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INSTRUMENTATION OF TRANSPORTATION EMBANKMENTS CONSTRUCTED ON SOFT GROUND

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TABLE OF CONTENTS

INTRODUCTION

Economic considerations, aesthetics, or other factors often require that a highway embankment be constructed over soft, saturated soils. A high content of silt, clay, organics and a high water table compound design and construction problems. Under these circumstances special treatment of the embankment materials and/or controlled construction procedures are warranted to ensure the safety and stability of the constructed embankment.

Several methods are available to reduce the risk of an embankment failure during construction. These include the use of berms and vertical drains, surcharging, and staged construction. Geotechnical instrumentation is often a vital part of embankment construction under these circumstances to monitor field performance and provide information relevant to decisions regarding the rate of construction progress.

The principal parameters monitored during embankment construction are pore water pressure and displacement, both vertical (i.e., settlement and heave) and lateral (shear). The following discussion outlines the most commonly used instrumentation systems for these applications. It is intended as a general guide to the principles of operation and the application of these instruments for the field personnel or associated staff involved in installation, monitoring and data analysis. For a more comprehensive discussion of the instruments presented, the reader is referred to *Geotechnical Instrumentation for Monitoring Field Performance*, John Dunnicliff, 1988.

Instrument suppliers, listed at the end of this report, are also a good source of information and are often able to provide installation guidelines and recommendations for application.

In relatively impermeable, soft, saturated soils, the applied load resulting from embankment construction increases the pore water pressure. This creates a potentially unstable situation by increasing the applied shear stress with essentially no increase in the shear strength of the soil mass. With time, the excess pore water pressure will dissipate and the soil mass will consolidate, increasing the intergranular stress, thereby increasing the shear strength. It is important to monitor the pore water pressure to determine when it is safe to proceed with additional loading or other construction activities. Instruments that monitor pore water pressure are called piezometers and are available in a number of designs.

OPEN STANDPIPE PIEZOMETERS (FIGURE 1)

Open standpipe piezometers are among the most widely used type of piezometer owing to their simple construction, ease of installation and low cost of materials. They consist of a porous tip (perforated plastic riser pipe, porous plastic or stone) which is attached to a plastic or metal standpipe which extends to the ground surface. The pore water pressure in the vicinity of the porous tip produces a corresponding column of water in the standpipe (piezometric head).

Readings in standpipe piezometers are obtained by measuring the depth to water within the standpipe using a portable water level indicator or dipmeter. This instrument consists of a probe connected to a graduated tape or cable stored on a reel. The tape/cable contains electrical conductors that are connected at the reel end to electrical circuitry including a light and/or buzzer. The electrical circuit is open at the probe end. The probe is lowered within the standpipe until it makes contact with the surface of the water. This completes the electrical circuit giving an audible or visual signal. The depth to the water surface is then read from the graduated tape/cable using the top of the standpipe as a reference.

Standpipe piezometers are usually installed within drilled boreholes. Clean, uniform sand is commonly packed around the porous tip to act as a filter medium. In order to ensure that the acquired measurements accurately reflect the pressures at the reading point, it is necessary to completely seal the tip against the inflow of water from shallower zones. This generally requires the placement of an impermeable seal, most commonly bentonite, around the standpipe directly above the sand pack with the remainder of the borehole typically back-filled with a cement/bentonite grout.

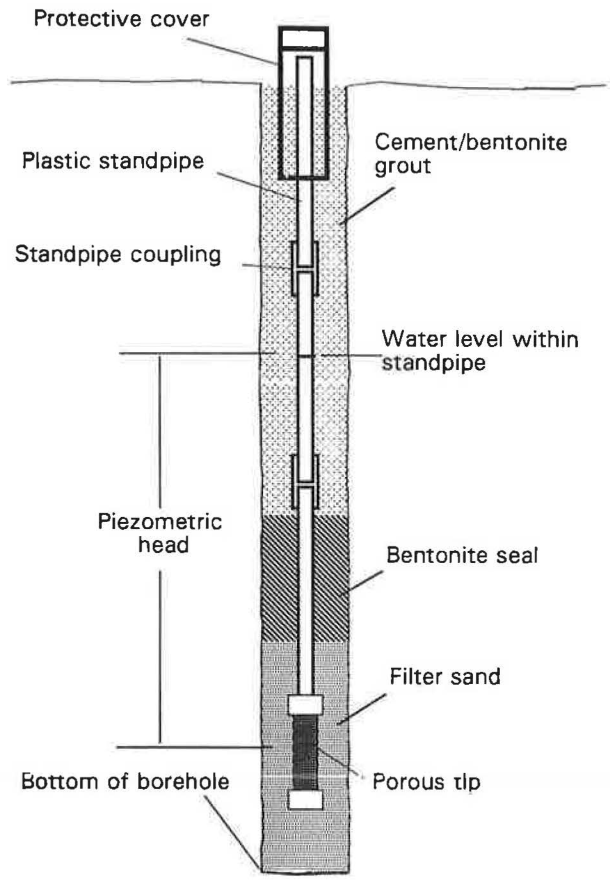

FIGURE 1 Open stand-pipe piezometer (Courtesy of Geotechnical Instruments, Inc.).

Advantages:

- Low cost of materials.
- Relatively simple installation.
- Can be monitored by personnel with minimal special training.
- Gases are vented naturally.
- Can be converted for remote monitoring by the use of a pneumatic or electric water pressure transducer.
- Water samples can be obtained.

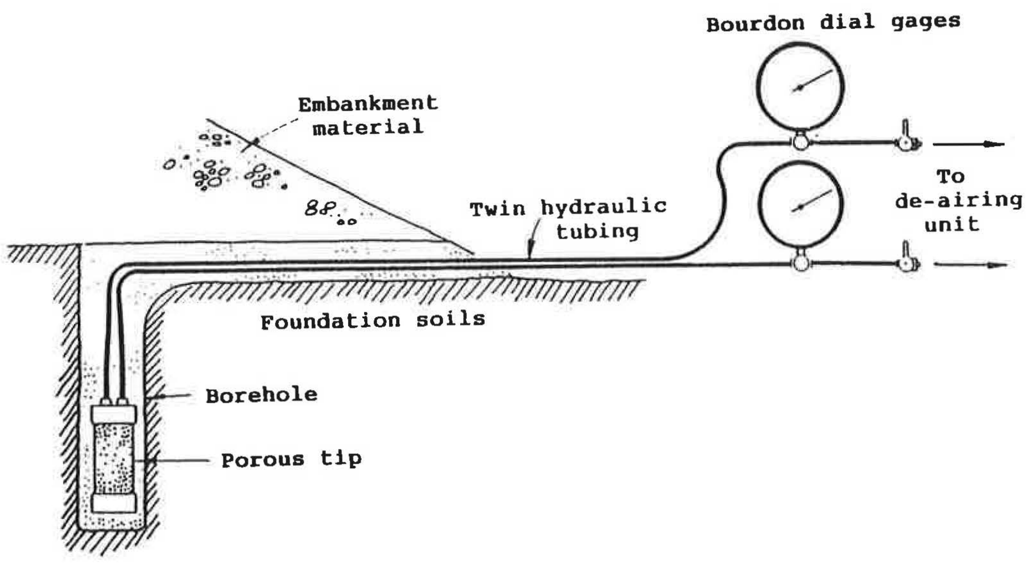

FIGURE 2 Twin tube hydraulic piezometer (Courtesy of Geotechnical Instruments, Inc.).

Disadvantages:

- Standpipe may interfere with construction activities.
- Slow response time to changes in pore water pressure in soils of low permeability.
- Standpipe must be protected from vandalism and damage from construction activity.
- Subject to damage by buckling and crushing of the standpipe as settlement occurs.
- Accuracy may be impaired by clogged filter (smearing in fine grain soils).

TWIN TUBE HYDRAULIC PIEZOMETERS (FIGURE 2)

Twin tube hydraulic piezometers are part of a closed system consisting of a porous tip connected to twin tubing. The tip is placed within a drilled borehole and sealed as with standpipe piezometers or placed in an excavated trench with the tubing routed to the readout point. The configuration of the system must be planned so that the piezometer tips are not located at significantly greater elevations than the minimum anticipated piezometric level. Differences of greater than 5 meters are not recommended.

Prior to installation, the tip is disassembled and the porous element is saturated to remove any entrapped air. The twin tubing is filled with de-aired water. One end of the tubing is submerged with the components of the tip in a vessel of de-aired water. The tip is re-assembled and the tubing connected while still submerged. The tip remains submerged until placed within the saturated soil.

Pore water pressure in the vicinity of the tip is transmitted through the saturated tip and the water filled tubes. At the readout point, in-line bourdon dial gages, a manometer board or electrical transducers detect the pressure variations. The elevation of the piezometer tip and the gages must be accurately measured and recorded during installation to allow proper calculation of the piezometric head from the acquired pressure readings.

Twin tube hydraulic piezometers are less commonly used in the U.S. today than in previous years due in part to variable accounts of their reliability and because of the labor intensive maintenance required. Proponents claim that when the system is properly constructed of quality components by experienced personnel, they are reliable piezometers for long term applications.

Advantages:

- No standpipes to interfere with construction activities.
- Much faster response time than for standpipe piezometers owing to the smaller volume change required.
- Can be used to measure negative pore water pressure in saturated or unsaturated ground conditions.
- System can be flushed with water to remove trapped air.
- Good long term reliability due to the absence of electronic or mechanical components at the tip.

• Can be coupled to an automatic data acquisition system for unattended, remote data collection.

