Guide to Geotechnical Instrumentation

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Reasons for Installing Instrumentation

Introduction

Geotechnical instrumentation provides data that helps engineers in every stage of a project. Here are the main reasons that instrumentation is used:

Site Investigations

Instruments are used to characterize initial site conditions. Common parameters of interest in a site investigation are pore-water pressure, permeability of the soil, and slope stability.

Design Verification

Instruments are used to verify design assumptions and to check that performance is as predicted. Instrument data from the initial phase of a project may reveal the need (or the opportunity) to modify the design in later phases.

Construction Control

Instruments are used to monitor the effects of construction. Instrument data can help the engineer determine how fast construction can proceed without the risk of failure.

Quality Control

Instrumentation can be used both to enforce the quality of workmanship on a project and to document that work was done to specifications.

Safety

Instruments can provide early warning of impending failures, allowing time for safe evacuation of the area and time to implement remedial action. Safety monitoring requires quick retrieval, processing, and presentation of data, so that decisions can be made promptly.

Legal Protection

Instrument data can provide evidence for a legal defense of designers and contractors should owners of adjacent properties claim that construction has caused damage.

Performance

Instruments are used to monitor the in-service performance of a structure. For example, monitoring parameters such as leakage, pore-water pressure, and deformation can provide an indication of the performance of a dam. Monitoring loads on tiebacks or rock bolts and movements within a slope can provide an indication of the performance of a drainage system installed in a stabilized slope.

Choosing Instrumentation

Critical Parameters

Each project presents a unique set of critical parameters. The designer must identify those parameters and then select instruments to measure them. What information is required for the initial design? What information is required for evaluating performance during and after construction? When the parameters are identified, the specification for instruments should include the required range, resolution, and precision of measurements. See instrument performance specifications below.

Complementary Parameters

The behavior of a soil or rock mass typically involves not one, but many parameters. In some cases, it may be sufficient to monitor only one parameter, but when the problem is more complex, it is useful to measure a number of parameters and to look for correlation between the measurements. Thus it is common practice to choose instruments that provide complementary measurements.

For example, inclinometer data indicating increased rate of movement may be correlated with piezometer data that shows increased pore pressures. The load on a strut, calculated from strain gauge data, should correlate with convergence data provided by inclinometer behind a retaining structure.

Ground Conditions

Ground conditions sometimes affect the choice of instrument. For example, a standpipe piezometer is a reliable indicator of pore-water pressure in soil with high permeability, but is much less reliable in soil with low permeability. A large volume of water must flow into the standpipe to indicate even a small change in pore-water pressure. In soils with low permeability, the flow of water into and out of the standpipe is too slow to provide a timely indication of pore-water pressure. A better choice in this case would be a diaphragm-type piezometer, which offers faster response since it is sensitive to much smaller changes in water volume.

Environmental Conditions

Temperature and humidity also affect instrument choice. Instruments such as hydraulic piezometers and liquid settlement gauges have limited use in freezing weather. In tropical heat and humidity, simple mechanical devices may be more reliable than electrical instruments.

Personnel and Resources at the Site

Consider the personnel and resources at the site when choosing instruments. Do technicians have the skills required to install and read a particular type of instrument? Are adequate support facilities available for maintenance and calibration of the instrument?

Data Acquisition

An automatic data acquisition system may be required when:

- There is a need for real-time monitoring and automatic alarms;
- Sensors are located at a remote site or in a location that prevents easy access;
- There are too many sensors for timely manual readings;
- Qualified technicians are not available.

If a data acquisition system is required, the choice of instruments should be narrowed to those that can be connected to the system easily and inexpensively.

Instrument Life

Are readings needed only during construction or will they be needed for years afterwards? Instruments, signal cables, and protective measures should be selected accordingly.

Instrument Quality

The difference in cost between a high-quality instrument and a lesser-quality instrument is generally insignificant when compared to the total cost of installing and monitoring an instrument. For example, the cost of drilling and backfilling a borehole is typically 10 to 20 times greater than the cost of the piezometer that goes in it. It is false economy to install a cheaper, less reliable instrument.

Instrument Performance

Instrument performance is specified by range, resolution, accuracy, and precision. The economical designer will specify minimum performance requirements, since the cost of an instrument increases with resolution, accuracy, and precision.

Range is defined by the highest and lowest readings the instrument is expected to produce. The designer typically specifies the highest values required.

Resolution is the smallest change that can be displayed on a readout device. Resolution typically decreases as range increases. Sometimes the term "accuracy" is mistakenly substituted for resolution. Resolution is usually many times better than accuracy and is never expressed as a plus/minus value.

Accuracy is the degree to which readings match an absolute value. Accuracy is expressed as a ± value, such as ± 0.5mm, ±1% of reading, or ±1% of full scale.

Precision or repeatability is often more important than accuracy, since what is usually of interest is a change rather than an absolute value. Every time a reading is repeated, the value returned by the instrument is slightly different. Precision is expressed as a ± value representing how close repeated readings approach a mean reading.

Applications and Instruments

Introduction

The tables below provide a general match between monitoring needs and instruments.

Pore Water Pressure

Reason for Monitoring

- Determine safe rates of fill.
- Predict slope stability.
- Design and build for lateral earth pressures.
- Design and build for uplift pressures.
- Monitor the effectiveness of drainage schemes.

Instruments Used

- VW Piezometer
- Pneumatic Piezometer
- Standpipe Piezometer

Lateral Deformation

Reason for Monitoring

- Evaluate the stability of slopes and embankments.
- Determine the need and timing for corrective measures.
- Verify the performance and safety of structures such as retaining walls and embankments.

Instruments Used

- Inclinometer
- Rod Extensometer

Vertical Deformation

Reason for Monitoring

- Verify that soil consolidation is proceeding as predicted.
- Predict and adjust the final grade of an embankment
- Verify the performance of engineered foundations.
- Determine the need and timing for corrective measures.

Instruments Used

- Settlement Cells
- Magnet Extensometer
- Sondex
- Settlement Point
- Rod Extensometer
- Horizontal Inclinometer

Monitoring Pore-Water Pressure

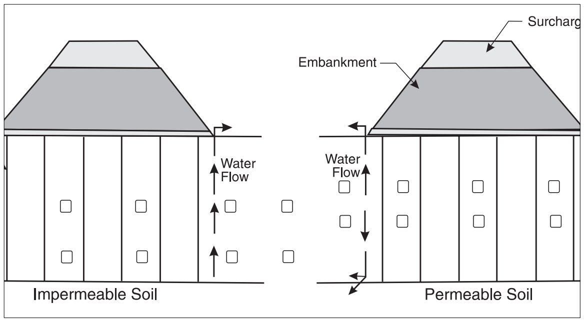
Pore-Water Pressure

Pore-water measurements help engineers to:

- Establish initial site conditions.
- Determine safe rates for placement of fill.
- Predict slope stability.
- Design and build for lateral earth pressures.
- Design and build for uplift pressures.
- Monitor the effectiveness of drainage schemes.

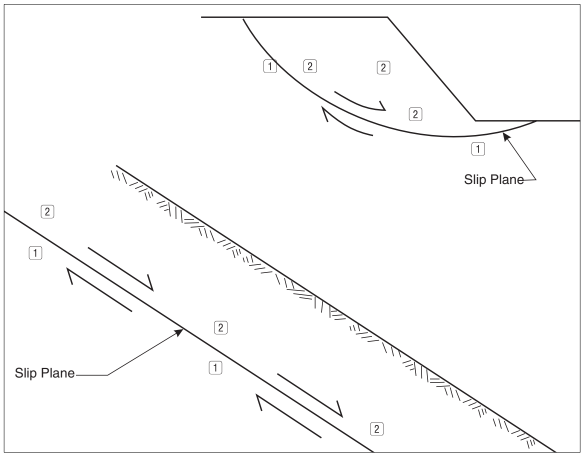
Embankments

- Control placement of fill.
- Monitor consolidation.



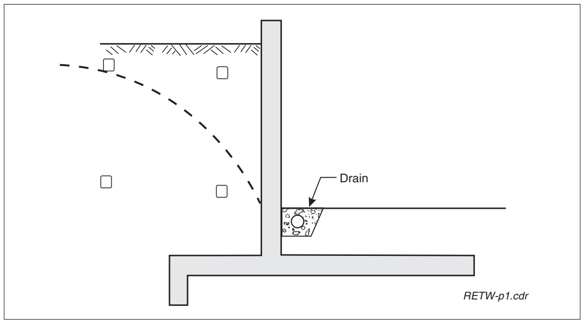
Landslides

1. Calculate the shear strength of soil.
2. Calculate the soil mass.



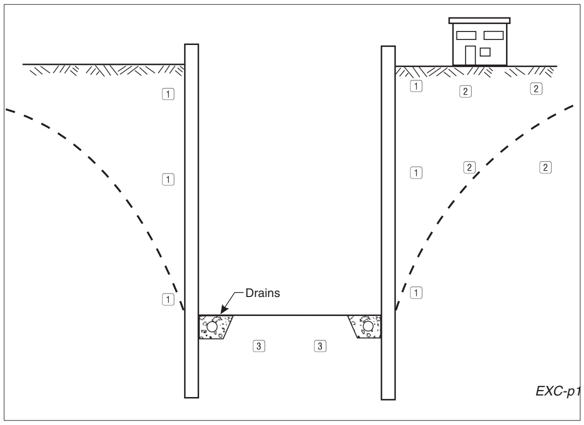
Retaining Wall

- Monitor pore-water pressure to calculated load applied to wall.



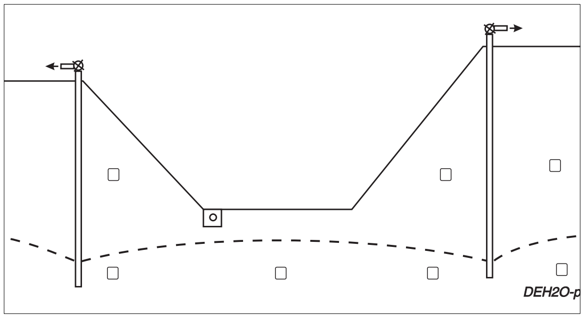
Diaphragm Wall or Sheet Pile Wall

1. Monitor load applied to wall.
2. Monitor draw-down due to seepage or dewatering to predict settlement of adjacent structures.
3. Monitor uplift pressures in floor of excavation.



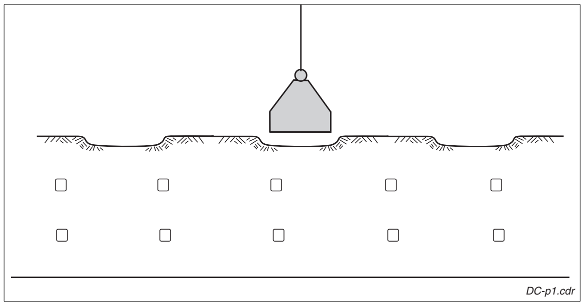
Dewatering an Excavation

- Determine efficiency of pumping scheme.
- Provide early warning of flooding.



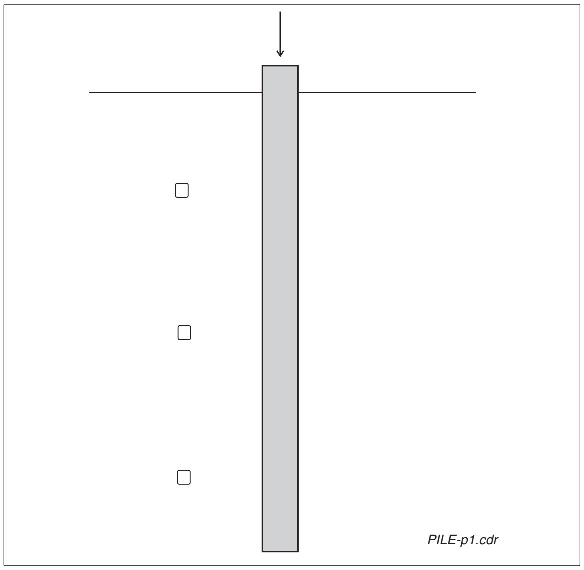
Dynamic Compaction

Monitor pore-water pressure to help evaluate consolidation of soil.



Pile Test

Monitor excess pore-water pressures generated by pile driving. Loading of pile can begin after excess pressure has dissipated.



Instruments for Monitoring Pore-Water Pressure

Piezometers are the only instrument used to monitor pore-water pressure. There are two basic types of piezometers:

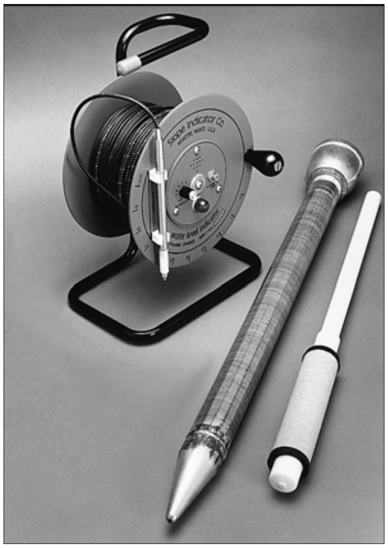
- Standpipe Piezometers
- Diaphragm piezometers (vibrating wire, pneumatic, or strain-gauge).

Standpipe Piezometers

The standpipe piezometer, sometimes referred to as an open-hydraulic piezometer or a Casagrande piezometer, consists of a porous water-intake element connected to a riser pipe.

Water enters the riser pipe through the intake element, which is normally sealed in the borehole at a specified depth. As pore-water pressure increases or decreases, the water level inside the standpipe rises or falls.

Readings are usually obtained with a water level indicator, which provides a depth-to-water measurement.

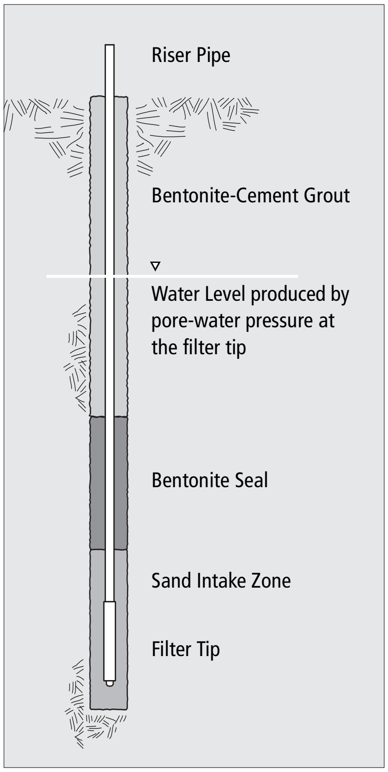


Components

The water intake element may be a filter or a well-screen, as shown above. The filter element is made of hydrophilic polyethylene or fused aluminum oxide, generally 12 to 24 inches long with 60 to 70 micron pores.

