Geotechnical Instruments in Structural Monitoring

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Abstract

Geotechnical instruments are used widely as a complementary tool to geodetic methods in monitoring natural and man-made structures. This paper provides an overview of geotechnical instruments used in structural monitoring. The transducers commonly used in geotechnical instrumentation are first introduced. This is followed by an introduction of the various types of instruments including their working principles and applications. The advantages and disadvantages of geotechnical instruments when compared with geodetic methods in structural monitoring are finally discussed.

1 Introduction

Many natural and man-made structures such as slopes, buildings, dams, bridges and tunnels need monitored to determine periodically such parameters of the structures as deformations and the states of stress. The aims of structural monitoring can vary from one project to another but generally fall into the following:

a) Safety assurance. Many structures can fail under certain conditions. Monitoring is often one of the most effective ways to understand the safety status of such structures.
b) Validation of design assumptions. Some parameters such as those defining the properties of soil or rock of a cut slope are often assumed at the design stage based on some field investigations. Results of monitoring during or after a construction can help to validate such assumptions so to carry out remedial work if necessary or to improve future designs.
c) Scientific experiments and research. Results from monitoring measurements may lead to new discovery or help to expand our existing knowledge.

The parameters of a structure that need monitored are many but the most common ones are deformation, load, stress, strain, and ground water pressure. A great number of methods are available for structural monitoring. These methods can however generally be classified into geodetic (surveying) methods and geotechnical methods. Geodetic methods are mainly used to monitor deformations while geotechnical methods can be used to determine some other important parameters beside deformations. The two types of methods complement each other in most of the times in terms of the types of information that they can obtain. It should be noted here that the above classification of the monitoring methods is mainly used in the fields of surveying and geodesy (e.g., Chrzanowski, 1994; Ding, et al., 1995). The engineers

and geologists often refer all the methods as geotechnical methods (e.g., Hanna, 1985; Dunnicliff, 1993).

This paper will provide an overview of geotechnical instruments as used for structural monitoring. It will first examine the various transducers that geotechnical instruments employ. The different types of geotechnical instruments will then be reviewed, including their working principles and applications. The advantages and disadvantages of geotechnical instruments in comparison with geodetic methods will be discussed at the end.

2 Transducers Used in Geotechnical Instrumentation

Transducers are the cores of any geotechnical instruments. This section will therefore briefly look into transducers that are commonly used in geotechnical instrumentation.

2.1 Mechanical Transducers

The two most frequently used mechanical transducers are dial indicators and micrometers. A dial indicator converts liner movement of a spring-loaded plunger to the movement of a pointer that rotates above a dial. Typical ranges of dial indicators are about 50 mm while long-range dial indicators of up to 300 mm can be obtained. The reading resolutions of dial indicators are generally within ± 0.025 - ± 0.0025 mm.

A micrometer measures displacements by measuring the rotation of a finely threaded plunger when it travels in or out of a housing. Fractional revolutions are measured with the assistance of a vernier. Accuracies of micrometers are limited to about +0.025 mm. The range of a micrometer can be extended to 150 mm. Micrometers are more robust than dial indicators.