Disadvantages:

• Strict limitations of placement of piezometers, tubing and gages relative to minimum piezometric level.
• Installation is somewhat more complex and critical to a properly functioning system.
• Maintenance program requires periodic flushing of the system with de-aired water to remove entrapped air.
• Care must be taken to avoid damage of tubes during construction.
• Freezing of twin tubes will cause damage to the system components.
• Differential settlement can pinch or break tubing.

PNEUMATIC PIEZOMETERS (FIGURE 3)

Pneumatic piezometers are used to monitor pore water pressures in saturated soils. Twin tubes connect the readout point to the piezometer tip. Pore water pressures transmitted through the tip act against a flexible diaphragm. Readings are obtained by balancing this pressure with a gas pressure applied through one of the tubes from a readout unit. When the applied pressure exceeds the pore water pressure acting on the opposite side of the diaphragm, the diaphragm deflects allowing the excess applied pressure to vent through the second tube. When the applied pressure is equal to the pore water pressure, the diaphragm seals against the tube ports, thus a balanced static pressure is achieved and a reading obtained on a bourdon gage or digital display at the readout unit.

Measurement of negative pore water pressure is conceivable by modification of the readout equipment.

Pneumatic piezometers are usually installed in drilled boreholes in a manner similar to standpipe piezometers. Like hydraulic piezometers, it is essential to saturate the tip prior to installation. However, since pneumatic piezometers do not rely on the transmission of pressure through a water filled tube, this does not limit the elevation of the readout point relative to the piezometer tip.

The elevation of the piezometer must be known to calculate piezometric elevation. Settlement of the instrument must also be tracked and corrections made to the reduced data.

Advantages:

• No standpipes to interfere with construction activities.

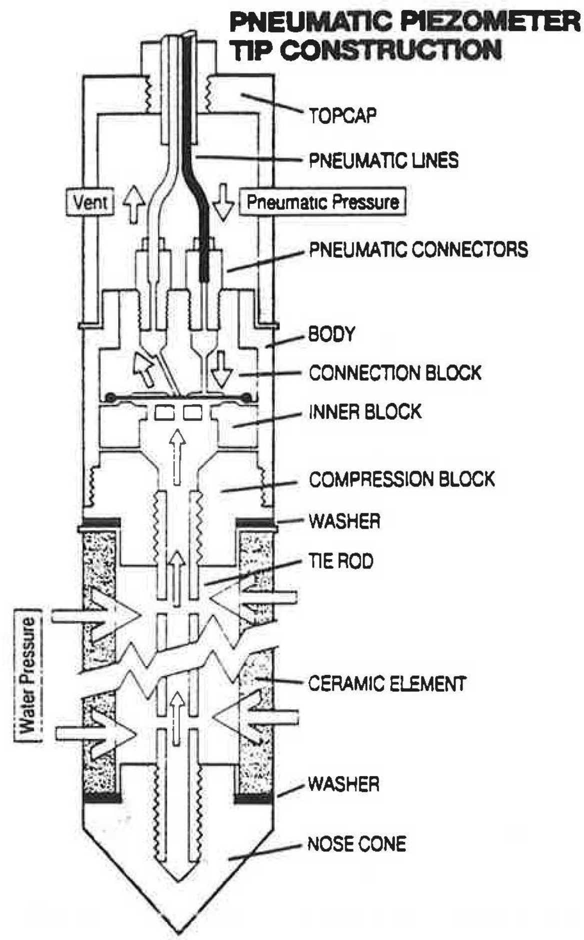

FIGURE 3 Pneumatic piezometer (Courtesy of Geotechnical Instruments, Inc.).

• Rapid response to changes in pore water pressure.
• Very reliable for long term monitoring.
• Sensors are less expensive than electrical types.
• Essentially no maintenance required.

Disadvantages:

• Long lengths of twin tubing will result in long reading times.
• Cannot be used to monitor negative pore water pressure without modifications.
• Monitoring requires a source of dry compressed air or nitrogen.
• Difficult to couple to an automatic data acquisition system.
• System cannot be flushed to remove any trapped air at the tip.
• Crimping or rupture of twin tubes can cause failure.

VIBRATING WIRE PIEZOMETERS (FIGURE 4)

Electrical sensors have gained popularity over recent years due to the ease of obtaining readings and their compatibility with electronic data collection systems and remote recording. Vibrating wire piezometers are preferred for embankment applications over other electrical sensors owing to their proven long term electrical/mechanical stability, the lack of limitations on signal cable length and high tolerance for cable moisture. The vibrating wire piezometer consists of a porous tip which transmits the pore water pressure to a stainless steel diaphragm. A wire is suspended between a fixed point and the surface of this diaphragm within an hermetically sealed chamber. Deflections of the diaphragm corresponding to variations in pore pressure alter the tension in the wire. An electromagnetic pulse excites the wire to vibrate at its resonant frequency which is a function of tension. The resonant frequency can be measured electronically with a portable readout unit, and converted to pore water pressure using the calibration data supplied with each sensor.

Vibrating wire piezometers can be installed in drilled boreholes in a manner similar to that described for pneumatic piezometers. Models are also available for pushing into place in soft soils.

The elevation of the piezometer must be known to calculate piezometric elevation. Corrections must be made for any settlement which occurs.

Advantages:

- Monitoring is quick and easy.
- No standpipes to interfere with construction activities.
- Electrical cables can be routed great distances.
- Electrical signal not effected by moisture.
- Fast response to changes in pore water pressures.
- May be used to measure negative pore water pressures.
- Easily connected to automatic data acquisition systems.
- Good long term stability.
- High resolution/accuracy.

Disadvantages:

- Relatively expensive system (piezometers, cable and readout).

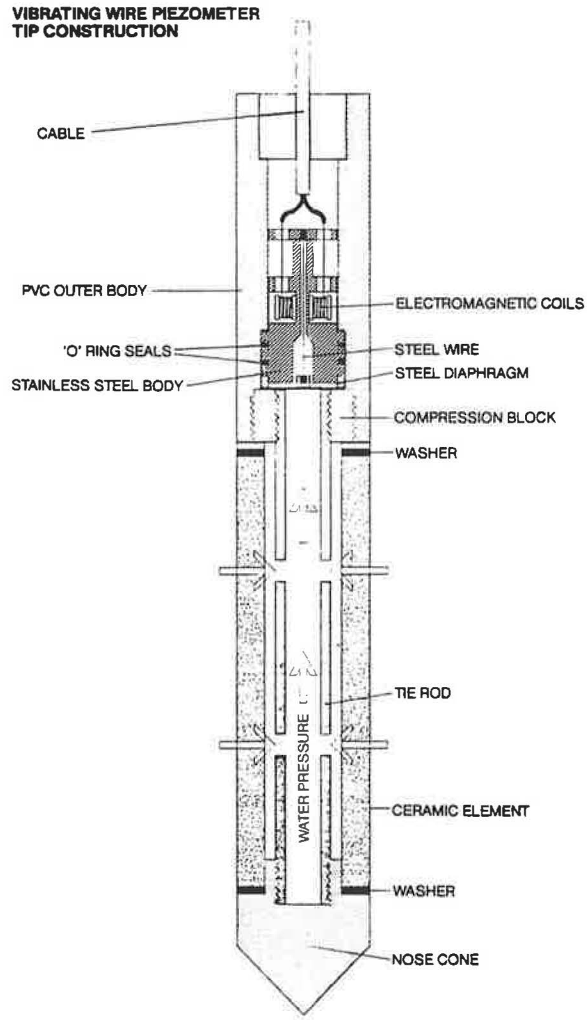

FIGURE 4 Vibrating wire piezometer (Courtesy of Geotechnical Instruments, Inc.).

- Susceptible to lightning damage; may require lightning protection.
- Calibration data required for analysis of results.
- Sensor range must be carefully selected to avoid damaging the diaphragm.
- Barometric pressure readings required when unvented sensors used.
- In-line moisture traps required when vented sensors used.
- Not suitable for dynamic pore pressure measurements.

MONITORING SETTLEMENT AND HEAVE

As excess pore water pressures dissipate from soft soils beneath an embankment, consolidation and settlement occur. It is important to monitor this settlement and to correlate it with the pore pressure measurements. This serves to confirm design assumptions relevant to the allowed rate of construction. Heave may also be a concern, particularly outside the limits of the embankment and in cases where a surcharge is applied prior to construction. A wide range of instruments is available to measure these vertical displacements. Only those which are most commonly used are described here.

SETTLEMENT PLATES (FIGURE 5)

Settlement plates are instruments used to monitor settlement of an interface, typically between the substrata and the overlying fill. They consist of a steel plate, typically 0.5 cm square and 10 to 20 mm thick, welded to a steel pipe having an outside diameter ranging from 10 to 50 mm. An outer pipe (steel, rigid PVC or corrugated plastic) with a diameter ranging from 20 to 100 mm is placed over the inner pipe and the embankment material built up around it. Both pipes are extended through construction to the completed surface.

The outer pipe serves to isolate the inner pipe from contact with the fill material. As the substrata settles, the steel plate pulls the inner pipe downward within the outer pipe. Optical surveys of the top of the inner pipe from the surface indicates the magnitude of settlement.

Advantages:

- Low cost of materials.
- Simple monitoring by optical survey.

Disadvantages:

- Pipes interfere with construction activities.
- Gives settlement only at a single point or interface.
- Requires protection of, or precautions to prevent damage to, the pipe during construction.