The riser pipe is 0.75 or 1-inch plastic pipe. If there is a chance that the standpipe piezometer readings will be automated in the future, choose a one inch or larger pipe that will accommodate a 3/4 inch diameter pressure transducer.

The key feature of a standpipe piezometer is the bentonite seal placed above the intake zone. This prevents water from other strata from entering the standpipe. Thus water in the standpipe is controlled by pore-water pressure at the intake zone.



Advantages

- Direct measurement of water level.
- There are no buried “sensing” components.

Limitations

- Readings require direct access to the top of the pipe.
- Slow response time in soils with low permeability.

Pneumatic Piezometers

The pneumatic piezometer is operated by gas pressure. In a typical installation, the piezometer is sealed in the borehole, and twin pneumatic tubes run from the piezometer to a terminal at the surface where readings are obtained with a pneumatic indicator.

Components

The piezometer consists of a transducer body, tubing, and a portable indicator. The transducer body has a 50 micron filter, suitable for most applications. The tubing bundle contains two polyethylene tubes, one to carry gas to the transducer, the other to return excess gas. The portable indicator contains a pressure gauge and a tank of compressed nitrogen gas.

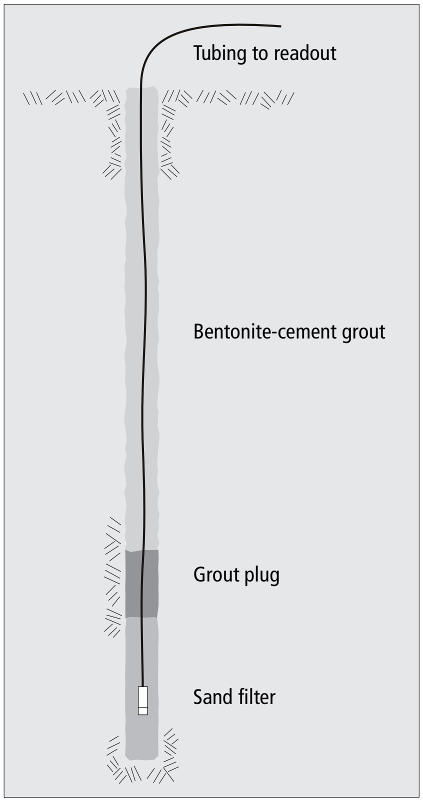
Pneumatic Piezometer Operation

The piezometer is installed in the same way as a standpipe piezometer, with the transducer sealed within a sand intake zone by a bentonite plug.

To obtain a reading, the operator connects the input tube to a pneumatic indicator and directs a flow of gas to the piezometer.

The operator shuts off the gas when a return flow is detected in the other tube.

The operator then watches the pressure gauge and notes the pressure when the reading is stable. The time it takes for the reading procedure varies with the length of the tubing.



Advantages

- Buried components are simple and do not need calibration
- Components are not affected by electrical transients.
- Fast response time in most soils.

Limitations

- Requires operator who is careful and consistent.
- Takes longer to read than a standpipe or VW piezometer.
- Indicator must be recharged regularly with dry nitrogen gas. The use of dry gas is important to keep tubing free of condensation.

Vibrating Wire Piezometers

The VW piezometer is a consists of a pressure transducer and signal cable. Readings are obtained with a portable readout or data logger. The transducer is available in 50, 100, 250, and 500 psi ranges.

There are two body styles, as shown in the photo. The upper instrument is the standard body, and is suitable for all applications. The lower instrument is a special push-in design used only in soft clays. Filters for both styles have a 50 micron pore-size and are suitable for all applications. Signal cable contains four wires and should have a jacket made of polyurethane or polyethylene.

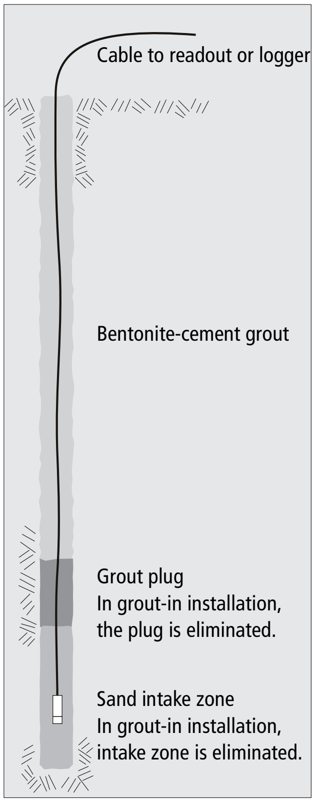
VW Piezometer Operation

The VW piezometer can be installed without a sand intake zone and bentonite seal. Instead, the entire borehole is backfilled with a bentonite-cement grout. See installation notes for more information.

The vibrating wire principle states that tension in a wire is proportional to the square of its natural frequency. The piezometer is designed so that pressure on its diaphragm controls the tension of the vibrating wire element inside.

When a readout is connected to the signal cable, it sends an electric pulse to a coil that plucks the wire, causing it to vibrate at its natural frequency. A second coil picks up the vibration and returns a frequency reading to the readout.

Calibration factors must be applied to the reading to obtain units of pressure. This may be done by the readout or on a computer.



Advantages

- Simple grout-in installation procedure opens the possibility of same-hole installation of multiple piezometers or installation of piezometers with inclinometer casing.
- The VW piezometer provides rapid response in all types of soils.
- Suitable for unattended monitoring with a data logger.

Limitations

- Calibrated component is buried (same as other electrical sensors).
- Must be protected from electrical transients in locations where lightning is common (same as other electrical sensors).
- VW sensors require data loggers and readouts with VW interfaces.

MultiLevel VW Piezometers

The multi-level VW piezometer is used in series to monitor pore-water pressure at multiple zones in a borehole.

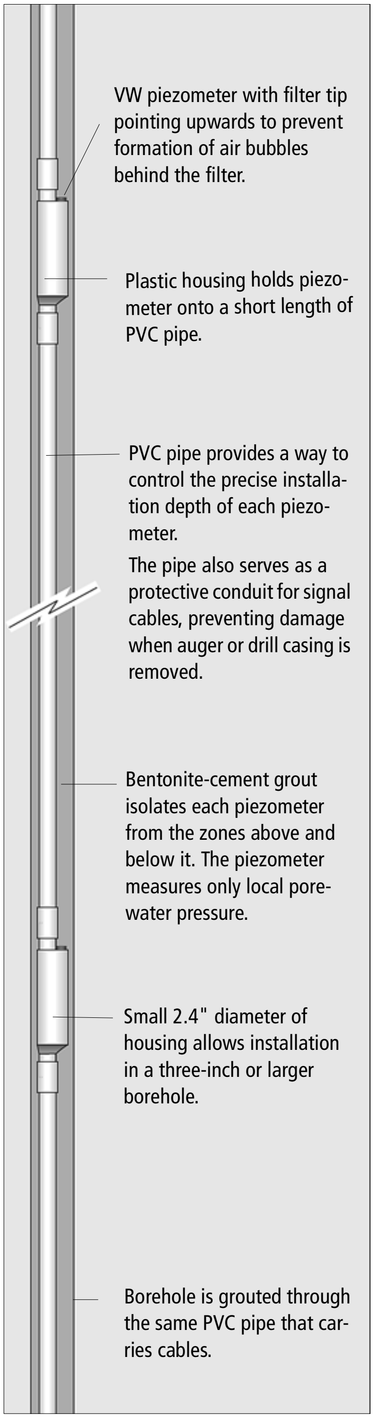
The system combines standard VW piezometers and PVC pipe. The piezometers are installed in-line with the PVC pipe. The assembled pipe controls the elevation and relative spacing of the piezometers. Signal cables run to the surface through the PVC placement pipe.

The entire assembly of pipe and piezometers is pushed into the borehole. e pipe controls the elevation and relative spacing of the piezometers. It is assembled pushed into the borehole.

When the components of the system are in place, bentonite-cement grout is pumped through the pipe to backfill the entire borehole, including the area surrounding each piezometer.

When the grout cures, each piezometer is isolated from the zones above and below it, but is highly responsive to changes in porewater pressures at its own elevation.

The multi-level piezometer shares the advantages and limitations of standard VW piezometers.



Choosing a Piezometer

All of the piezometers discussed here, whether standpipe, pneumatic, or VW, have the accuracy and resolution needed for good pore-water pressure measurements. The choice of a piezometer should be based on the factors summarized in the table below. Items with * are explained in the text following the comparison table.

Piezometer Comparison

	Standpipe	VW	Pneumatic
Range	Depth of standpipe	50, 100, 250, 500 psi	180 psi
Response Time*	Slow	Fast	Fast
Reading Time*	Minutes	Seconds	5 minutes with 200 feet of tubing. Longer times with longer tubing.
Readout*	Water level indicator. Size and weight depend on reel capacity.	Portable readout. Lightest, smallest.	Portable readout. Large and heavy because of internal tank.
Remote Access*	No. Reading is obtained at top of standpipe.	Yes. Signal cable can be run to remote readout station.	Yes. Tubing can be run to remote readout station
DataLog*	No	Yes	No
Main Advantages	Simplicity. Nothing to go wrong.	Easy to read. Simple grout-in installation. Remote access.	Remote access. Not affect by electrical transients.
Main Limitations	No remote access.	Long horizontal runs of cable should be protected from electrical transients.	Slow reading time
Main Cost of Installation	Borehole. Components are the least expensive of any type of piezometer.	Borehole. Components are more expensive than pneumatic or standpipe.	Borehole. Components are less expensive than VW piezometers.

Piezometer Response Time

Response time is relevant mainly in cohesive soils, such as clays, that do not easily release their water. When pore-water pressure changes, some volume of water flows into or out of the piezometer until an equilibrium is established between the pore-water pressure in the soil and the water in the piezometer. The time required for this equilibrium to occur is called the piezometer's response time.

Factors affecting response time are the hydraulic conductivity of the soil and the volume of water that must flow into or out of the piezometer. Diaphragm piezometers require less water and therefore have faster response time. Standpipe piezometers are intrinsically slower than diaphragm piezometers because the standpipe requires a larger volume of water. For example, a small-diameter 3/4-inch standpipe requires an inflow of 240 ml of water to show a 1 psi change in pore-water pressure. A VW piezometer, which has a very sensitive diaphragm, requires an inflow of only 0.00002 ml (12 million times smaller) to show the same 1 psi change. In highly permeable soils where water is readily available, the difference in response times may be insignificant. However, in clays and other soils where permeability is very low, the response times will be very different, making the VW piezometer or some other electric piezometer the only useful choice.

In certain conditions, the response time of a diaphragm piezometer can be slowed if there is an air bubble between the filter and the diaphragm. The air bubble must deform (change volume) before it can transmit the pressure of the water, and this requires a greater inflow or outflow of water than if there were no air bubble. In saturated soils with high permeability, the presence of a bubble has little effect, since water is in good supply, and the bubble is easily compressed. In tight soils, such as clays, response time may be slowed by the presence of a bubble, because the free water needed to compress the bubble, is scarce.

Remote Access

Measuring the water level in standpipe piezometers requires direct access to the top of the pipe. If regular and continued access is not possible, then a diaphragm piezometer, which can be operated from a remote readout station, is the only choice.

Reading Time

In general, pneumatic piezometers take longest to read. Standpipes can occasionally present problems if they are not installed straight or if false triggering occurs due to organics grow on standpipe walls. VW sensors can normally be read in seconds.

Readout

Readout size and weight become an issue because field technicians often take several readouts with them. The pneumatic indicator is the largest and heaviest. Its internal tank requires regular refills. The VW indicator is the smallest and lightest. The size and weight of the water level indicator depends on the quantity of cable on its reel. All three readouts use batteries, which must be changed from time to time.

Data Logging

Data loggers allow readings to be taken without a technician present. More important, data loggers allow many more readings to be taken, sometimes revealing trends that otherwise would go unnoticed. VW sensors are suitable for data logging. However, to read VW sensors, the data logger must have a VW interface. Pneumatic piezometers can be automated, but this is a costly undertaking and is therefore quite rare. Sometimes standpipes are adapted to data loggers by installation of a diaphragm piezometer within the standpipe. The response time for the converted standpipe will remain the same, since the pipe must still fill with water.

Note on Filters

Specifications sometimes mention the importance of saturating piezometer filters. Standpipe and diaphragm piezometers are usually equipped with a standard filter that has 50 to 60 micron pores. These filters become saturated when immersed in water without any elaborate saturation procedure.

Saturation procedures are important for special filters with smaller pores, called high air entry filters. However, these filters are not appropriate for standpipe or diaphragm piezometers.

The high air entry filter relies on the surface tension of water in its pores to sustain a pressure difference between air and water on the filter surface. This keeps air out of the measuring system (which is a fluid) and allows measurement of matrix soil suction (negative pore-water pressure) that is present in non-saturated soils. The high air entry effect is operative only when the filter is saturated with water. When water drains out of the filter, the high-air entry effect disappears.

Only one type of piezometer, the hydraulic piezometer, is capable of maintaining saturation of the filter in non-saturated soils. Diaphragm piezometers and standpipe piezometers do not normally have this capability, and therefore should not be specified with high air entry filters.

