in Engineering Practice*, John Wiley and Sons, Inc., 1967. (Article 68 of Chapter 12 provides a survey of tip types and recommendations on installation procedure.)

A-2 U. S. Department of the Interior, Bureau of Reclamation. *Earth Manual*, U. S. Government Printing Office, Washington 1974. (Designations E-27 and E-28 in the appendix give detailed guidance on piezometer installation in dam foundations.)

A-3 Bishop, A. W., P. R. Vaughan, and G. E. Green (1969), Report on specialty session, *Pore Measurements in the Field and in the Laboratory*, Proc. 7th, Int. Conf. Soil Mech. and Found. Eng. 3, 427. (A review of recent practice and instrumentation, related principally to earth structures.)

A-4 *Suggested Methods for Determining In-Situ Permeability, Groundwater Pressure and Flow*, Int. Soc. for Rock Mechanics, Committee on Field Tests (Draft report, 1974 - Final report in course of preparation.)

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.

A-7 Corps of Engineers (1984), *Publications Relating to Geotechnical Activities*, USACE DAENECE-G, September 27th.