BORROS POINTS (FIGURE 6)

Borros points are single point settlement devices installed from the surface. They feature a specially designed steel tip with three angled barbs which extend outward when driven from inside with a 6 mm diameter (typical) steel rod.

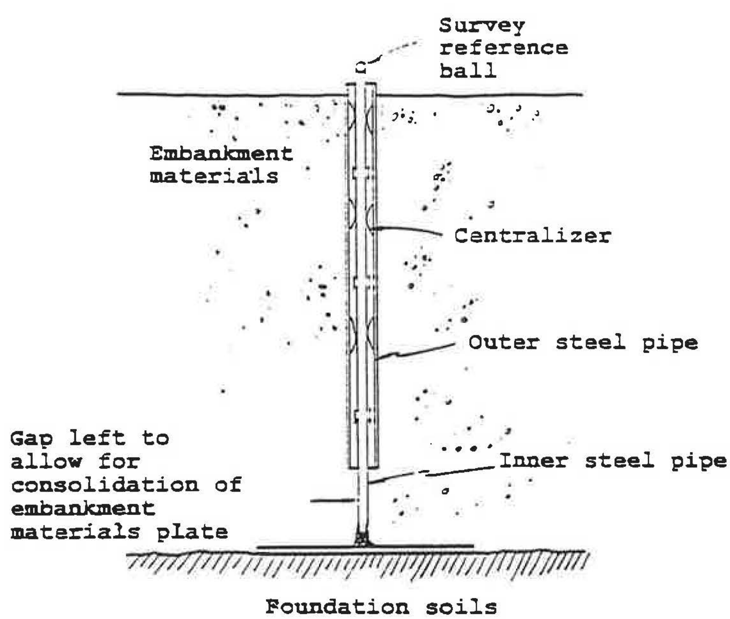

FIGURE 5 Settlement plate (Courtesy of Geotechnical Instruments, Inc.).

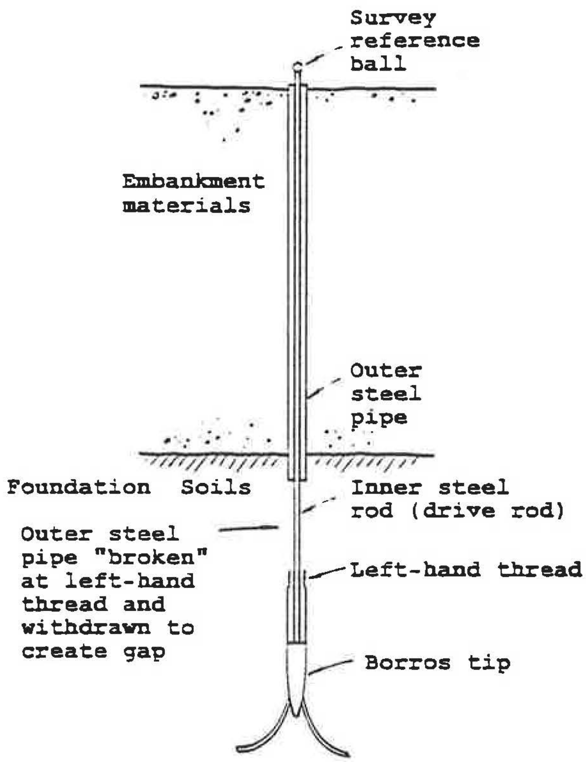

FIGURE 6 Borros point (Courtesy of Geotechnical Instruments, Inc.).

Casing is advanced by driving or is grouted within a drilled borehole to a depth of approximately 1 meter above the planned monitoring point. The casing is washed clean and the borros tip with attached steel pipe and inner steel rod is lowered to the base of the hole. The first joint in the outer casing is made with a left hand thread to facilitate separation later. The instrument is advanced beyond the bottom of the borehole by driving on the outer casing until the monitoring depth is reached. The inner rod is then driven, advancing the three barbs outward, firmly anchoring the tip into the soil. The outer casing is then rotated, "breaking" the left hand threaded joint above the tip. The outer casing is withdrawn about 1 meter to create a gap to allow for consolidation of the overlying material. Settlement of the anchor is detected by optical survey of the top of the inner rod.

Advantages:

- Low cost of materials.
- Simple monitoring by optical surveys methods.

Disadvantages:

- Measures settlement only at a single point within the soil mass.
- Requires protection of the standpipe and rod.
- The weight of the assembly may cause settlement and false readings in very soft soil.

SETTLEMENT CELLS (LIQUID LEVEL GAGES)

Settlement cells are single point measurement devices used for determining the rate and magnitude of vertical settlement or heave within an embankment or at the embankment-subsoil interface.

The main advantage of this type of instruments is that, in most cases, tubes can be placed horizontally and routed to a convenient terminal location adjacent to the embankment. Hence no vertical riser pipes passing through and protruding out of the embankment material are necessary. This allows free and easy access for contractor's operations. When installing these type of instruments, the following general points should be considered:

- Any liquid filled tubes or cells should be protected from freezing weather conditions or an anti-freeze solution used.
- The terminal unit should be surveyed periodically to ensure that settlement outside the limits of the embankment is not influencing the readings.

There are basically four types of settlement cells that are currently used for routine construction control purposes:

- Vented Overflow Cell
- Sealed Overflow Cell
- Pneumatic Settlement Cell with a pressurized water column
- Electrical (Vibrating Wire) Settlement Cell

The first two types above are both liquid overflow cells, the last two are transducer types.

Vented Overflow Cells (FIGURE 7)

Vented overflow cells consist of cylindrical vessels with vent holes and an internal cylinder which connects to a flexible tube. This flexible tube is routed back to a graduated sight tube at the readout point.

The cell is installed at the same level as the reading point. The tube is filled with de-aired water until it overflows in the cell and drains into the fill through the vent holes. Assuming there is a continuous column of de-aired water between the cell and the terminal unit, the water at each end of the system will be at the same level. This level is termed the weir point. As settlement occurs, water overflows in the cell, lowering the water level at the readout point. The graduated sight tube

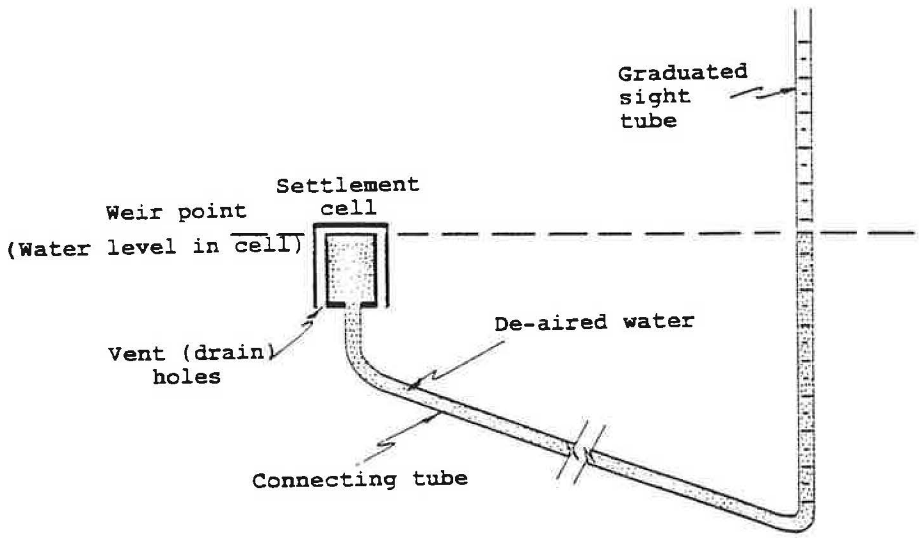

FIGURE 7 Vented overflow cell (Courtesy of Geotechnical Instruments, Inc.).

provides a direct visual indication of the magnitude of settlement.

Advantages:

• High accuracy (±2 mm).
• No riser pipes through the fill material.

Disadvantages:

• Vent tubes may become locked by condensation forming slugs of water.
• Barometric pressure must be equal at both ends of the system.
• The cell and reading point must be at the same elevation and the anticipated settlement must not exceed the range of the sight tube.
• The fill material must be permeable to allow free drainage of the overflow.
• Water in the flexible tube is subject to freezing.

Sealed Overflow Cells (FIGURE 8)

The sealed overflow cell works on the same principle as the vented overflow cell, with the following differences:

• The outer cylinder of the cell does not contain vent holes and is sealed.
• A second flexible tube routed back to the terminal unit acts as a drain line for the de-aired water.
• A third, larger diameter flexible tube routed back to the terminal unit keeps the barometric pressure equal at both ends of the system.

The disadvantages of this systems are similar to that of the vented overflow cell.

Note: The operating range of both types of overflow cells may be extended with the addition of a back pressure system such as a water/mercury manometer and reservoir. This also eliminates the need to install the cell and readout unit at the same elevation.

Pneumatic Settlement Cells (FIGURE 9)

In recent years the operation and precision of pneumatic settlement cell systems have been improved. The cell is subjected to a column of de-aired water from a reservoir in the reading unit. A pneumatic back pressure is also applied to the water column via the reservoir to prevent dissolved air from emerging from solution and minimize surface tension effects.

The back pressure is connected to a readout unit on the reference side of a differential pressure transducer. The readout unit supplies a gas pressure via separate tubes to balance the combined water column pressure and pneumatic back-pressure via a flexible diaphragm in the cell. This pressure value is recorded on the reading side of the differential pressure transducer.