Monitoring Lateral Deformation

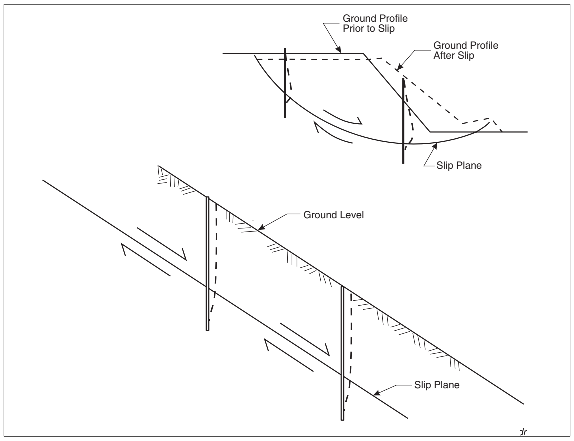
Lateral Deformation

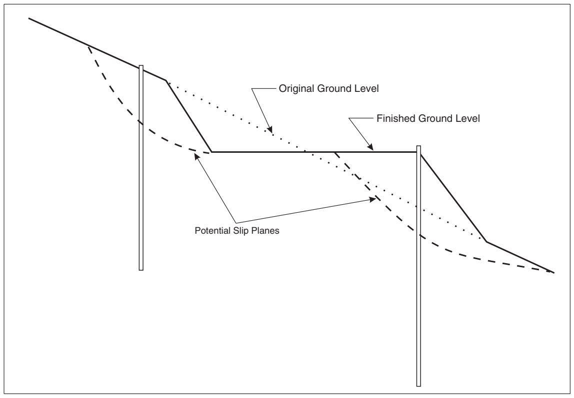
Measurements of lateral deformation help engineers to:

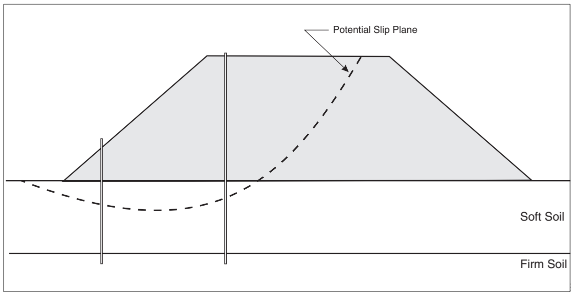
- Evaluate the stability of slopes and embankments.
- Determine the need and timing for corrective measures.
- Verify the performance and safety of structures such as retaining walls and embankments.

Landslides, Cuttings, and Embankments

- Monitor stability of slope, cut, or embankment.
- Detect shear zones and help determine whether shear is planar or circular.
- Determine whether movement is constant, accelerating, or slowing.

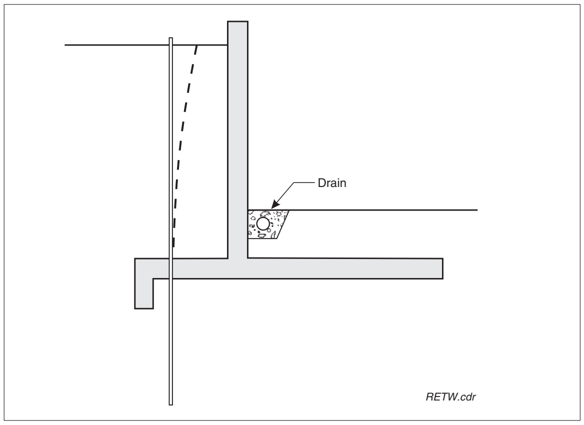






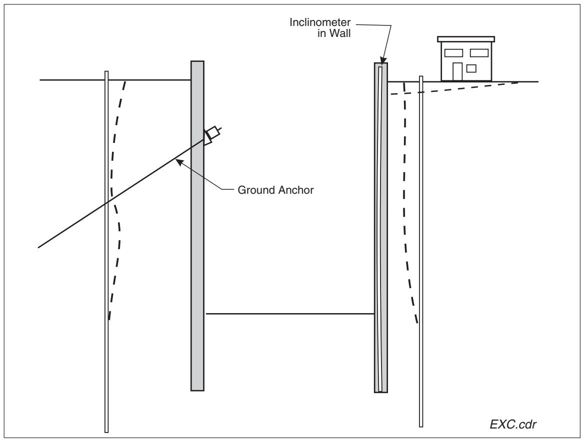
Retaining Walls

- Monitor deformation of soil behind retaining wall.
- Check for rotation of retaining wall.



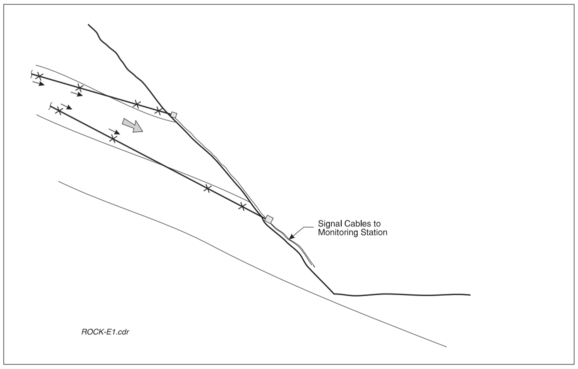
Diaphragm Wall or Sheet Pile Wall

- Check that deflections of wall are within design limits.
- Check for ground movement that may affect adjacent buildings.
- Verify that struts and ground anchors and performing as planned.



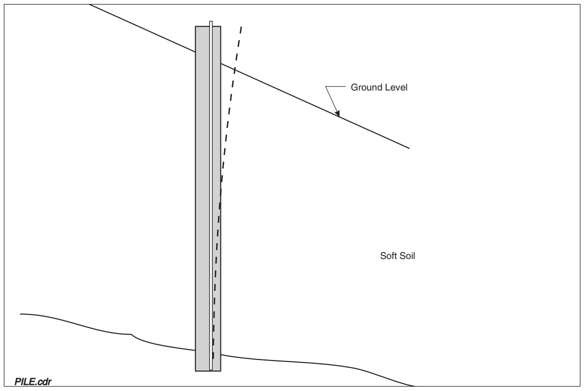
Rock Slides and Rock Abutments

- Monitor the magnitude and rate of movements in rock masses.



Pile Tests

- Monitor deformation of laterally loaded pile.
- Warn of impending failure.



Inclinometers

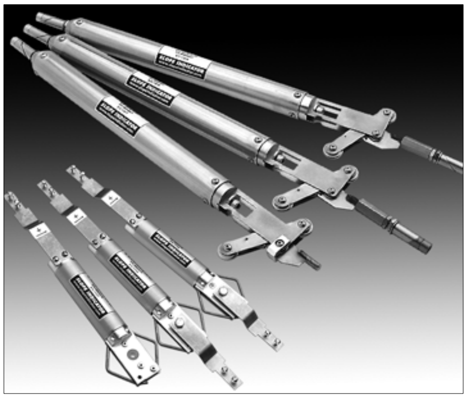
The primary instrument for monitoring lateral, subsurface deformations is the inclinometer. There are two types of inclinometer systems: the portable, traversing probe system and the dedicated, in-place sensor system. Both systems require the use of inclinometer casing.

Inclinometer Components

- Inclinometer casing is used with both types of inclinometer. This special-purpose, grooved pipe is installed in a borehole that passes through suspected zones of movement. It can also be embedded in fill, cast into concrete, or attached to structures.

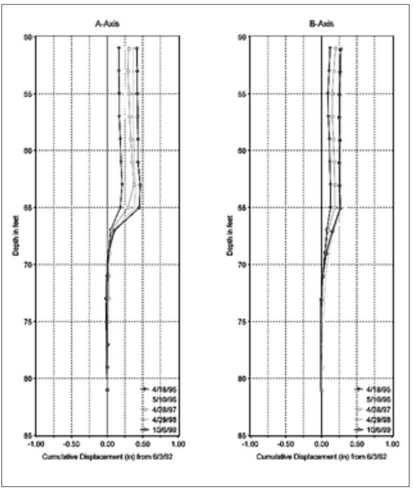
  Inclinometer casing provides access for the inclinometer probe, allowing it to obtain subsurface measurements. Grooves inside the casing control the orientation of the probe and provide a surface from which repeatable measurements can be obtained.

- The traversing probe system consists of a portable wheeled probe, graduated control cable, and a portable readout. With this system, the operator makes a survey of the borehole, taking tilt readings at two-foot intervals, from the bottom to the top of the casing to the top. The probe is then rotated 180 degrees and a second survey is obtained. The resulting data provides a detailed profile of the casing. If ground movement occurs, subsequent surveys will reveal changes in the profile. These changes can be plotted to determine the magnitude, depth, direction, and rate of ground movement.



- In-place inclinometer systems are installed when continuous monitoring is required for construction control or safety. The in-place system consists of one or more dedicated sensors connected to a data logger. The sensors are positioned to span the zones where deformation is likely to occur (a traversing probe system may be used to detect such zones).

- An optional component of an inclinometer system is software for data reduction and graphing. Inclinometers generate more data than do other types of sensors. A single survey may generate several hundred data points. Over time, tens of thousands of data points are manipulated, reduced, graphed, and archived. In-place inclinometer systems connected to data loggers generate even more data. With such systems, near-real time processing is usually a requirement as is software that shows the location of the sensors, the readings, alarm status, and trend plots.



- Another optional component is the spiral sensor, which is used to determine if the casing was twisted during installation. Spiral surveys may be appropriate when the installation is very deep or when inclinometer readings indicate movement in unlikely directions.

Choosing between Traversing and In-Place Systems

Both types of inclinometer offer sufficient resolution and accuracy for geotechnical purposes. The choice between the traversing probe system and the in-place system should be based on other factors, summarized below:

Comparison

	Traversing System	In-Place System
Full Profile*	Yes	No
Reading Time	45 minutes per 100 feet	Seconds
Remote Access*	No	Yes
Data Logging*	No	Yes
Main Advantages	Least expensive way to monitor many installations.	Only way to obtain near real-time readings and remote readings.
Main Limitations	Probe cable and readout are bulky and heavy. Reading takes time.	Long horizontal runs of cable must be protected from electrical transients.
Installation Costs	Borehole for inclinometer casing is the main cost.	Borehole for inclinometer casing is the main cost. However, sensors and logger system can cost nearly as much.
On-Going Costs	Sending a technician to read the installation is main cost.	Few on-going costs.

Full Profile

The traversing probe system yields a detailed survey of the entire length of the inclinometer casing. This allows identification of multiple shear zones and provides a context for understanding deformations in those zones.

In contrast, the in-place system provides a narrow sample of the installation. Proper positioning is critical. Often a traversing probe is used first until the shear zone has been identified.

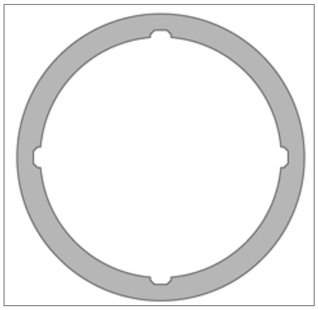
Remote Access

The traversing system requires direct access to the top of the casing for 45 minutes or more to complete a survey. If it is difficult to maintain access for this long, the in-place system is the only choice.

Data Logging

If real-time data and alarms are important, the in-place system is the only choice.

Choosing Inclinometer Casing



Casing Diameter: Casing is designed to deform with movement of the adjacent ground or structure. The useful life of the casing ends when continued movement of the ground pinches or shears the casing, preventing passage of the inclinometer probe. Large diameter casing (3.34 inch OD) is suitable for landslides and long term monitoring. Medium diameter casing (2.75 inch OD) is suitable for construction projects. It can also be used for slope stability monitoring when only a moderate degree of deformation is anticipated. Small diameter casing (1.9" OD) is suitable for applications where small deformations are distributed over broad zones. It is generally not installed in soils.

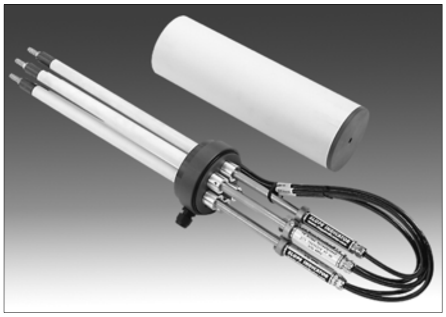
Casing Grooves: Look for machine-broached grooves. Measurement accuracy is directly influenced by the quality of casing grooves. Machine broaching of grooves allows the width and chamfer of the grooves to be optimized for the wheels of the probe. It also minimizes spiralling of the grooves.

Couplings: Look for couplings that can be sealed easily and consistently. Some designs feature O-ring seals, others feature tight-fitting surfaces that are fused together with solvent cement. Snap-together casing goes together very quickly and performs very well in most situations. That said, some driller/installers using hollow-stem augers can twist the casing out of alignment when they spin the auger to withdraw it. In such cases, cemented couplings are more suitable.

Casing Material: ABS plastic is the standard material for inclinometer casing. ABS plastic retains its shape and flexibility over a wider range of temperatures than PVC plastic. ABS plastic is much easier to handle and seal than fiberglass casing. Finally, ABS plastic is suitable for long term contact with all types of soils, grouts, and ground water, unlike aluminum casing, which is no longer recommended for any application, except possibly in environments that heat the casing above 120 degrees F.

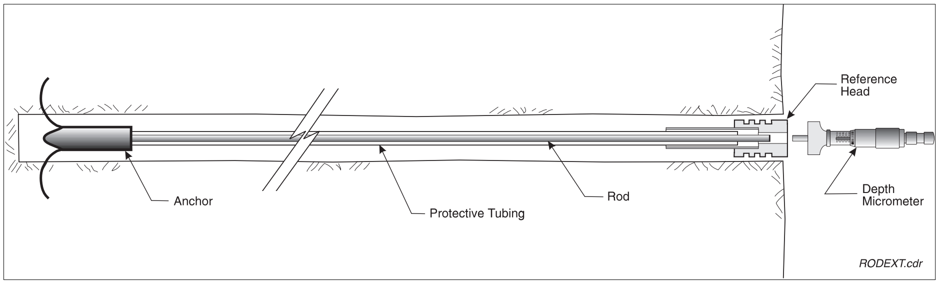
Rod Extensometers

Rod extensometers are used to monitor small displacements of soil or rock along the axis of a borehole. They can also be used to monitor lateral movement of a wall or structure.



Operation

A single-point rod extensometer, shown in the drawing below, consists of an anchor, a rod, and a reference head. The anchor, with rod attached, is installed down hole. The reference head is installed at the borehole collar. The rod spans the distance from the anchor to the reference head. A change in this distance, measured at the reference head, indicates that movement has occurred. Measurements are obtained with a depth micrometer or an electric sensor..



A multi-point extensometer consists of up to six anchors and rods monitored at one reference head. Anchors are set near different stratigraphic boundaries. Multipoint measurements can reveal the distribution of movement along the axis of the borehole in addition to the total movement as reported by the single-point extensometer.

Rod extensometers are covered in greater detail in Monitoring Vertical Deformation.

Advantages

- Provides high resolution measurements.
- Electric head allows unattended monitoring by a data logger.

Limitations

- Anchor depth is limited by rod material and orientation of rods. Free movement of horizontal rods can be restricted by friction and by pinching due to vertical movements.
- Placement is important because the rod extensometer monitors movements along the axis of a borehole. In contrast, the inclinometer can report deformation over a wide area.

Monitoring Vertical Deformation

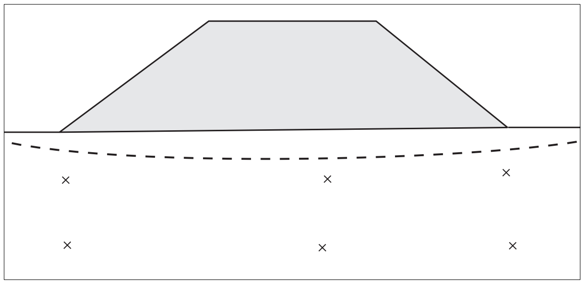
Vertical Deformation

Measurements of vertical deformation help engineers to:

- Verify that soil consolidation is proceeding as predicted.
- Predict and adjust the final elevation of an embankment.
- Verify the performance of engineered foundations.
- Determine the need and timing for corrective measures.

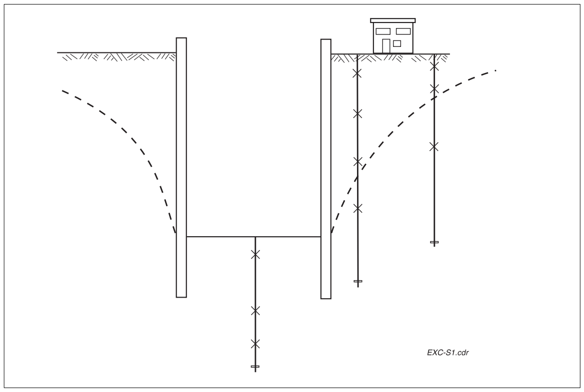
Embankment

- Monitor the progress of consolidation.
- Monitor the performance of foundation soil.



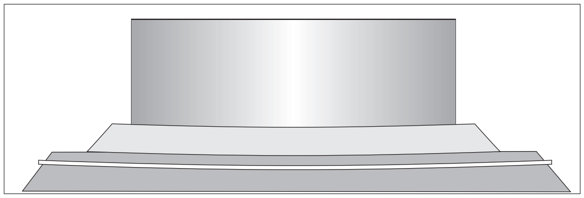
Excavation

- Monitor heave in floor of excavation.
- Monitor settlement due to ground loss or heave outside of excavation.



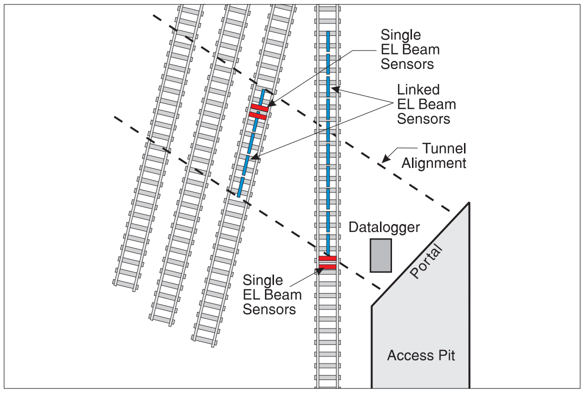
Foundations

Monitor performance of foundation under structures such as storage tanks to warn of stresses that can cause leaks or ruptures.



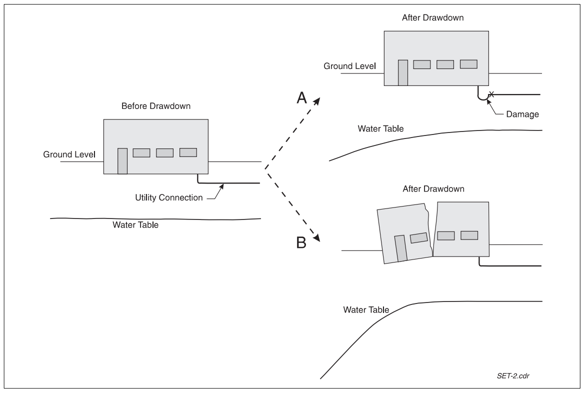
Rail and Road Beds

Monitor settlement of rail or road bed when tunnel or underpass is built.



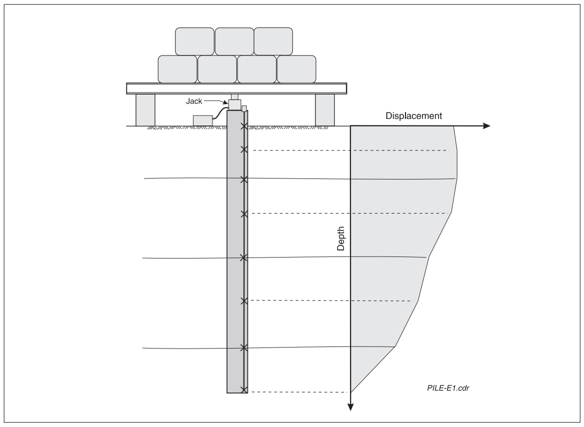
Structures

Monitor for settlements that may damage buildings or service connections. Such differential settlements may be caused by nearby excavations or dewatering operations.



Pile Test

- Monitor compression of pile.
- Monitor settlement below pile.

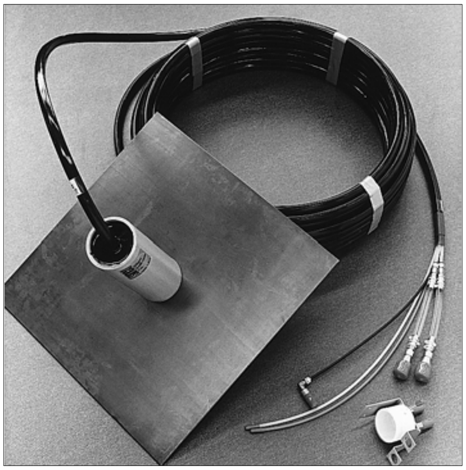


Single Point Measurements

Single point instruments provide information needed to calculate movement of a single point. These devices include:

- Settlement cells
- Settlement points or single-point extensometers.
- Settlement extensometer

Settlement Cells



The settlement cell is used to monitor a single, subsurface point.

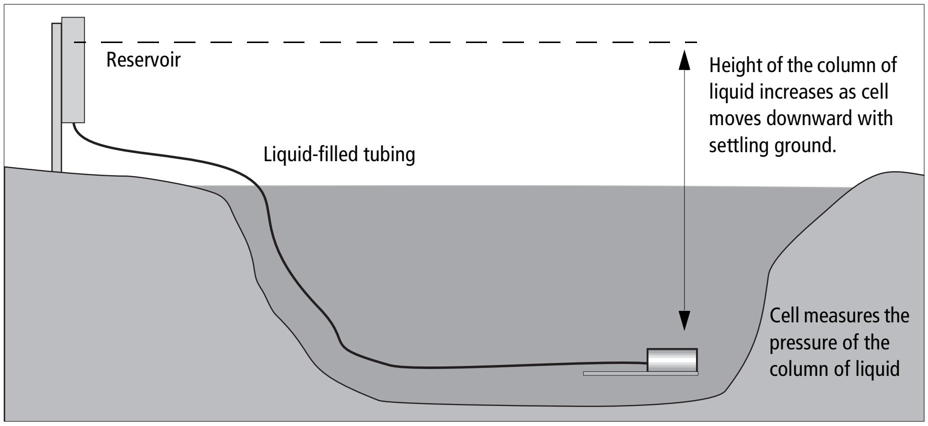
Components include a reservoir, tubing that is filled with water, and the settlement cell, which is a specially packaged VW or pneumatic pressure transducer.

The reservoir is positioned on stable ground, at a higher elevation than the cell. The cell is typically installed at the original ground surface before an embankment or fill is constructed. The water-filled tubing runs from the reservoir down to the cell. See the illustration below.

The cell measures the pressure created by the column of liquid in the tubing. As the transducer settles with the surrounding ground, the height of the column increases, and the transducer measures higher pressure.

The linear measure of settlement or heave is calculated by converting the change in pressure to millimeters or inches head of water.

Typical installation of settlement cell



Advantages

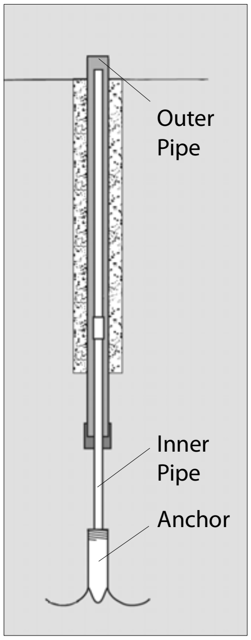
- The reservoir can be located outside the active construction area.
- Once installed, the cell and tubing are unlikely to be damaged by construction activities.
- Does not require borehole.

Limitations

- Changes in temperature affect the density of the liquid in the tubing and the pressure reported by the cell. Temperature effects can be reduced by minimizing the length of tubing above the surface and by shading the reservoir.
- Changes in atmospheric pressure will appear as movement of the cell. This effect can be eliminated by recording barometric pressure at the site or using a vented cell.

Borros Anchor Settlement Point

The settlement point consists of an anchor and two concentric riser pipes. The inner pipe, which is connected to the anchor, can move freely within the outer pipe. A change in the distance between the top of the inner pipe and the top of the outer pipe indicates movement.



Advantages

- Simplicity and economy.
- No range limits.

Limitations

- Top of pipe must be surveyed if both anchor and top of pipe are expected to move.
- Extensions to the pipe must be carefully noted.
- Measurements require direct access to top of pipe unless survey equipment is used.
- Borros anchor works best in soft clays.

Single-Point Rod Extensometers

This instrument is similar to the settlement point. Components include an anchor, a rod inside protective pipe, and a reference head. Rod extensometers are discussed in detail under MultiPoint Rod Extensometers.

Advantages

- High resolution measurements are possible (to thousandths of an inch).
- Remote reading is possible with electric version of reference head.

Limitations

- Limited range. Total range is about 10 inches, but both the depth micrometer and the electric sensors will have to be reset to obtain that range.

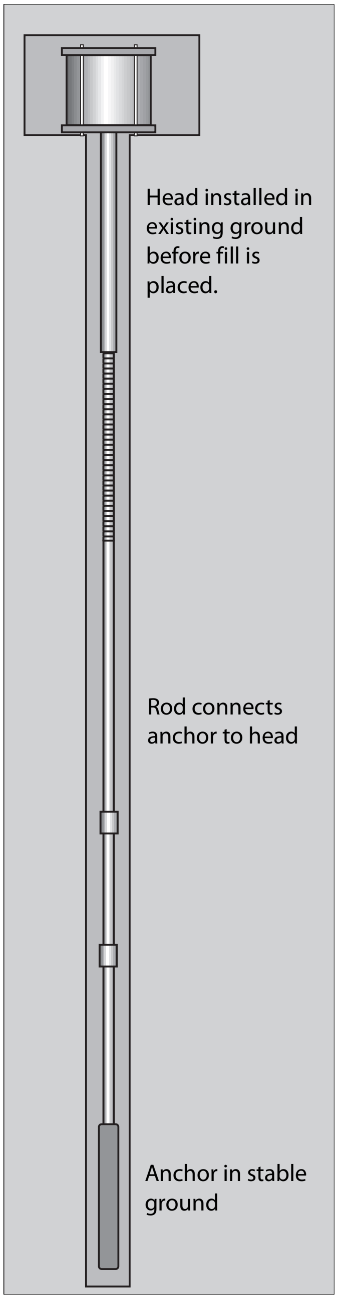
Settlement Extensometer

The settlement extensometer is a new device used to monitor large settlements in soft ground below fills. It consists of an anchor, a stainless steel rod inside protective pipe, and a potentiometer inside a waterproof head.

A borehole is drilled from the elevation of interest down to competent ground. The anchor and rod are installed downhole. The borehole is then backfilled with a soft grout.

A small excavation is made for the head. The head is then attached to the rod, tested, and then covered with at least six inches of hand-compacted sand. Signal cable from the extensometer is then connected to a data logger.

As the ground settles with the placement of fill, the head moves downward. The potentiometer inside the head measures take-up of a tensioned wire. Readings are obtained remotely, either by a portable readout or a data logger.



Advantages

- Range is 25 inches or more.
- High resolution measurements (thousandths of an inch).
- Remote readout

Limitations

- More expensive than settlement cell or single-point rod extensometer.

Comparison of Single Point Systems

	Settlement Cell	Settlement Point	Rod Extensometer	Settlement Extensometer
Range	10s of feet	1 to 2 feet	2 to 4 inches	25 inches or more
Accuracy	Inch	Fractional inch	Thousandths of inch	Hundredths of inch
Duration	Typically short term	No restriction	No restriction	No restriction
Remote Reading	Yes	No	No (mechanical head) Yes (electric head)	Yes
Data Log	No (Pneumatic cell) Yes (VW cell)	No	No (mechanical head) Yes (electrical head)	Yes
Advantages	No interference with construction activities.	Simple	High resolution measurements	No interference with construction activities.
Main Limitation	Reservoir must be higher elevation than cell.	Pipe obstructs activities.	Small range.	More expensive than other systems
Main Cost	Components Cell is generally not installed in boreholes.	Borehole. If constructed through fill, components are main cost.	Borehole.	Borehole.

Comparison of Multi-Point Systems

	Sondex	Magnet Extensometer	Rod Extensometer	Horizontal Inclinometer	Horizontal In-Place Inclinometer
Monitors	Vertical Profile	Vertical Profile	Vertical Profile	Horizontal Profile	Horizontal Profile
Range	Large deformations	Large deformations	2 to 4 inches	25 inches or more	25 inches or more
System Accuracy	Fractional inch	Fractional inch	Thousandths of inch	Fractional Inch	Fractional Inch
Remote Reading	No	No	No (mechanical head) Yes (electric head)	No	Yes
Data Log	No	No	No (mechanical) Yes (electrical)	No	Yes
Advantages	Works with inclinometers	Works with 1” pipe or inclinometers	High resolution measurements	Monitors settlement over a broad area	Monitors settlement in critical areas.
Main Limitation	No remote reading	No remote reading	Small range	Friction becomes factor in lengths over 300 feet	Expensive
Main Cost	Borehole for inclinometer casing.	Borehole for inclinometer casing or access pipe..	Borehole	Trench or borehole.	Trench or borehole. Components can be expensive.