The net output of the transducer is equivalent to the pressure resulting from the weight of the water column

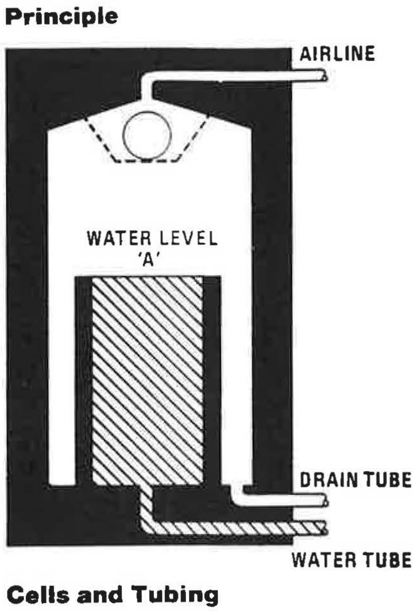

FIGURE 8 Sealed overflow cell (Courtesy of Geotechnical Instruments, Inc.).

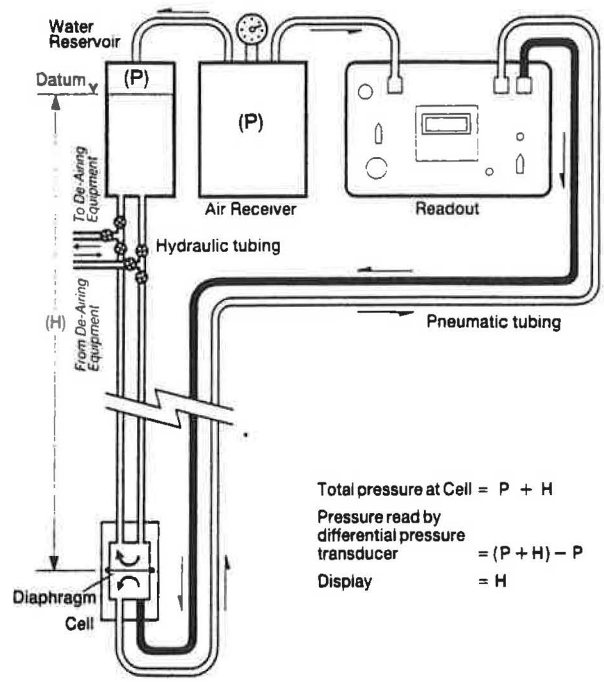

FIGURE 9 Pneumatic settlement cell (Courtesy of Geotechnical Instruments, Inc.).

between the datum level at the reading point and the flexible diaphragm in the cell. Provided that the datum remains constant any change in elevation of the cell will result in a change in pressure acting on the cell. Thus settlement can be measured.

This type of settlement cell has a much greater working range (5 meters above to 20 meters below the elevation of the readout point) than the overflow types, but is not as precise.

Advantages:

- Cells can be installed above or below the elevation of the readout point.
- Large operating range.

Disadvantages:

- Precision is less than overflow type cells, i.e. 20 mm.
- Requires regular maintenance and inspection.
- Competent, well trained operator is essential.

Vibrating Wire Settlement Cells (FIGURE 10)

Vibrating wire settlement cells combine a fluid loaded system with an electrical readout from a vibrating wire pressure transducer. The fluid reservoir is contained in the settlement cell. A flexible tube connects the fluid in the reservoir to a vibrating wire pressure transducer firmly fixed at a point beneath the settlement cell. As the elevation of the cell decreases due to settlement, the head of fluid acting on the pressure transducer decreases giving a corresponding decrease in the pressure reading from the transducer. Electrical cable from the transducer is routed through a trench to some suitable readout location.

While the use of mercury offers greater sensitivity across the working range of the cell, environmental concerns over the hazards of heavy metals have restricted its use. Therefore, de-aired water with an antifreeze solution is more commonly used as the fluid medium.

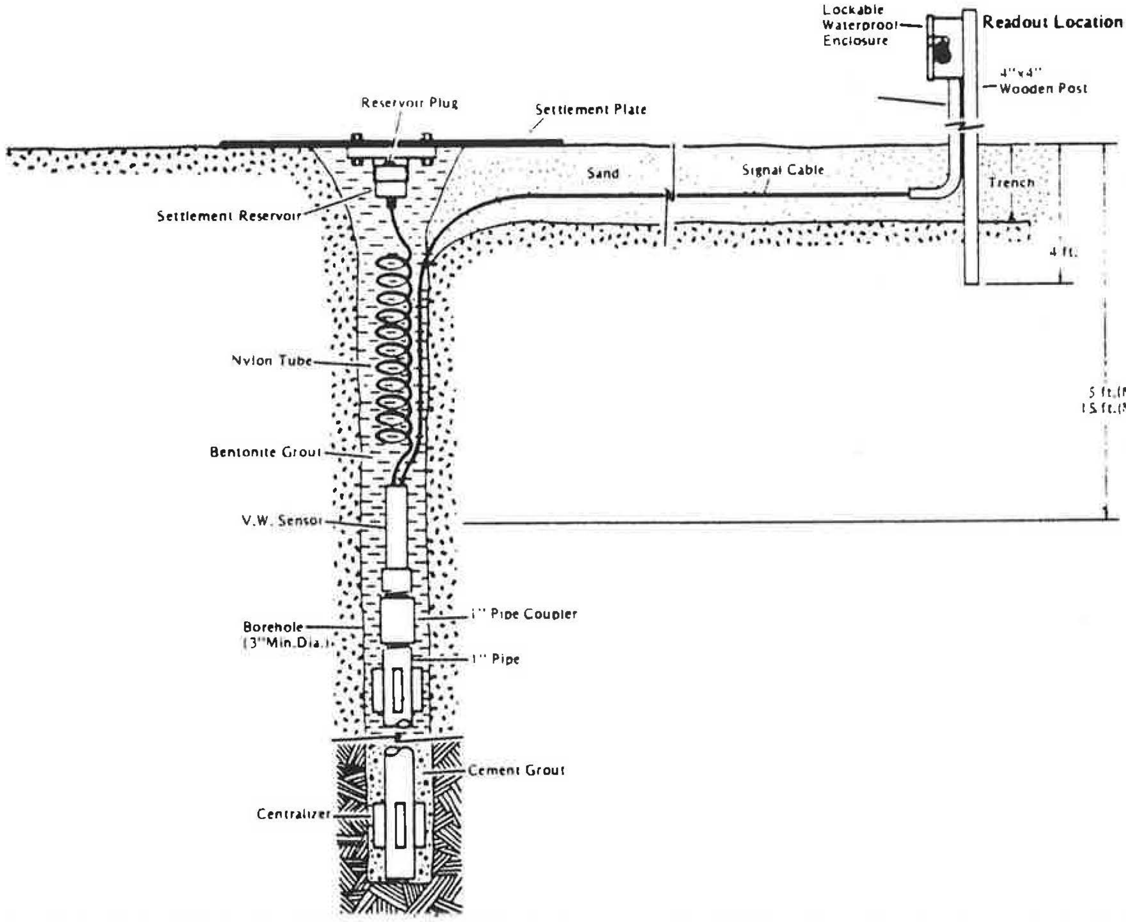

FIGURE 10 Vibrating wire settlement cell (Courtesy of Geokon, Inc.).

Advantages:

- No standpipes to interfere with construction activities.
- Cells can be installed above or below the elevation of the readout point.
- Large operating range depending on the choice of pressure transducer.
- Fluid filled lines do not have to be routed to the readout location.
- Electrical signal cable can be routed great distances.
- Electrical signal not effected by moisture.
- Monitoring is quick and easy.
- Accuracy of ±3 mm possible.

Disadvantages:

- Installation involves drilling a borehole at each measuring point.
- Base of the assembly must be grouted in place.
- Settlement at the base of the assembly cannot be measured and will affect readings.
- Fluid filled lines are inaccessible for maintenance.
- Fluid filled lines must be protected from freezing.

MAGNETIC EXTENSOMETERS (FIGURE 11)

Magnetic extensometers consist of a series of magnetic targets placed at intervals along a vertically installed access tube. This tube can be installed within a drilled borehole or built up as successive lifts of an embankment are constructed. In either case, telescoping joints are used to accommodate changes in lengths caused by settlement or heave. Each magnet is free to move along the access tube and is in direct contact with the surrounding soil. Magnets installed in boreholes contain three or more spring loaded legs which expand outward to grip the sides of the borehole. Installations involving successive lifts incorporate plate magnets placed on the top of each lift as construction progresses.