Multi-Point Measurements

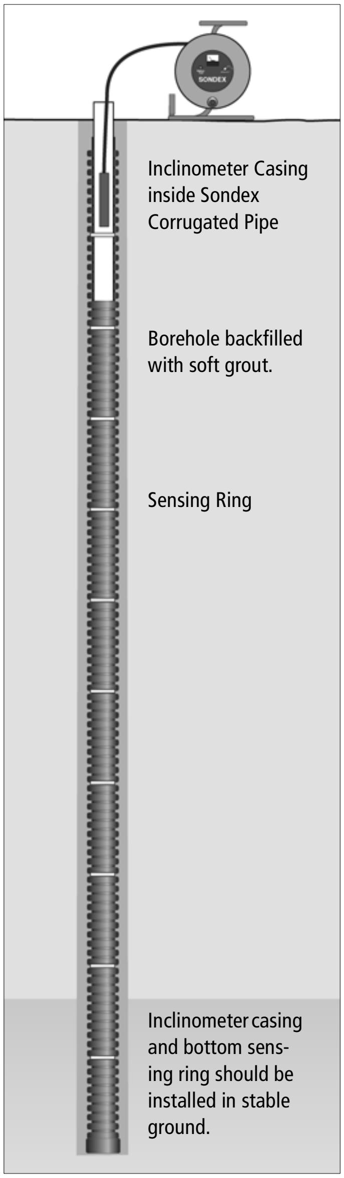
Multi-point instruments provide information needed to calculate vertical or horizontal profiles of settlement. These devices include:

- Sondex and Magnet Extensometer
- Multi-Point Rod Extensometer
- Horizontal Inclinometer

Sondex Settlement System

Sondex is a multi-point extensometer system that is installed with inclinometer casing.

The Sondex system consists of a portable readout, sensing rings, and Sondex pipe, a flexible, non-perforated, corrugated drain pipe. Before installation, the sensing rings are attached to the drain pipe at regular intervals or at depths of interest.



The Sondex pipe and inclinometer casing are usually installed at the same time. Soft grout backfill couples the Sondex pipe to the surrounding ground, so that the pipe and rings move with settlement or heave.

The readout consists of a reel with a built-in voltmeter, a cable, and a probe. To obtain measurements, the operator draws the probe, with a survey tape attached, up through the inclinometer casing. The buzzer sounds when the probe nears a ring, and the voltmeter peaks when the probe is aligned with the ring. The operator then refers to the survey tape and records the depth of the ring.

Readings are referenced to the bottom ring, which is assumed to be in stable ground. Settlement and heave are calculated by comparing the current depth of each ring to its initial depth.

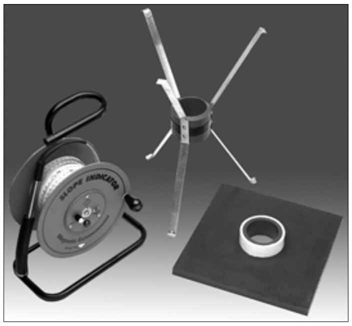
Advantages

- Can provide detailed settlement profile.
- Makes double use of a borehole, supplementing inclinometer data.

Limitations

- Can be difficult to install.
- Good readings require careful operator.

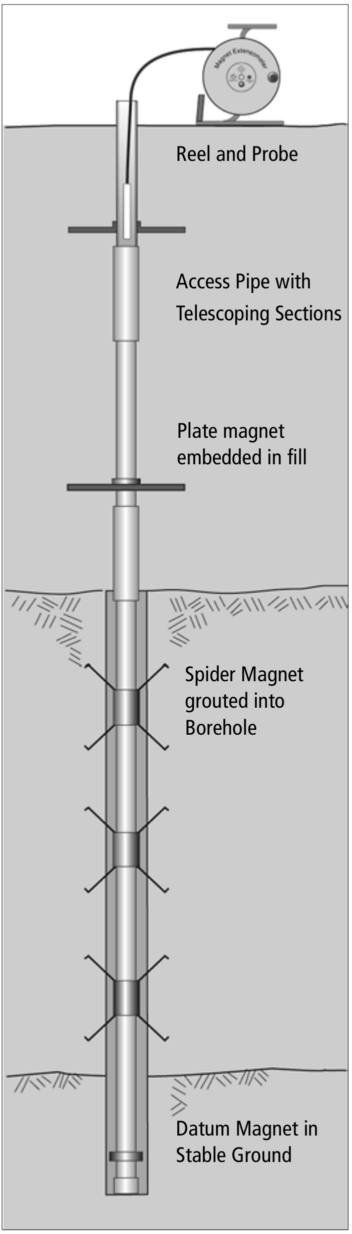
Magnet Extensometer



The magnet extensometer is a multipoint extensometer that can be installed with inclinometer casing or with 1-inch access pipe.

The system consists of a probe, a steel measuring-tape, a tape reel with built-in light and buzzer, and a number of magnets positioned along the length of an access pipe.

Three types of magnets are available: a datum magnet, which is installed at the bottom of the access pipe, a spider magnet, which is used in boreholes, and a plate magnet, which is used if the extensometer is being built up through fills. Telescoping joints are required to accommodate settlement.



The magnets move with settlement or heave of the surrounding ground.

Readings are obtained by drawing the probe through the access pipe to find the depth of the magnets. When the probe enters a magnetic field, a reed switch closes, activating the light and buzzer on the reel at the surface. The operator then refers to the 1 millimeter or 0.01' graduations on the tape and notes the depth of the magnet.

Settlement and heave are calculated by comparing the current depth of each magnet to its initial depth. Movement is generally referenced to the datum magnet at the bottom, which is anchored in stable ground.

Advantages

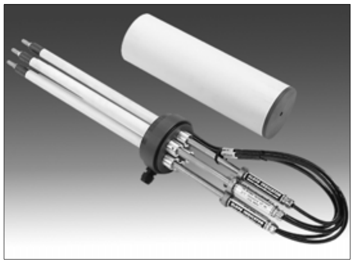
- Supplements inclinometer data, if installed with casing.
- Simpler installation than Sondex.

Limitations

- Good readings require careful operator.
- Remote readings are not possible.

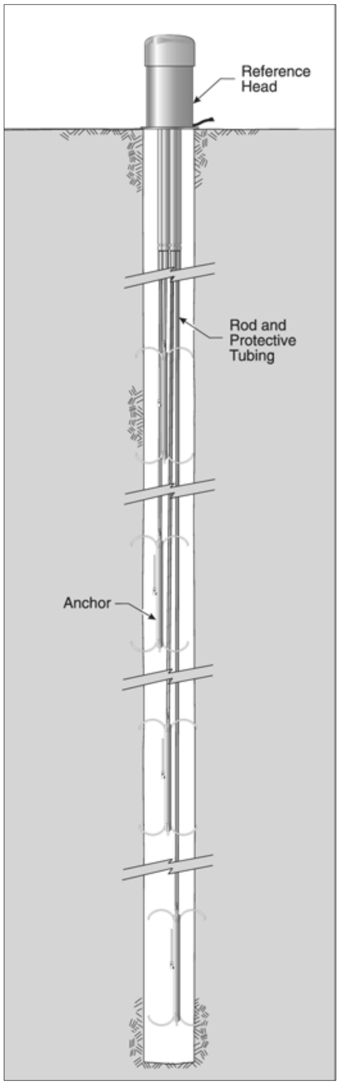
MultiPoint Rod Extensometers

The multipoint rod extensometer provides high resolution multipoint measurements of vertical deformation.



The main components of a rod extensometer are anchors, rods inside protective pipe, and a reference head.

The anchors are installed downhole with rods attached. The rods span the distance from the downhole anchors to the reference head at the surface. The protective plastic pipe prevents bonding between rods and grout backfill. Readings are obtained at the reference head by measuring the distance between the top of the rod and a reference surface. A change in this distance indicates movement has occurred.



Movements are referenced to a stable elevation, typically a downhole anchor. The resulting data can be used to determine the zone, rate, and acceleration of movements, and to calculate strain.

Components

Anchors re selected to match field conditions. The groutable anchor is suitable for rock and is sometimes used in soils; the hydraulic anchor, shown at right, is suitable for soft soil; and the packer anchor can be used in either rock or soil.

Rods are made of fiberglass or stainless steel. Fiberglass rod extensometers are assembled at the factory and shipped to the site, ready to install. The flexibility of these extensometers also makes them easier to install in confined areas, such as tunnels. Stainless steel rod extensometers must be assembled on site. However, their stiffer rods can be used for deeper anchor depths.

In general, rods in tension can be longer than rods in compression, and steel rods can be longer than fiberglass rods. In non-vertical installations, friction between rods and the protective pipe becomes a limiting factor.

The table below suggests maximum lengths for rods in tension and compression.

Max Rod Length: Tension / Compression		
Orientation	Fiberglass	Steel
Vertical Down	20 / 15 m	40 / 30 m
Vertical Up	45 / 30m	60 / 45 m
45° Down	25 / 20 m	40 / 30 m
45° Up	35 / 25 m	55 / 40 m
Horizontal	35 / 20 m	45 / 30 m

Reference Heads: Mechanical reference heads can be used when there is easy access to the extensometer. Measurements are obtained with a depth micrometer.

Electric reference heads are used when access to the reference head is difficult or where continuous monitoring is required. In this case, measurements are obtained with displacement sensors and a readout or data logger.

Advantages

- High precision measurements.
- Remote readings possible with electric sensors.
- Fiberglass rod extensometer is prefabricated at the factory and shipped ready to install.

Limitations

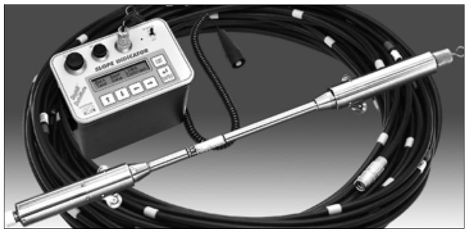
- Narrow range, typically 1 to 4 inches.

Horizontal Inclinometer

The horizontal inclinometer provides a horizontal profiles of settlement. Traversing probe and dedicated in-place systems are available.

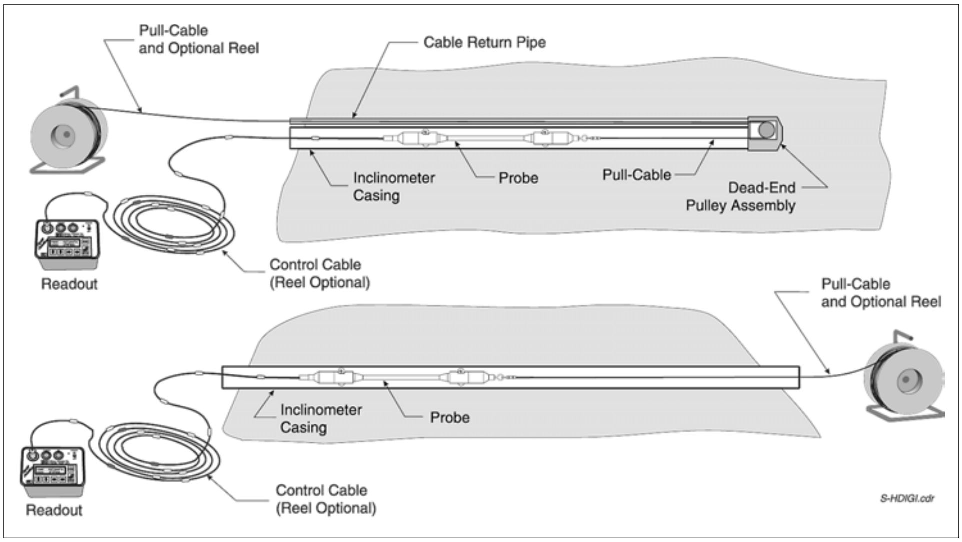
Components

Inclinometer casing is used with both types of horizontal inclinometer. 3.34 inch diameter casing is required for the traversing probe and either 3.34 or 2.75 casing can be used with the in-place system. Horizontal installations of casing are typically installed in a trench, but may also be installed in a horizontal borehole. Grooves inside the casing control the orientation of the probe. One set of grooves (top and bottom) must be aligned with vertical. Telescoping sections are generally not needed.



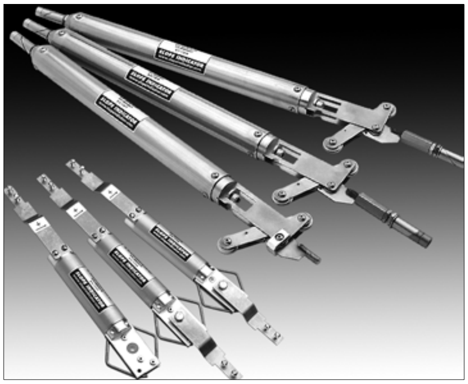
The traversing probe system consists of a portable wheeled probe, graduated control cable, a pull wire, and a portable readout. With this system, the operator makes a survey of the borehole, taking tilt readings at two-foot intervals, from the far end to the near end of the casing. The probe is then turned end for end a second survey is obtained. The resulting data provides a detailed profile of the casing. If ground movement occurs, subsequent surveys will reveal changes in the profile.

The drawing below shows how the horizontal inclinometer is used when there is access from both ends or just one end.



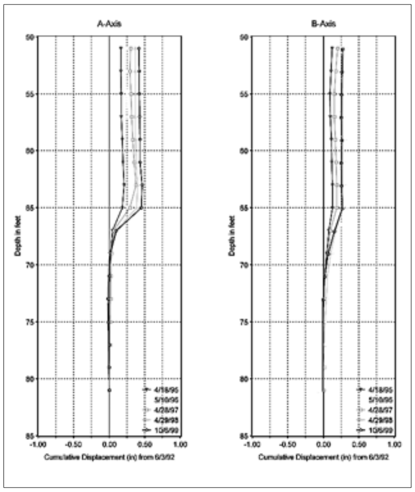
Components Continued

In-place inclinometer systems are installed when continuous monitoring is required for construction control or safety. The in-place system consists of one or more dedicated sensors and a data logger. The sensors are positioned to span the zones where deformation is likely to occur. The photo shows the less expensive but non-retrievable sled sensors (lower left) along with the larger, standard IPI sensors.

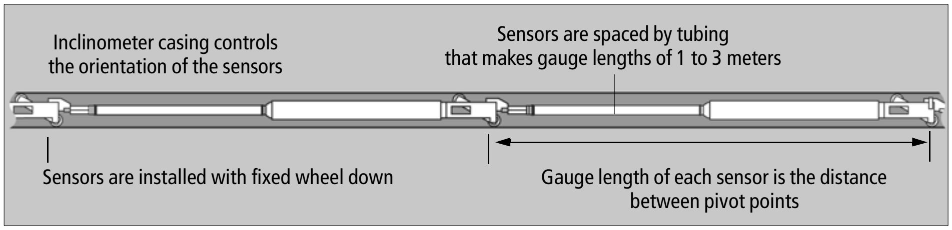


Data reduction software is a useful component of either inclinometer system. Inclinometers generate more data than do other types of sensors. A single survey may generate several hundred data points. Over time, tens of thousands of data points are manipulated, reduced, graphed, and archived.

In-place inclinometer systems connected to data loggers generate even more data. With such systems, near-real time processing is usually a requirement as is software that shows the location of the sensors, the readings, alarm status, and trend plots.



The drawing below shows how horizontal in-place sensors are configured:



Advantages

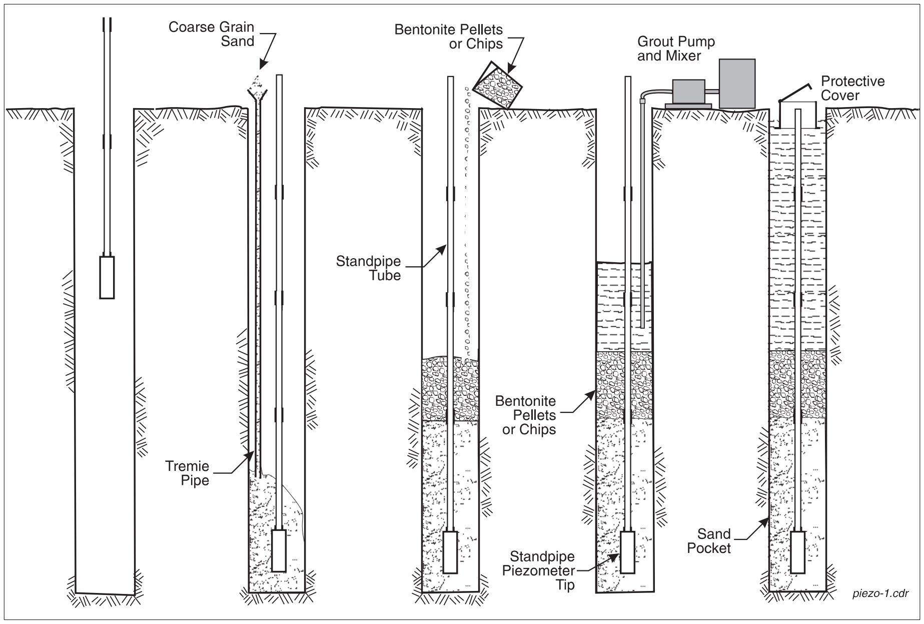
- Provides profile of settlement over broad area.
- Does not interfere with site operations
- In-place version provides real-time data when connected to data logger.

Limitations

- Traversing system takes time to read. Friction becomes a factor in casing over 300 feet long.
- Complete coverage with in-place system is expensive.

Installing Piezometers

Standpipe Piezometers



1. Drill the borehole slightly below the required depth of the piezometer. Flush the borehole with water or biodegradable drilling mud.

2. Form a sand intake zone by placing sand at the bottom of the borehole. Tremie wet sand to the bottom. Sand should be graded number 80 to number 10 US sieve size in most soils.You must pull drill casing upwards to keep it above the level of the sand. When the sand reaches the required depth of the filter tip, lower the filter element and the attached riser pipe downhole, assembling the pipe as you go.When the standpipe is in place, tremie sand around the filter tip, again pulling the casing to keep it above the level of the sand. Place at least 6 to 12 inches of sand above the tip.

   If you are using a well point and installing the piezometer in soft ground, it is sometimes possible to push the point into position. In this case, the sand intake zone is not required. In clay, a pushed or driven piezometer shears and remolds the clay adjacent to the porous element. This can lead to erroneous measurements of in-situ pore pressures. Note that the action of pushing or driving may set up high excess pore-pressures, which in soils of low permeability may take a long time to dissipate.

3. Place a bentonite seal above the intake zone, using bentonite chips. A typical seal is typically 1.5 feet thick, but refer to project specifications. Again, be sure to pull the casing up above the level of the bentonite. Drop chips in slowly to ensure proper placement of the seal and to avoid bridging. The bentonite seal typically requires 2 to 3 hours to set up, but refer to your bentonite instructions for exact times. Keep the borehole filled

with water to fully hydrate the bentonite and prevent it from drawing water from the surrounding soil.

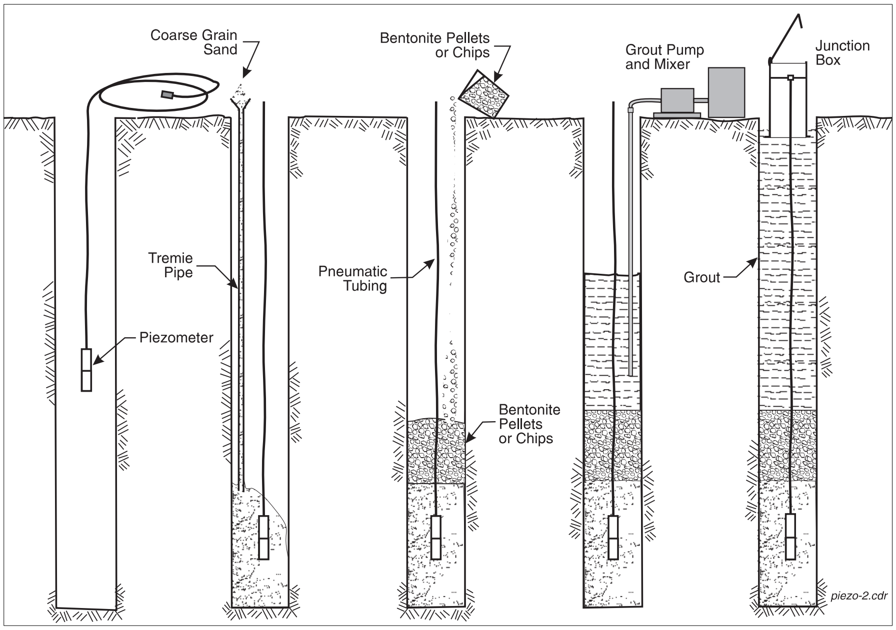
4. Fill the remainder of the borehole with a bentonite-cement grout. Use a tremie pipe to place the grout starting a foot or two above the bentonite seal and then slowly raising the tremie pipe (and the drill casing, if any) as the level of the grout rises. The exact mix of the grout will vary and you should follow project specifications if available. It is important that the constituents of the mix not segregate and that the grout is easily pumped. A typical mix might be four parts bentonite mixed thoroughly with eight to twelve parts water, to which is added one part of ordinary Portland cement. Special mixes and chemical additives may be necessary if the grout is to be used in sea water or very acid water.

5. Terminate the installation as specified. The top 1.5 feet of the borehole should be sealed with a cement grout to prevent entry of rainwater and other surface runoff. A well-drained, lockable surface box should be provided for every piezometer installation.

6. Readings taken after completion of the installation should be treated with caution, as it is unlikely that equilibrium will have been re-established, especially if mud rotary drilling methods were used. A datum reading can be taken 24 hours to several days after installation, depending on the permeability of the soil. Take readings periodically to determine when recovery has occurred. Water level readings should be performed in accordance with ASTM Standard D-4750, "Determining Subsurface Liquid Levels in a Borehole or Monitoring Well."

7. After installation, a response test should be conducted on each piezometer, where possible, to check the adequacy of the installation. The response test may be of the falling head type with the results presented on falling head permeability test results sheets. Unexpected results in a response test may indicate that the piezometer is defective. Similar response tests carried out at intervals during the life of the piezometer are recommended to ensure that the head used in response tests does not cause hydraulic fracture in the soil.

Pneumatic Piezometers



1. Drill the borehole below the required depth of the piezometer. Flush the borehole with water or biodegradable drilling mud.
2. Form the bottom of the sand intake zone. Tremie the wet sand into place.
3. Hold the piezometer in a bucket of water, filter side up, and shake it to dislodge air between the filter and the diaphragm. Note that in tight soils, it may be beneficial to keep some air between the filter and diaphragm. Activation of the piezometer forces the diaphragm outwards. If no bubble is present, the diaphragm must push water into the soil. However, if a bubble is present, the diaphragm has only to compress the air bubble rather than force water into the soil, so the reading is obtained quickly.
4. Lower the piezometer and its tubing to its specified depth. You will have to add weight to the piezometer to lower it into a water filled borehole. Sometimes the piezometer is placed in a sand-filled canvas bag, which serves two purposes: it creates part of the sand intake zone and it serves as a weight to help sink the piezometer and its tubing.
5. Tremie sand around the piezometer. Continue until at least six inches (150 mm) of sand has been placed above the piezometer. You may have to pull the drill casing upwards to keep it above the level of sand.
6. Place a bentonite seal above the intake zone, using bentonite chips. A typical seal is at least one foot thick, but refer to project specifications for the required length. Again, be sure to pull the casing up above the level of the bentonite. Drop chips in slowly to ensure proper placement of the seal and to avoid bridging. Be sure to pull the drill casing upwards to prevent the seal from setting inside the casing.

7. The bentonite seal typically requires 2 to 3 hours to set up, but refer to your bentonite instructions for exact times. Keep the borehole filled with water to fully hydrate the bentonite and prevent it from drawing water from the surrounding soil.

8. Backfill with a bentonite-cement grout. (Step 6 and 7 could be eliminated if the backfill contains adequate amounts of bentonite. See notes on grouting-in VW piezometers below.)

9. Terminate the installation as specified. It is important to terminate the tubing above ground level and keep quick connectors clean and dry. Protect the installation from construction traffic and mark its location with a stake.

10. Drilling a borehole and backfilling it temporarily changes the pore-water pressure in the ground, so readings taken immediately after installation will not be good datum readings. Recovery of the natural pore-water pressure make take a few hours to a few weeks, depending on the permeability of the soil. Recovery is indicated by stable readings over a period of a few days. A datum reading can then be obtained.

VW Piezometers

Vibrating wire piezometers have traditionally been installed in the same manner as pneumatic piezometers or standpipe piezometers. A sand intake zone is tremied around the piezometer and then sealed with bentonite. The remainder of the hole is then filled with a bentonite cement grout.

Grout-In Installation

As mentioned above, the volume of water required to operate a VW piezometer is so small that the VW piezometer needs no sand intake zone. Instead, the borehole can be backfilled directly with a bentonite cement grout. This simplifies installation and opens the possibility of same-hole installation of multiple piezometers or piezometers with inclinometer casing. The grout-in procedure is described below:

1. Drill the borehole below the required depth of the piezometer. Flush the borehole with water or biodegradable drilling mud.

2. Prepare the piezometer: Submerse the piezometer in a bucket of clean water, pull off the filter to allow air to escape from the piezometer, then replace the filter. Hold the piezometer with filter end up to prevent water from draining out.

3. Tie the piezometer to its own signal cable. This puts the filter end upward and makes a loop in the signal cable. Lower the piezometer, filter-end up, into the borehole. In shallow boreholes, you can push the looped cable and piezometer to its intended depth with a plastic pipe. This helps you confirm that the piezometer is at its intended depth. In deeper boreholes, you may need to add weight to the piezometer. If you install the piezo-

meter along with inclinometer casing, tape the piezometer, filter-end up, to the casing. Stay away from the coupling area.

4. Back-fill the borehole with bentonite-cement grout. The grout mixes that we suggest for our inclinometer casing, shown below, have also been tested for this application with good results. While specifications usually state that the grout should have a permeability the same as the surrounding ground, testing has shown that permeability of the grout can be an order of magnitude higher than the surrounding formation. Radial pressure gradients from the borehole wall to the piezometer are normally one to several orders of magnitude higher than those produced vertically through the grout from another strata. Radial pressure gradients, not vertical gradients, will control the response of the piezometer.
5. Readings taken immediately after installation will be high, but will decrease as the grout cures. Datum readings can be taken hours to days after installation, depending on the permeability of the soil. The lag time caused by the grout itself is measured in minutes.
6. Terminate the installation as specified. It is important to terminate the cable above ground level in a waterproof enclosure or with a waterproof connector. Protect the installation from construction traffic and mark its location with a stake.

Grout Mixes

Grout Mix For Hard and Medium Soils		
Materials	Weight (US Units)	Ratio by Weight
Portland Cement	94 lb (1 bag)	1
Water	30 gallons	2.5
Bentonite	25 lb (as needed)	0.3

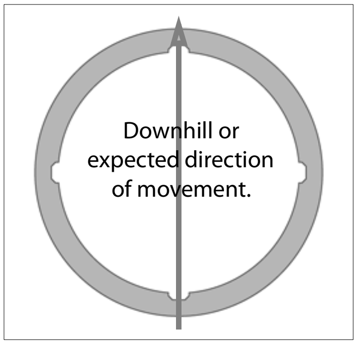
Grout Mix For Soft Soil		
Materials	Weight (US Units)	Ratio by Weight
Portland Cement	94 lb (1 bag)	1
Water	75 gallons	6.6
Bentonite	39 lb (as needed)	0.4

Use the mixes above as a starting point. Modify them as needed. Mix cement with water first, then mix in the bentonite. (Drillers are accustomed to mixing water and bentonite first). Adjust the amount of bentonite to produce a grout with the consistency of heavy cream. If the grout is too thin, the solids and the water will separate. If the grout is too thick, it will be difficult to pump. There is no particular amount of bentonite that you must add. Both of these mixes have been used for combined installations of piezometers and inclinometers.

Installing Inclinometer Casing

Planning

Depth: Casing should be installed 10 or 20 feet into stable ground. Readings from this part of the casing should never show movement and thus act as a check on the condition of the inclinometer probe. If casing is to be installed behind a sheet pile wall or diaphragm wall, specify a depth that is 10 feet deeper than the bottom of the wall. This provide assurance that the base of the wall is stable.



Orientation: Installation specifications should include the orientation of the casing. In general, one set of (opposed) grooves should be aligned with the direction of expected movement, typically downhill or towards the area of excavation. This makes data interpretation easier because most of the movement can then be captured in one axis. Precise orientation is not necessary. Even if the orientation is off 10 degrees, the inclinometer's A axis reading will still capture 98% of the magnitude of the total movement.

Verticality and Straightness: Inclinometer sensors work best in casing that is installed within 3 degrees of vertical. The likelihood of systematic errors increases with the tilt of the casing. Straightness is also important for error free data. Wavy casing makes depth control of the probe much more critical, increasing the likelihood of error. Wavy casing can be avoided. See the section below on countering buoyancy.

Settlement: Settlement affects both inclinometer casing and inclinometer readings. ABS inclinometer casing can accommodate 2% settlement or even more if it occurs over a number of years. However, if settlements greater than 2% are expected to occur within a short period of time, the casing should be supplied with telescoping sections for zones in which settlement is likely to occur. Alternatively, casing can be installed within corrugated drain pipe, which decouples the casing from the grout backfill and the surrounding ground.