Measurements are taken by passing a reed switch probe attached to a graduated tape down the center of

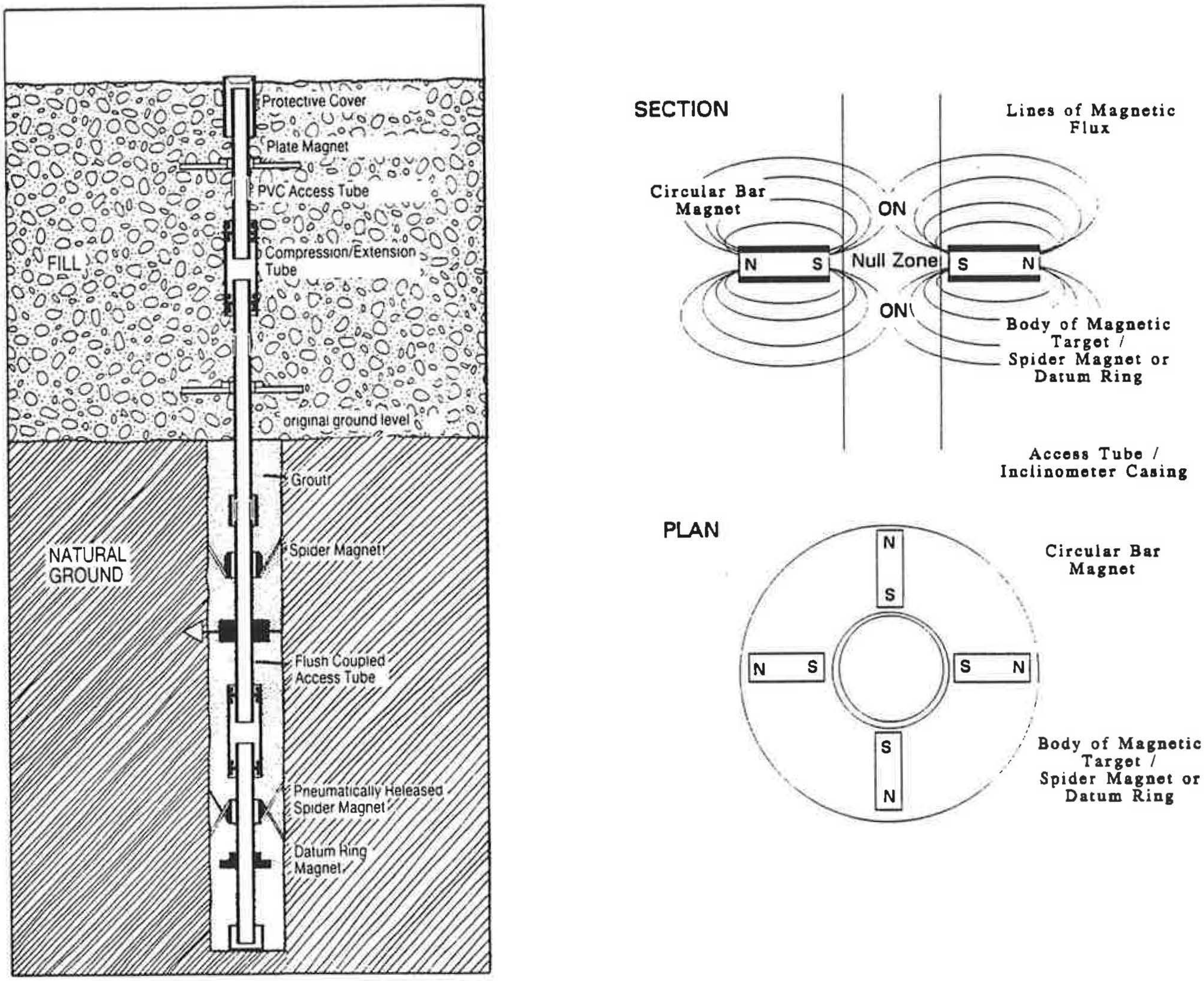

FIGURE 11 Magnetic extensometer (Courtesy of Geotechnical Instruments, Inc.).

the access tube. The magnetic targets create a uniform magnetic field with a well defined null zone in the center. As the reed switch probe enters the magnetic field of each magnet, two audible signals are given separated by this null zone. The depth to the beginning and end of the null zone is recorded using the graduated tape and the top of the access tube as an index. The average of these two readings defines the location of each magnet to within ±1 mm. Successive readings over a period of time are compared to determine changes in the relative positions of each magnet corresponding to settlement or heave.

Magnetic extensometers can be combined with borehole inclinometers (see section above) to monitor both vertical and lateral displacements. Larger diameter magnetic targets are available which enable the use of standard inclinometer casing as the access tubing.

It is important to establish a stable reference point on which to base the recorded measurements. If the installations can be extended to a depth where no disturbance is anticipated, a reference magnet can be permanently attached to the bottom of the access tubing. Relative movements of each target can then be referenced to this datum. Alternatively, the top of the access tube can be used as a reference. This will require monitoring the changes in elevation of the top of the tube by optical survey methods as settlement occurs and as successive lengths are added.

Advantages:

• Attempts to better represent vertical displacement due to direct contact of magnetic targets with soil material.

• Readings can be obtained at selected points to give a vertical distribution of settlement.
• May be combined with borehole inclinometer installations (see section above).

Disadvantages:

• Accurate representation of settlement depends upon the grout/soil straw compatibility.
• Grout mix has to have similar compressibility to that of the surrounding soil.
• Installation can be relatively complicated especially when many targets are required.
• Access tube may interfere with construction activities.
• Access tube requires protection from vandalism and damage from construction activities.
• Monitoring process is fairly labor intensive.
• Accuracy of readings dependant on skill of the operator.

SONDEX SYSTEM (FIGURE 12)

As with the magnetic extensometer system, the Sondex System is also used for monitoring settlement at several points at depth, in and beneath embankments. The system can be assembled around inclinometer casing for a combined installation.

Stainless steel wire loops are placed on a plastic corrugated pipe at predetermined locations. The plastic corrugated pipe is placed over an access casing and installed in a borehole back-filled with a suitable grout mix.

The locations of the stainless steel wire loops are determined by means of electrical induction measurements from a portable readout unit.

The probe can locate the loops to ±1.25 mm and is capable of measuring localized settlements of up to 50 mm.

Advantages:

• Relatively simple to install and does not require telescoping casing sections.
• Economical.
• Can be assembled around inclinometer casing.

Disadvantages:

• Accurate representation of settlement depends upon the grout/soil strain compatibility.
• Requires compression of corrugated pipe to correspond to ground movement.
• Limited range (20% compression of soil layer).

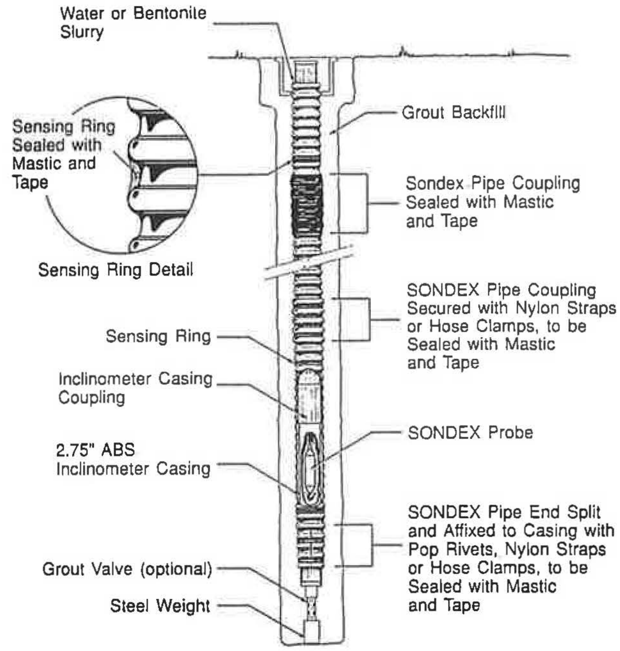

FIGURE 12 Sondex system (Courtesy of Slope Indicator Co.).

• No direct contact with the subsoil.
• Labor intensive monitoring.
• Grout mix has to have similar strength and compressibility to that of the surrounding soil.
• Electrical cable type readout needs to be calibrated regularly.

PROFILE GAGES

Profile gages are used to obtain a profile of settlement across the width of an embankment usually at the interface with the subsoil.

Casings or pipes are laid horizontally in trenches extending beyond the limits of the embankment. The trenches are normally backfilled with a stone free material and compacted to the same density as the fill or subsoil.

A small diameter casing with a blind pulley connection and draw cord is fixed and laid adjacent to the measuring casing. This arrangement allows monitoring to be carried out from one end. A reading unit is set up on a concrete pad where the monitoring and draw cord casings are terminated. The concrete pad should be periodically surveyed to check for possible settlement.

The sensor or probe is connected to the draw cord and pulled to the far end of the monitoring casing. Readings are then obtained at regular intervals by pulling the sensor back towards the readout unit, obtaining a profile of the measuring casing relative to

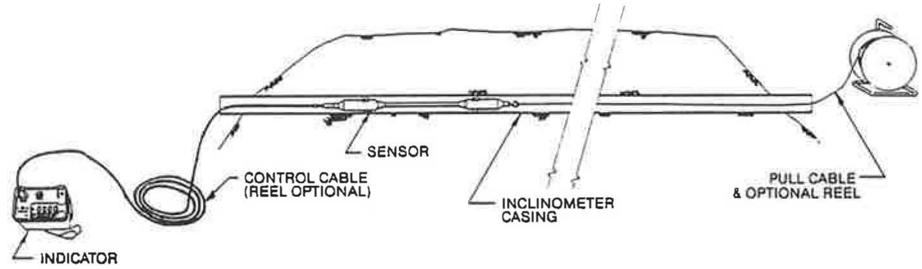

FIGURE 13 Horizontal inclinometer (Courtesy of Slope Indicator Co.).

the readout point. By comparing successive sets of data, a profile of settlement can be plotted with respect to time.

There are two basic types of profile gages; the horizontal inclinometer and the liquid level gage with the transducer situated in the probe or in the readout unit.

Horizontal Inclinometer (FIGURE 13)

Horizontal inclinometers are used to measure vertical deflections along a grooved guide casing placed horizontally beneath the embankment. The components of the monitoring system include a probe with spring loaded guide wheels, graduated electrical cable and an electronic readout device. The probe is a uniaxial instrument with a servo accelerometer mounted in the same axis as the tracking wheels. This is pulled through the installed casing and readings of inclination relative to horizontal are obtained at specific intervals. By adding these inclination readings from one end of the installation casing to the other provides a profile of the installed casing.