When settlement occurs, the overall length of (vertically installed) casing decreases. This introduces error into inclinometer data. Thus it is important to have a way to measure settlement so that corrections can be made. Settlement sections may be installed with magnets (for magnet extensometers) or sensing rings (for Sondex systems), both of which must be installed at the same time as the casing. Alternatively, settlement can be measured by various hook-type instruments, which are lowered into the casing and latch onto the edges of the telescoping section. If the corrugated drain pipe method is used, sensing rings are attached to the drain pipe and settlement is measured with the Sondex system.

Termination: The casing installation should be protected from traffic, vandalism, and debris. In some locations, a locked cap may provide sufficient protection. In other locations, a locking steel enclosure or a monument case may be required. Keep in mind that the inclinometer user will want to attach a pulley assembly to the top of the casing. If the top of the casing is deep inside the protective enclosure, the user will not be able to attach the pulley. Ideally, the enclosure should be installed so that the top of the casing is only an inch or two below the top of the enclosure. When the top of the casing is deeper, the enclosure must provide 10 inches of clearance, measured from the outside of the inclinometer casing, so that the pulley can be attached.

Grout and Casing Buoyancy: During installation, when the grout is still a fluid, it exerts an uplift force on the bottom cap of the casing. This uplift force is greater than the down force exerted by the weight of the casing and even the weight of water-filled casing. If no counter-measures are taken, the uplift force can push casing out of the borehole. The net uplift can be calculated as the density of grout minus the density of water filled casing x depth of casing x area of bottom cap. Lateral forces do not contribute to uplift.

Unfortunately, the easiest way to keep the casing in place is also the worst way: holding the casing down from the top. The uplift force acts on the bottom of the casing, and if the casing is held in place from the top, the casing goes into compression. When the casing goes into compression, it tends to snake from side to side in the borehole. This problem is particularly severe in large diameter boreholes and in deep installations, where the uplift force is largest and where portions of the borehole may be enlarged. Snaked casing increases the potential for kinked or separated joints which render the installation useless. Snaked casing also increases the likelihood of data errors, due to slight variations in the positioning of the inclinometer probe. Better ways to counter buoyancy are:

1. Suspend a steel pipe or drill rods inside the casing. For the best results, suspend the pipe just an inch or so off the bottom cap of the casing.This ensures that the steel pipe remains straight and avoids resting the full weight of the pipe on the bottom cap. As the casing rises to meet the pipe, the down force of the pipe is activated to keep the casing in place. The main drawback to this method is that you must use the drill rig to suspend the pipe or you must return with the drill rig to retrieve the pipe. A variation is to rest the pipe on the bottom cap, which you must reinforce.
2. Pre-install an anchor at the bottom of the casing. Simple prong anchors or packer types have been used. Different soils may require different types of anchor.

3. Grout the borehole in stages. The uplift force of grout varies with the height of the grout column. If the column is short, the uplift force is low and the casing can be held in place by its own weight or with very little down-force applied from the top. When the grout sets, the bottom cap is isolated from the column of grout and there is no surface for the uplift force to act on. No more than two or three meters to 3 m need to be grouted in the first stage.
4. Fill the casing with drilling fluid that is heavier than the grout. This is a sure and easy method, but requires disposal of the drilling fluid. One of the COE districts uses this approach.

Grouting

Grout is preferred over sand or gravel backfill. Grout is dimensionally stable and also prevents unwanted migration of water between soil zones. Grout can be delivered by tremie pipe or by a grout valve. You will need a mixer, a grout pump, a pipe or hose for delivering the grout, and, optionally, a grout valve. If there is room for the tremie pipe in the annulus between the casing and the borehole wall, grout can be tremied into the borehole. When there is no room for a tremie pipe, a grout valve can be used. This one-way valve is attached to the bottom section of casing. A grout pipe is lowered through the casing to mate with the grout valve and deliver the grout. The borehole must be slightly deeper to accommodate the grout valve, which must not be pushed into the soil. In very deep holes, the pressure of grout will be too great for the casing, so the borehole must be stage grouted, and a grout valve is useful for the first stage.

Grout Mixes

In theory, the strength of the grout used to backfill the borehole should match the strength of the surrounding ground. However, the properties of grout and soil are so different that only a rough match is possible. The key thing to remember is that the cement-water ratio controls the strength of the grout. To decrease the strength of the grout, add more water.

Use the bentonite-cement grout recipes below as a starting point. Modify them as needed. Both recipes specify that you mix cement and water first. Drillers are accustomed to mixing water and bentonite first. However, this does not allow you to control the water-cement ratio.

Mix cement with water first, then mix in the bentonite. Adjust the amount of bentonite to produce a grout with the consistency of heavy cream. If the grout is too thin, the solids and the water will separate. If the grout is too thick, it will be difficult to pump. There is no particular amount of bentonite that you must add. The thickness of the grout varies with alkalinity of the water, temperature, and agitation, so the amount of bentonite required will also vary.

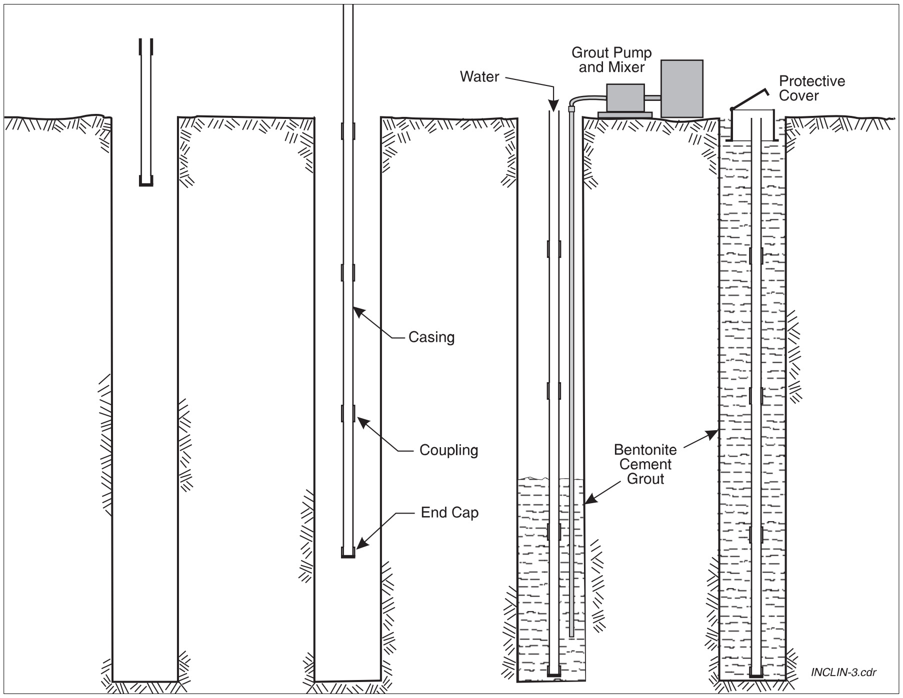
Both of these mixes have been used for combined installations of piezometers and inclinometers.

Grout Mix For Hard and Medium Soils		
Materials	Weight (US Units)	Ratio by Weight
Portland Cement	94 lb (1 bag)	1
Water	30 gallons	2.5
Bentonite	25 lb (as needed)	0.3
28-day compressive strength is about 100 psi (similar to hard clay). Modulus is 10,000 psi		

Grout Mix For Soft Soil		
Materials	Weight (US Units)	Ratio by Weight
Portland Cement	94 lb (1 bag)	1
Water	75 gallons	6.6
Bentonite	39 lb (as needed)	0.4
28-day compressive strength is about 4 psi		

Vertical Installation

Store casing horizontally, fully supported and out of the sunlight. To ensure that the correct length of casing is installed, some installers number each length of casing and then assemble the casing numerically.



1. Drill the borehole to the depth specified. A larger diameter borehole is required if you plan to tremie the grout. A smaller borehole is possible if you plan to use a grout valve. If you plan to use a grout valve or some type of casing anchor, drill the borehole deep enough to accommodate this. In some situations, drilling mud alone will keep the borehole open. If you

must use a hollow stem auger or drill casing to keep the hole open, keep in mind that casing must not be twisted after it is in the borehole.

2. Verify the depth of the borehole. Then install casing to the specified depth. Maintain the alignment of one set of grooves with the expected direction of movement throughout the installation process.

   If the borehole is filled with water, you must fill the casing with clean water as you assemble it. If the borehole is dry, attach a safety line to the bottom of the casing to prevent it accidently slipping downhole and do not fill the casing with water during assembly.

3. When the assembled casing reaches the proper depth, verify proper tracking with a dummy probe. If the dummy probe returns in a different set of grooves or if it does not reach the bottom, the casing should be pulled and repaired.

4. Prepare for grouting. If you plan to tremie the grout (Fig 10-17), cap the open inclinometer pipe, then work the tremie pipe downhole. If you are using a grout valve (Fig 10-16), lower the grout pipe into the casing to mate with the grout valve. Follow the manufacturer's procedures for the grout valve. Check for lumps in the grout that could block the valve.

5. Begin grouting. Grout to the level specified. Drill casing or hollow stem augers must be withdrawn without rotation as the grout is placed. In general, continue grouting until the surface of the grout is ground level.

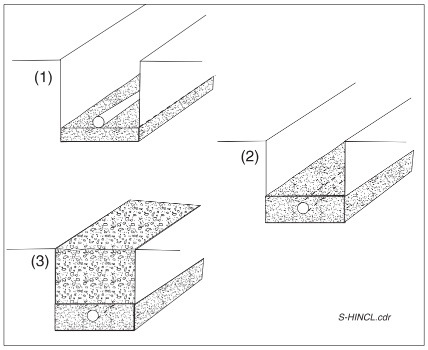
6. At this point, drill casing or hollow stem auger sections have been removed. Verify proper tracking with a dummy probe. As in the previous check, if the probe does not go all the way down or if the probe goes down one set of grooves and returns in another set of grooves, the casing must be replaced. Do not attempt to re-align casing grooves at this stage.

7. Terminate the installation as specified.

Horizontal Installation

1. Excavate trench with a small (5% gradient for drainage. Bottom of trench should be flat. Place a 6 inch layer of sand in the trench and compact it. Lay assembled casing in trench.

   Orient casing so one set of grooves is vertical. This is very important.



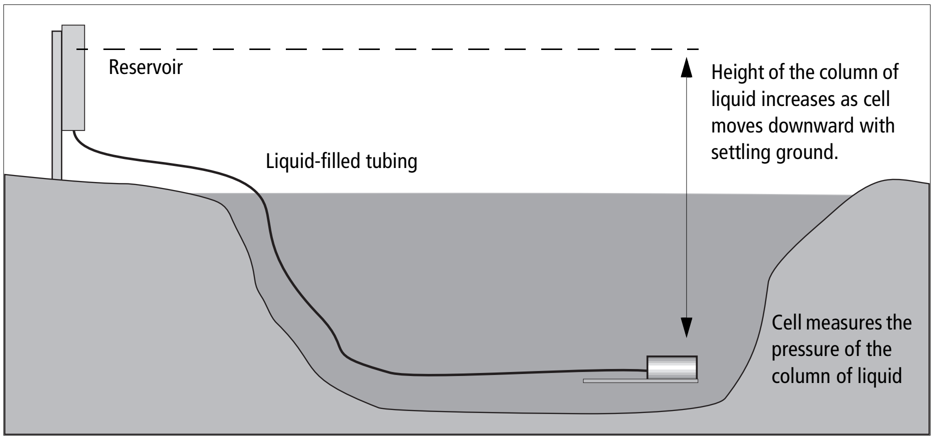
2. Cover casing with 6 inches of sand and compact evenly.

3. Backfill remainder of trench with select fill. Compact evenly. Obtain initial readings.

Installing Settlement Cells

Settlement Cells

The drawing below shows the relation between the reservoir and cell.



Reservoir

Choose location for the reservoir that is:

- On stable ground at a higher elevation than the cell.
- Can be protected from extremes of temperature.
- Allows tubing to stay below ground surface, i.e.. minimizes the length of tubing that is above ground.

Tubing

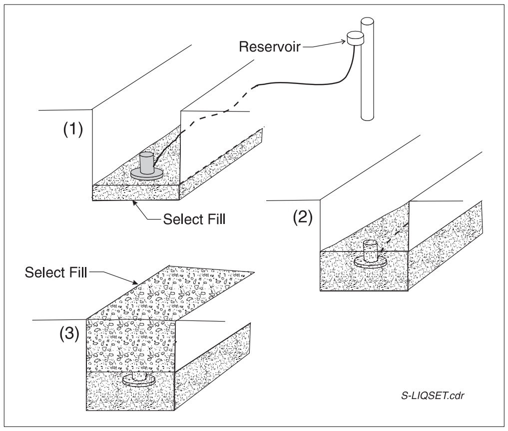
Tubing is typically installed in a trench and buried in sand. Allow some extra tubing for vertical runs to accommodate settlement.

Reservoir and Liquid

Use only deaired liquid in tubing. Keep the reservoir full to the base of the overflow tube to keep air out of the system.

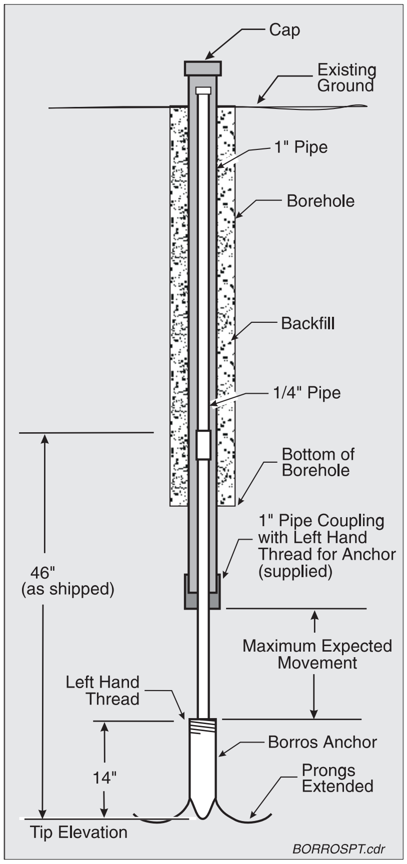
Installation

1. Excavate trench from intended location of transducer to reading station (on stable ground). Place 100 mm layer of fine sand on bottom of trench. Place pneumatic settlement cell in vertical orientation.
2. Backfill with wet sand. Connect settlement cell to reservoir and test.