The horizontal inclinometer is a highly accurate system for obtaining settlement data. Accuracies of better than 2 mm per 30 meters of casing are typical.

Large diameter telescoping inclinometer casing should be used to allow for settlement and accommodate extension.

Advantages:

- High accuracy.
- Can utilize some readout components of the vertical inclinometer system.

Disadvantages:

- Grooved Casing needs to be used and placed with great care in the trench so that the grooves are correctly aligned.
- The gage length of the sensor is typically 2 feet, thus the turning radius is large compared to other profile gages.
- Should only be used where relatively small settlements are anticipated, i.e. up to 6 inches.

Hydrostatic Profile Gages

Two main types of hydrostatic profile gages are available.

- With the transducer at the readout point.
- With the transducer in the probe.

Transducer at the Readout Point (FIGURE 14)

A differential pressure transducer and associated electronics are mounted inside a cable reel and connected to a digital readout unit. A flexible twin tubing connects the transducer to the probe.

A bladder arrangement inside the probe is connected to one of the tubes which is pressurized. The second tube is filled with de-aired water and is also under the same pneumatic pressure to minimize surface tension effects and to prevent the formation of air bubbles.

The pressure transducer within the readout unit detects the difference in pressures within the two tubes. This difference is created by the column of water within one of the tubes. As the elevation of the probe changes relative to the readout point, the differential pressure changes accordingly. The pressure is converted to elevation and is displayed on the digital readout unit.

Advantages:

- Does not require grooved casing.
- Capable of monitoring large settlements.

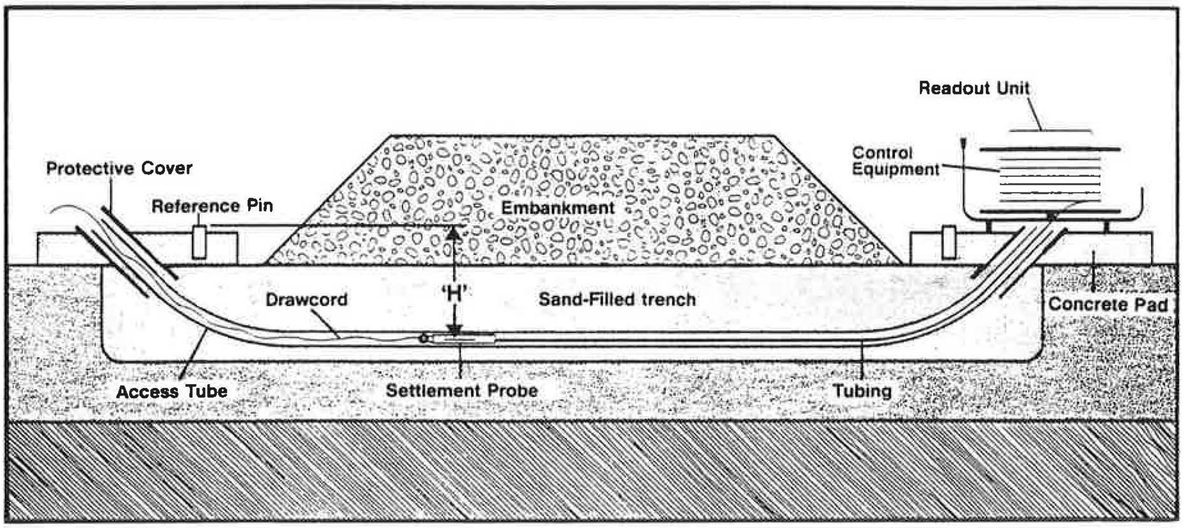

FIGURE 14 Hydrostatic profile gage (Transducer at the readout) (Courtesy of Geotechnical Instruments, Inc.).

- Has a smaller turning radius than a horizontal inclinometer.

Disadvantages:

- Precision is typically ±10 mm per reading.
- Can be affected by temperature changes.

Transducer at the Probe

This system has a pressure transducer (vibrating wire or strain gage type) housed at the probe end. A fluid-filled flexible tube acts on the pressure transducer from a reservoir at the reading unit, hence any change in elevation of the probe relative to the reservoir will cause a change in pressure on the sensor. This pressure is converted to elevation and displayed on a digital readout unit.

The advantages and disadvantages of this system are similar to those listed for the system having the transducer at the readout point (as described in the above section).

MONITORING LATERAL DISPLACEMENTS

SHEAR PROBES (FIGURE 15)

Shear probes are simple instruments used to detect the location of a slide plane. They consist of PVC pipe (typically 20 mm diameter) grouted within a vertical borehole. The installation is extended through the soft material into firm ground thereby providing a stable base. Shear probes can be installed at any point along the embankment but are typically placed beyond the toe a distance of 1 to 3 meters.

The monitoring sequence for the shear probe involves lowering a series of rods down the access tube. Generally, three rods having lengths of 1 m, 0.5 m, and 0.3 m are passed through the access tube beginning with the longer length. If horizontal displacement occurs in the vicinity of the tubing, the access pipe will deform, eventually restricting passage of some or all of the rods. Depths of refusal for the different lengths of rod are recorded indicating the depth of ground displacement and an estimate of the magnitude. Subsequent monitoring of the changes in the depths to refusal for the various length probes can be used to infer the rate of shear.

Advantages:

- Inexpensive.

Disadvantages:

- Provides only an approximate magnitude and rate of lateral displacement.
- Requires protection of the vertical access tubing during installation.
- May be able to detect only one slip surface if tubing deflection is excessive.

BOREHOLE INCLINOMETERS (FIGURE 16)

Borehole inclinometers are widely used for monitoring slope stability. The system uses specially designed 50 to 75 mm diameter casing containing two sets of orthogonal grooves running the full length of its inner surface. The casing is typically constructed of aluminum, plastic or fiberglass. Lengths of casing are assembled with telescoping couplings to accommodate settlement or

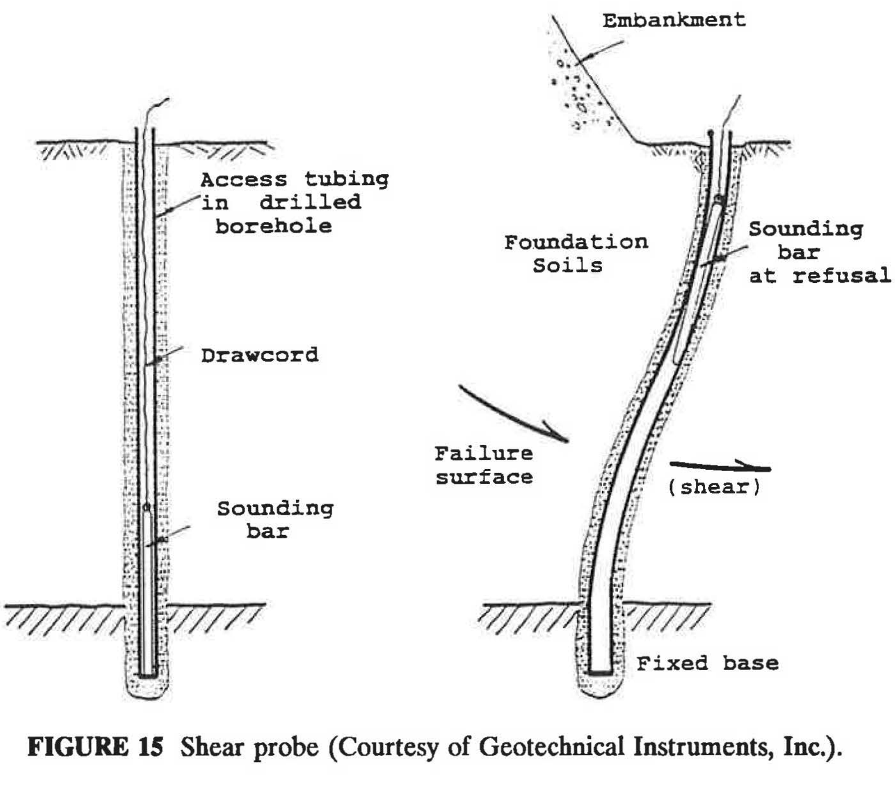

FIGURE 15 Shear probe (Courtesy of Geotechnical Instruments, Inc.).

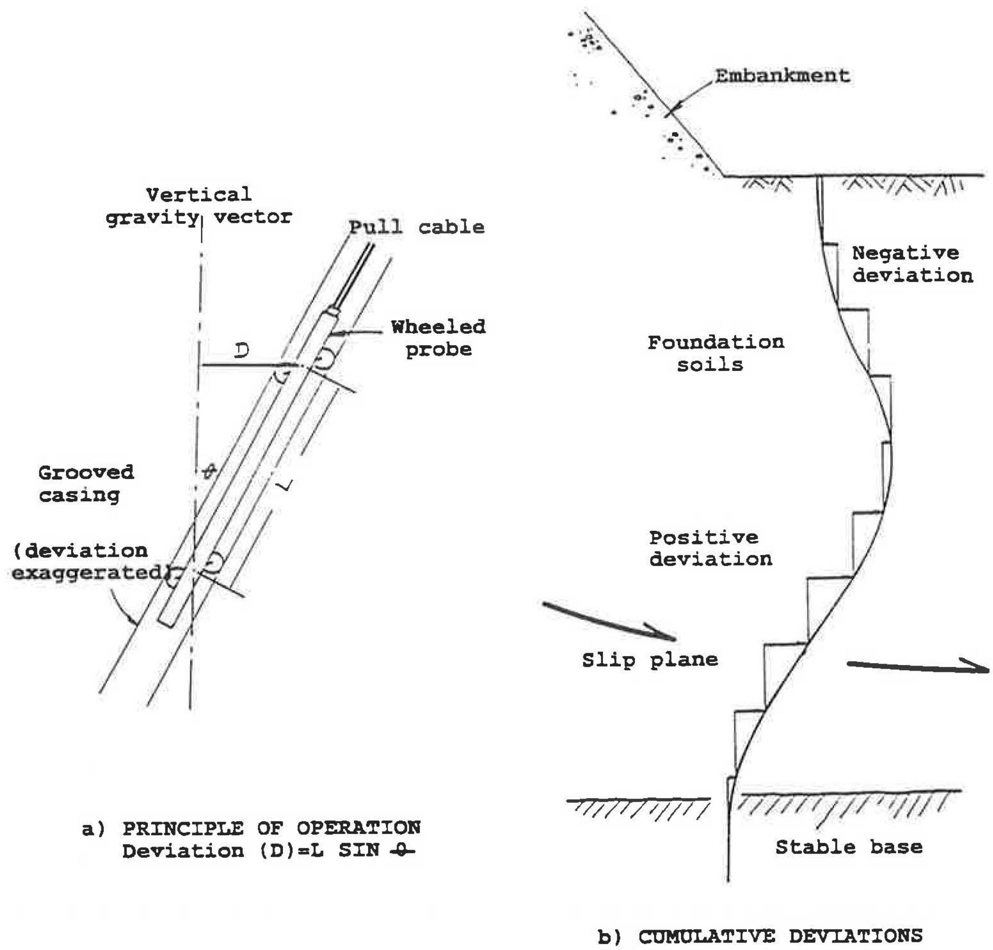

FIGURE 16 Borehole inclinometer (Courtesy of Geotechnical Instruments, Inc.).

heave and grouted within drilled boreholes. The bottom 3 to 6 meters of casing should be set in firm material or extended to a depth beyond the anticipated area of ground disturbance. Borehole inclinometers are usually installed along the embankment slopes 1 to 3 meters beyond the toe.

The monitoring equipment consists of a probe with two sets of spring loaded wheels, a graduated electrical cable and an electronic readout device. Sensors (usually servo accelerometers) within the probe convert the angle of inclination (the angle between the axis of the probe and true vertical) into an electrical signal. Most probes contain two such sensors oriented at right angles to each other to detect the angle of inclination in two planes.

The probe is passed through the casing, oriented via the guide grooves. Inclination readings are taken at consistent intervals (usually 1/2 meter) over the length of the casing. Summing the deflection values for each interval from the bottom to the top yields a profile of the installed casing. Comparing these calculated profiles over a period of time will indicate any changes in shape resulting from ground displacement. Magnitude, direction, location and rate of movement can be determined.

Inclinometer installations should be overseen by an experienced instrumentation engineer to ensure that the lengths of casing are properly aligned, that the couplings are properly set to accommodate settlement or heave, and that every effort is made to provide a near vertical installation without twist (Most of the twist experienced in inclinometers is introduced during installation, not during the manufacturing of the casing).

Attention must also be given to the grout mix used to backfill the installed casing. The mix should closely approximate the surrounding material in shear strength and compressibility. A mix that is too weak may allow the displaced soil to "flow" around the casing without causing deflection. Conversely, a mix that is too strong will prevent the casing from responding along with the soil.

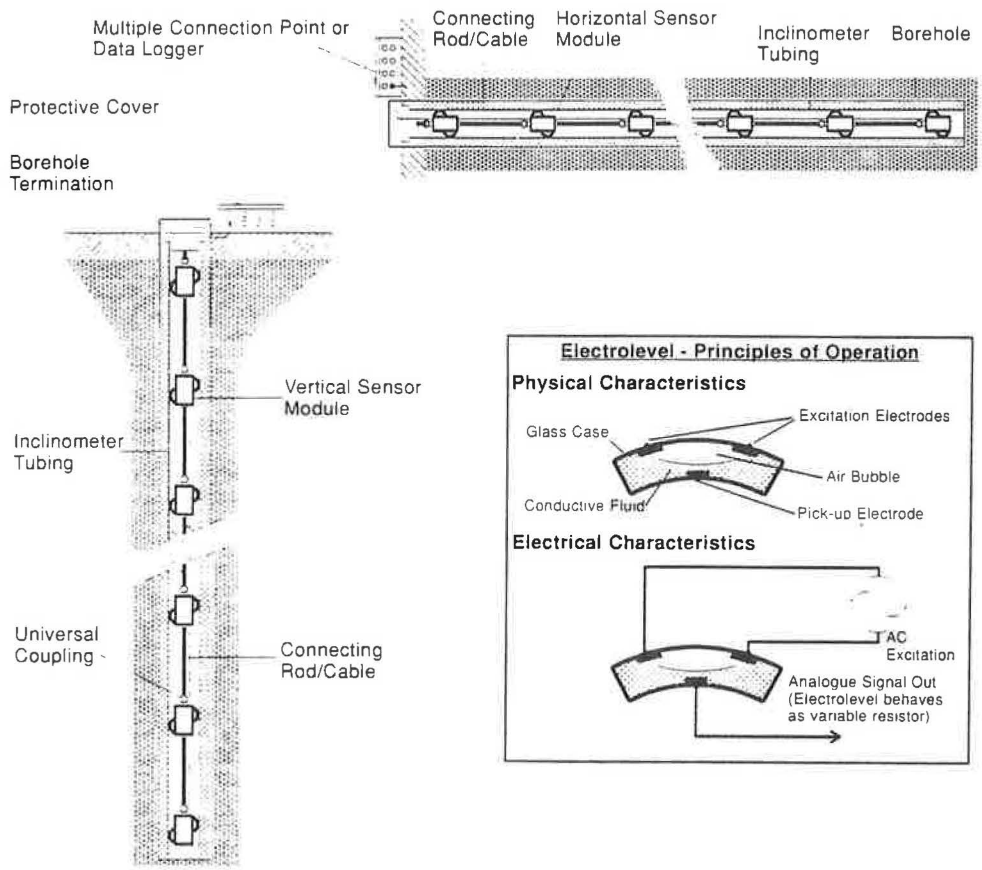

FIGURE 17 In-place inclinometer (Electrolytic level type) (Courtesy of Geotechnical Instruments, Inc.).

Advantages:

- Installations are relatively inexpensive.
- Gives an accurate measure of displacement in two directions and indicates the depth at which the movement occurs.
- Electronic readout equipment has greatly reduced monitoring time and the sources of human error in data collection.
- Computer interfaces have simplified data handling, calculations and presentation.
- Commercially available software packages produce enhanced graphic representation.

Disadvantages:

- Monitoring equipment is expensive.
- Monitoring and data processing can be relatively labor intensive (although current system incorporate solid state circuitry and computer capabilities to greatly reduce the hours required and possible sources of error).
- Requires protection of the vertical access casing.
- Monitoring equipment is sensitive to shock.
- Data can be affected by careless or inconsistent monitoring practices.

IN-PLACE INCLINOMETERS

As described in the previous section, borehole inclinometers are fairly inexpensive to install, but are labor intensive to read and reduce the data. To automate the data collection process, individual sensors can be placed at intervals along the installed inclinometer casing. The sensors are attached to rods of selected lengths (typically 1 to 3 meters) and connected to adjacent sensors with universal articulating joints. Electrical cable from each sensor is wired to a data logging computer.

Each sensor measures the inclination of a section of the installed casing. As with borehole inclinometers, these inclinations can be summed to produce a shape profile. Readings collected over time are compared to detect changes in shape resulting from lateral ground displacements. The data logger allows readings to be collected at selected time intervals. Many also contain alarms which can be set to sound when threshold levels are exceeded, thus providing an early warning of displacements.

The sensors used may be of the servo accelerometer type as described in the previous section. These are proven devices but tend to be expensive, therefore fewer sensors are placed along the inclinometer casing. These also require an individual electrical cable from each sensor (two if the sensor is biaxial). This tends to make for a bulky assembly and further limits the number of sensors placed.

Some manufacturers produce sensors based on the principle of the electrolytic level (FIGURE 17). These are similar to carpenter levels having a glass vial containing a conductive fluid and several electrodes. An air bubble within the fluid remains bisected by the vertical gravity vector regardless of the orientation of the sensor. As the sensor tilts, the bubble moves relative to the vial and changes the electrical resistance measured across the electrodes.

Electrolytic sensors may be configured using digital signalling techniques allowing a common electrical connection between all the sensors. This reduces the bulk and cost of the installation. Electrolytic sensors are also typically less expensive than the servo accelerometer type.

In-place inclinometers are usually used in conjunction with conventional borehole inclinometers. Each inclinometer is read with the portable field equipment and the in-place sensors installed at critical locations. As construction progresses, the string of in-place sensors is relocated.

Advantages:

- Easily data logged.
- High accuracy.
- Biaxial measurement possible.
- Can be used to supplement conventional inclinometer readings.

Disadvantages:

- Expensive.
- Limited working range, typically ±20 degrees from the vertical (or horizontal).

SURFACE MONITORING

The instruments described in this section are used to detect ground movement at or near the surface. Survey stakes are simple instruments placed in arrays to detect localized displacements and distinguish overall trends of ground movement. Tiltmeters are electronic instruments used to detect minute variations in the orientation of a plane. Both can be useful as indicators of an impending stability problem. In the case of road embankments, it is often best to detect displacements before they become evident at the surface.