3. Cover tubing with 100mm layer of fine sand. Fill remainder of trench with selected fill. Obtain datum readings, then hand over to client.

Installing Settlement Points



1. Drill a borehole to approximately 3-ft above the desired anchor elevation. Flush clean.
2. Remove the right-to-left hand thread 1-in coupling supplied with the anchor. Thread the coupling to the bottom section of 1-in pipe and tighten.
3. Thread the first section of 1/4-in pipe into the anchor and tighten.
4. Grease the 1-in left hand thread on the anchor and slip the 1-in pipe with the left to right hand adapter coupling over the 1/4-in pipe. Hand tighten the 1-in pipe to the anchor. Do not over tighten as the pipe must later be detached from the anchor.
5. Lower the assembly into the borehole attaching more inner and outer pipe as required.
6. When the anchor reaches the bottom of the borehole, use the drill rig to advance the 1-in inner pipe and attach the anchor to the desired elevation. Verify this elevation before setting the anchor, since afterwards the anchor cannot be relocated.

Installing Sondex

Overview

Sondex is a multi-point extensometer system that is installed with inclinometer casing.

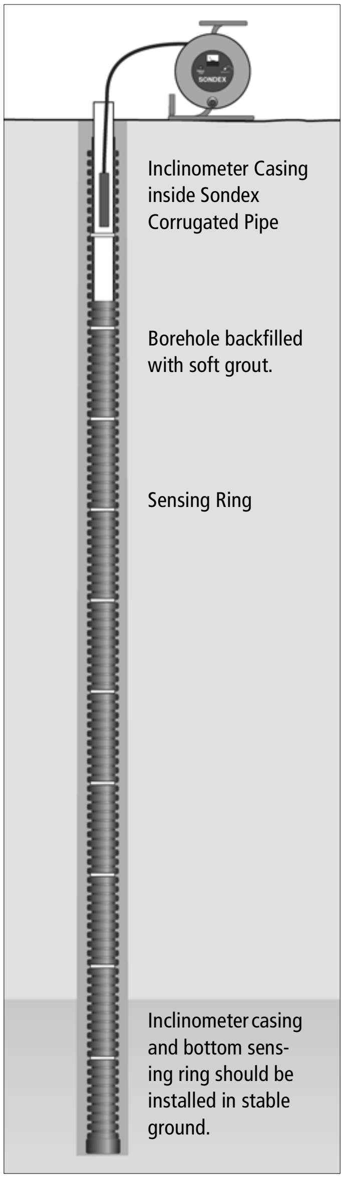
The Sondex system consists of a portable readout, sensing rings, and Sondex pipe, a flexible, non-perforated, corrugated drain pipe. Before installation, the sensing rings are attached to the drain pipe at regular intervals or at depths of interest.

Installation

Equipment needed for installation includes corrugated plastic pipe used for drains, couplings for this drain pipe, Sondex sensing rings, strong cable ties (16 inches or longer) or wire, mastic tape, and vinyl tape. In the instructions below, the drain pipe and couplings are called Sondex pipe and Sondex couplings.

Sondex couplings are used to join lengths of Sondex pipe. The cable ties or wire are used to secure the Sondex pipe to the bottom of the casing and to hold the Sondex couplings onto the Sondex pipe. The mastic tape an vinyl tape are used to seal the bottom and each coupling so that grout cannot enter in the void between the Sondex pipe and the inclinometer casing. You should also consider installing a grout pipe (or hose) along with the casing and Sondex pipe, since it can be difficult to work a grout pipe between the Sondex pipe and the borehole wall.

1. Cut an 8 foot section of Sondex pipe. This will be attached to the bottom section of inclinometer casing. Cut the remaining Sondex pipe into 10 foot sections.
2. Attach sensing rings to the Sondex pipe at specified intervals. Protect the rings from corrosion with mastic and tape.
3. Prepare the bottom section of casing as usual, then secure the bottom 12 to 18 inches of the 8 foot section of Sondex pipe to the bottom of the casing. This can be dif-



ficult because (1) the Sondex pipe is quite strong and larger in diameter than the casing, and (2) the bottom of the Sondex pipe must be sealed against entry of grout. Some people seal the bottom of the Sondex pipe using a Sondex cap, mastic and tape. Then they rivet the Sondex pipe to one side of the casing, and waterproof the rivet holes. Other people do not use the Sondex cap. They slit the bottom of the Sondex pipe to flatten it against the pipe, secure it to the casing with cable ties or wire, and then carefully waterproof it.

4. Lower the first section into the borehole so you can connect the next section. If the borehole is full of water, you must fill the casing and Sondex pipe with water to counter buoyancy.

5. Slide a 10 foot length of Sondex pipe over a 10 foot length of casing. Join the casing, then join the Sondex pipe. Fit the Sondex coupling onto the butted ends of Sondex pipe. Secure with cable ties and then waterproof the entire coupling.

6. Lower the pipe into the borehole so you can connect the next section. Join the casing, then join the Sondex pipe. Continue until the casing has reached the specified depth.

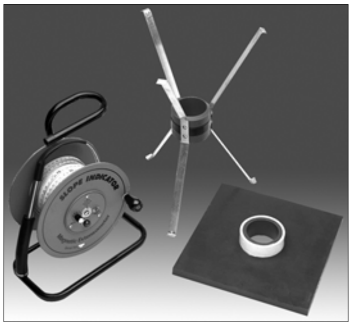
7. Protect the top of the casing and Sondex pipe from grout spills, then backfill the borehole with grout. Use the same grout mixes that you would use for the inclinometer casing alone.

Installing Magnet Extensometers

Overview

The magnet extensometer is a multipoint extensometer that can be installed with inclinometer casing or with 1-inch access pipe.

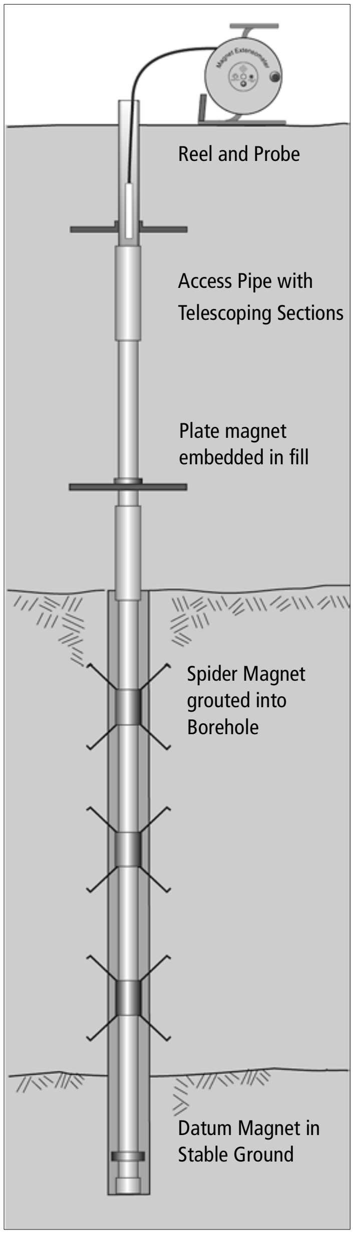
The system consists of a probe, a steel measuring-tape, a tape reel with built-in light and buzzer, and a number of magnets positioned along the length of an access pipe.



Installation

Access pipe, magnets, and grout backfill must all move with the surrounding ground in order for the magnet extensometer to work. Access pipe must be installed with telescoping sections in zones where settlement is expected to occur. Spider magnets are coupled to the soil by the grout that surrounds the pipe and the magnets. Thus grout must be fairly weak, so that it can deform or crumble as settlement occurs.

1. Number magnets and sections of access pipe with their intended depth. Prepare release cords for spider magnets. Release cord must be of sufficient length to extend between intended magnet depth and surface. Allow a minimum of 3m (10ft) of extra cord for surface handling
2. Fix the datum magnet to the bottom section of access pipe. The datum magnet is usually installed at least 0.5 meter or 2 feet above the bottom of the pipe.
3. Compress and attach spider magnets to pipe. Spider magnets must be securely attached to the pipe so that they reach their required locations as the pipe is installed.
4. Check that pipe sections are marked for order of installation, magnets are fixed to each section of pipe, and release cords are labeled, coiled and taped to pipe sections.

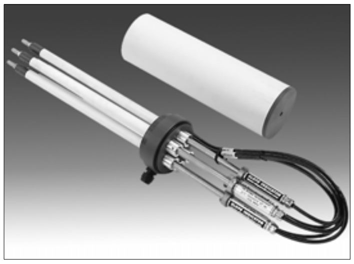


5. Install pipe with magnets attached. As each section of pipe is installed with its magnet, uncoil release cord and lay out in straight line. Check that cord will not be snagged, since this could release legs prematurely. Plan to lay out release cords from other magnets as well and take care to avoid tangling cords. If possible, assign someone to feed cords down hole as pipe is lowered.
6. Check depth of each magnet using magnet extensometer probe. Pull drill casing, if used, to an elevation that is above the upper legs of the deepest magnet. If legs are released into drill casing, the entire installation will have to be replaced.
7. Release legs of the magnet, pulling upwards on release cord. If necessary, pull drill casing above next magnet. Then pull release cord to release the legs. Repeat this step until all spider magnets are anchored.
8. Backfill borehole with a weak bentonite-cement grout as specified by project engineer.

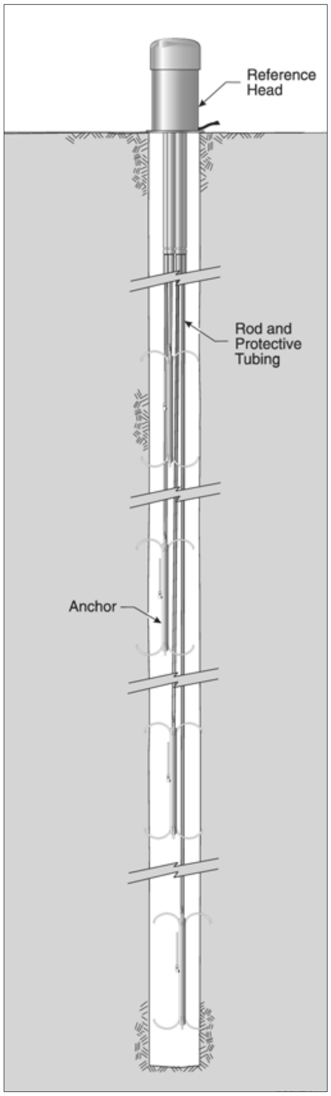
Installing Rod Extensometers

Introduction

The main components of a rod extensometer are anchors, rods inside protective pipe, and a reference head. The anchors are installed downhole with rods attached.The reference head is fixed at the borehole collar.



Installation Issues



Most rod extensometers can be installed in a 3-inch or larger borehole. Reference heads for multipoint extensometers typically require a larger opening at the borehole collar. Boreholes should be free-draining, if possible. Holes must be clean and free of debris before installation.

The extensometer measures only axial movement, so boreholes should be drilled to accommodate this. In tunnels, the axis of the extensometer is typically perpendicular to the tunnel wall. In a fault zone, the extensometer is placed to monitor separation. In a shear zone, the extensometer is placed at a shallow angle to monitor displacement.

The depth of the anchors is determined mainly by geological factors and the size and geometry of the mass being instrumented. It is useful to have one of the anchors located in stable ground so that it can serve as a reference for movements of the other anchors. In a tunnel, the deepest anchor should be at least three tunnel diameters away from the tunnel wall.

Hydraulic anchors are activated by a hand operated hydraulic pump. Packer anchors are activated by a hand-operated, high pressure grout pump. Follow manufacturer's instructions for deployment and activation of these anchors.

Grouting

In general, all boreholes must be grouted unless the geology makes it impossible to grout. With hydraulic anchors or packer anchors, the purpose of grouting is to seal the borehole, preventing unwanted migration of water.

The grout used with these anchors should be weak and deformable. With groutable anchors, grout serves a different purpose. In this case, grout couples the anchor with the surrounding rock. A neat cement grout is suitable if the rod is expected to go into extension. The grout will fracture at the joints where movement occurs. When grouting through long lengths of polyethylene tubing, first pump water through the tubing to minimize friction.

Grouting Down-Holes: A single grout tube is usually adequate for vertical and inclined down-holes. Tape the end of the tube to the protective pipe near the bottom anchor. Tubing will be drawn into the borehole as the extensometer is installed. Sometimes a second, shorter grout tube is taped to a pipe about half-way down the length of the extensometer. This tube can be used if difficulties arise with the longer tube. When you begin pumping the grout, pull the grout tube free from the protective pipe. Draw it upwards as the level of grout rises in the borehole.

Grouting Up-Holes: Tape a tube to the protective pipe so that it projects beyond the deepest anchor. This will be the vent tube. Tape a second tube just below the deepest anchor. Tape a third tube to the protective pipe about 2 or 3 meters from the borehole collar. Install the extensometer hardware, then seal the borehole collar with rags soaked in quick-set cement. Then form a plug by pumping quick-set grout into the borehole through the shortest tube. Allow time for the plug to set. Finally pump grout into the borehole using the longer grout tube. When grout returns via the vent tube, you know the borehole is completely grouted. Fold and tie-off tubes with wire.

Installing Steel Rod Extensometers

Steel rod extensometers must be assembled on site. When space allows, you can assemble the extensometer on the surface. This is the easiest approach and should be used when possible.

1. Assemble the complete extensometer (except for sensors) and attach grout tubing.
2. Park a pick-up truck near the borehole, then position your installers so that they lift the extensometer up and over the truck and down into the borehole. By lifting the extensometer over the truck, you can maintain a minimum bending radius of 3 meters or 10 feet to avoid permanently bending the rods.

When space is tight, it is necessary to assemble the steel rod extensometer as it is installed downhole. Downhole assembly requires careful organization. Sometimes it is possible to assemble and install each anchor and rod independently, starting with the deepest anchor. A safety rope should be attached to each anchor. Grout tubing can also be attached to the anchors

Installing Fiberglass Rod Extensometers

Fiberglass rod extensometers are assembled at the factory and coiled for shipment. Be sure to uncoil the rods carefully. Uncontrolled release of the rods is dangerous.

1. When possible, lay extensometer on ground and check rod lengths.
2. Attach grout tubing if you plan to grout the borehole. Attach a safety rope to the bottom anchor, if there is danger of losing the extensometer downhole
3. Push the extensometer into the borehole. Grout the borehole, from bottom to top. Finish and protect installation as specified.
4. After grout cures and installation is stable, install sensors and take the initial readings.