SURVEY STAKES

Survey stakes may consist of simple 50 X 50 mm wooden stakes or T-stakes with graduated scales on one or both axes. They are driven into the surface of the embankment beyond the toe. The stakes are monitored using optical survey techniques to detect changes in horizontal position and elevation. Usually a grid is established with stakes driven at 15 meter centers or less.

A transit or theodolite is used to reference each stake to a site target located outside the anticipated area of influence. It is best to have two independent sight targets for each end of the stake lines. Elevations should be tied-in to stable bench marks. A bench mark at each end of the line is advisable, so that readings can begin at one and close on another.

Advantages:

- Simple and reliable.
- Can yield a quick visual check of surface stability.

Disadvantages:

- Installations are very susceptible to damage from construction activity.
- Effected by soil shrinkage and heave.
- Monitoring is labor intensive and interpretation unreliable without other instrumentation.
- Unstable conditions are best detected before surface manifestations are evident.

TILTMETERS

Tiltmeters are instruments for detecting rotational movement of a planar surface. In embankment application they are most often used for monitoring the finished road surface or associated structures, i.e. for long term monitoring. However, they may also be installed within shallow excavated pits. Special models are also available for installation within boreholes. These may be used to detect rotational movement of the embankment slopes.

Tiltmeters contain gravity sensing transducers (usually accelerometers, electrolytic levels or vibrating wire sensors) and are commonly biaxial to detect inclinations in two directions. An array of tiltmeters is generally connected to a central data logger for data acquisition at pre-set intervals to yield magnitude as well as rate of deflections.

Tiltplates offer an alternative to the permanent installation of a series of tiltmeters. These are ceramic or brass discs which serve as reference surfaces for a portable tiltmeter. The plates contain locating pins to ensure the precise positioning of the tiltmeter for periodic measurement. This option is considerably less expensive than permanent tiltmeters, but accuracy is compromised and data acquisition is much more labor intensive.

Advantages:

- Easily coupled to automatic data acquisition systems.
- Quick and easy installation.
- Instruments are small and can be located to minimize the possibility of vandalism and accidental damage.
- Very accurate.

Disadvantages:

- Limited range, typically ± 2 degrees.
- Surface installations require protection from damage.
- Temperature sensitive.

SELECTION OF INSTRUMENTS

During the planning of any instrumentation program, it is essential to create a liaison between the designers and the instrumentation suppliers. Suppliers can provide input on recent developments and the state-of-the-art-practice in instrumentation. To ensure that the most appropriate instrument is selected to monitor a particular parameter, the following factors should be considered.

ACCURACY

Accuracy is the relationship between the measured value and the true or actual value. Since most instrumentation systems consist of many components, it is essential to consider the total system accuracy, and not just the theoretical accuracy of each component, as is often stated in the literature.

REPEATABILITY

The repeatability or precision of an instrument is often more critical than the accuracy of the measurements. As an example, when monitoring an inclinometer, determining the lateral movement which has occurred at a point over a period of time is typically more significant than the absolute position of that point. Since inclinometer data builds on successive readings, good repeatability is essential for meaningful results.

Any instrumentation selection process should therefore consider whether the measured value will be critical or if changes in this value over time are the main concern.

RESPONSE TIMES

Response time refers to the time required for a measured value to reflect a change in the parameter being measured. With regard to embankment construction, this applies most often to piezometers and their response to rapid changes in the piezometric head. Response time in piezometers is a function of the volume of water displaced within the instrument. Standpipe piezometers for instance have the longest response times since the entire volume of water within the standpipe must adjust to changes in the piezometric pressure by flowing into or out of the soil mass. Under conditions of low permeability, the time required for this adjustment may be quite significant.

Vaughan calculated response times for the following types of piezometers in fine grain soils:

Standpipe	34 days
Hydraulic	1.6 hours
Pneumatic	0.1 hours
Vibrating wire	0.1 minutes

RANGE

The working range of an instrument must be carefully matched to the anticipated change in the parameters to be measured. Since accuracy is often sacrificed with increased range, a careful balance between the two must be achieved and instruments chosen accordingly.

RELIABILITY

Documentation on the reliability of equipment should be reviewed to ensure that the instruments selected will perform properly under the anticipated site conditions for the duration of the monitoring program. As a general rule, the simpler the instrument, the less likely it is to fail in service.

The materials used in the construction of the instruments should be evaluated if there is a possibility of contact with caustic chemicals or harsh environmental conditions. It is sometimes advisable to install different instruments to measure the same parameters to guard against unforeseen problems which may affect an instrument of a given type.

SYSTEM CHECKS

Where possible, system checks on the performance of an instrument and its readout equipment should be included in the monitoring program. If such checks are not possible, consideration should be given to a combination of instruments to measure the same parameter.

CALIBRATION

Instrumentation suppliers usually have high standards of quality control. All equipment supplied should contain the appropriate calibration records and certificates of conformity. When possible, calibration and quality control procedures should follow set standards such as ASTM or ISO 9000.

MAINTENANCE

Once equipment has been installed and monitoring commences, maintenance is important to prevent an interruption in the collection of vital data. It may be advisable to provide spare or back-up parts and/or equipment.

Readout equipment should be checked, calibrated and serviced on a regular basis by the supplier. The user should compliment this by carrying out simple checks and calibrations on site.

INSTRUMENTATION COSTS

Costs of instrumentation programs should be determined during the planning stage to protect the project budget. Drilling and any associated costs, i.e., installation, commissioning, monitoring, maintenance and data processing and analysis should all be considered.

Budget limitations may restrict the amount of data that can be obtained, so equipment should be selected carefully.

INSTALLATION

Equipment poorly installed will yield erroneous data, so it is important that even a simple instrument such as a stand-pipe piezometer be installed by personnel with the right experience and training.

The key to a good installation is planning and preparation before hand. Guidelines are given in *Chapter 17 - Example of Installation Procedure, with Materials and Equipment List - Geotechnical Instrumentation for Monitoring Field Performance*, Dunnicliff (1988). If these guidelines are followed, the risk of any mistakes or errors occurring is greatly reduced.

Instruments are often damaged after installation due to inadequate protection. Ensure that each instrument is adequately protected from vandalism and construction activities.

It is advisable to use lockable steel cabinets installed above ground terminating piezometer and settlement cell tubes rather than manholes which could flood or fill with dangerous gases. If long term monitoring is required, more substantial facilities may be warranted for monitoring, e.g., a secure gage house.

MONITORING, DATA PROCESSING, AND ANALYSIS

The staff obtaining data should be familiar with each instrument. They should know why measurements are being made and have a basic knowledge and understanding of how a particular instrumentation system operates. They should have the capability of recognizing what might be erroneous data and trouble shooting systems if problems occur.

It will also be necessary for the staff to know what action to take if some anomaly is met or if excessive changes in data have occurred. Action limits set by the design engineer should be clearly identified to the field personnel.

A few instrumentation suppliers now have manually operated portable readout equipment that allows the user to store data and make comparisons with previous readings, making the task of identifying significant changes quicker and easier. Most of these readouts have the ability to transfer data to a computer which reduces the time to process and analyze the data. If these facilities are not available, data should be recorded on standard forms that should also contain historical data so the necessary comparisons can be made in the field.

Continuous data acquisition equipment is available from many instrumentation suppliers for most necessary instruments. These have many features such as alarm levels, control functions, external event triggers, etc. These systems can produce large volumes of data making the task of data processing and analysis a full time job. All data should be processed and analyzed promptly.

Computer software is readily available from instrumentation suppliers and specialty software developers. Although the versatility and sophistication of these commercially available programs vary significantly between sources, most are designed to meet the needs of the user under typical circumstances. Users are advised to investigate the capabilities of the various software packages as rigorously as they would the instruments themselves. Some manufacturers will provide demonstration disks to introduce their programs. At the least, manufacturers should be able to provide documentation on their software packages and sample printouts of tabulated data and plots. For specific projects requiring unique data reduction or presentation (i.e., combining readings from different instrument types or correlating readings with construction activities) the user may be best served by developing his own data processing package.

APPENDIX

SELECTED SOURCE LIST

Following is a list of North American suppliers of geotechnical instrumentation and related materials identified by the members and friends of the Soil and Rock Instrumentation Committee.

Applied Geomechanics, Inc.
1336 Brommer Street
Santa Cruz, CA 95062
408/462/9368

Geokon, Inc.
48 Spencer Street
Lebanon, NH 03766
603/448/1562

Geonor, Inc.
P.O. Box 903
8 Greenwood Hills
Milford, PA 18337
717/296/4884

Geomation, Inc.
15000 W. 6th Avenue
Golden, CO 80401
303/278/2350

Geotechnical Instruments, Inc.
7507 Standish Place
Rockville, MD 20855
301/309/6580

MITRE Software Corporation
Suite 200. 9636-51 Ave.
Edmonton, Alberta
CANADA T6E 6A5
403/434/4452

Roctest, Inc.
7 Pond Street
Plattsburgh, NY 12901-3003
518/561/3300

RS Technical Instruments Ltd.
No. 5-200 Golden Drive
Coquitlam, B.C.
CANADA V3K 6MB
604/941/4848

Solinst Canada Ltd.
515 Main Street
Glen Williams, Ont.
CANADA L7G 3S9
416/873/2255

Slope Indicator Co.
3668 Albion Place North
Seattle, WA 98103
206/633/3037

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