2.2 Hydraulic Transducers

Hydraulic transducers are mainly used to measure pressures. There are two basic designs: the Bourdon tube pressure gages and manometers. A Bourdon tube is made by flattening a metal tube and coiling it into a C-shaped configuration (Fig. 1). The liquid pressure in the tube is measured by measuring the changes in the curvature of the tube. Typical accuracies of Bourdon tubes are $\pm 0.1\%$ - $\pm 0.5\%$ of the full-scale (FS) reading. A manometer uses a liquid-filled U-tube (Fig. 2). A pressure on one side of the U-tube is balanced by an equal pressure on the other.
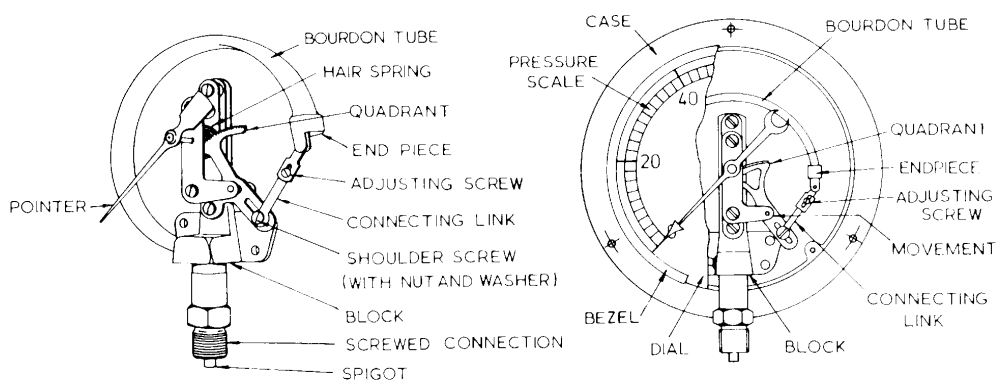
**Figure 1** Bourdon tube hydraulic transducer (after Hanna, 1985)
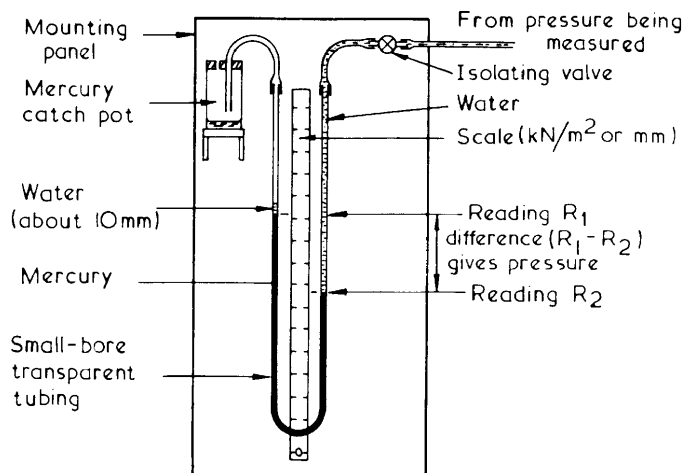
Figure 2 Schematic of U-tube mercury manometer (after Hanna, 1985)

2.3 Pneumatic Transducers

Pneumatic transducers measure pressures through the measurement of gas pressures. There are different designs of pneumatic transducers. Fig. 3 shows the design of a so-called normally closed pneumatic transducer where there is no gas flow between the inlet and the outlet tubes normally. During a measurement, the gas pressure in the inlet tube is gradually increased. When the gas pressure reaches P, the measured pressure, the diaphragm deflects and the gas starts to flow from the inlet tube to the outlet tube. The recorded gas pressure at that point equals P.

2.4 Electrical Transducers

There are a large number of different types of electrical transducers used in geotechnical instrumentation. The following is a brief sample of the major ones:
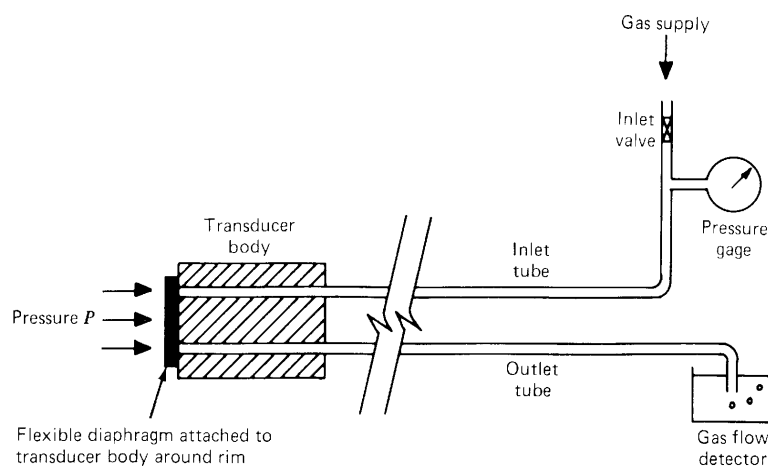
Figure 3 Schematic of normally closed pneumatic transducer (after Dunnicliff, 1993)

Electrical resistance transducers

Electrical resistance transducers use the basic property of an electrical conductor that the resistance of the conductor changes in direct proportion to the change in the length of the conductor:

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} GF \qquad\qquad (1)$$

where $\frac{\Delta R}{R}$ is the relative resistance change; $\frac{\Delta L}{L}$ is the relative length change; *GF* is the gage factor. Output from electrical resistance gages is normally measured using a Wheatstone bridge circuit.

Linearly Varying Displacement Transducers (LVDT)

A linearly varying displacement transducer, also called linear variable differential transformer, consists of a movable magnetic core passing through one primary and two secondary coils (Fig. 4). When an AC voltage, called the excitation voltage, is applied to the primary coil, an AC voltage in each secondary coil is generated, with a magnitude depending on the relative position between the magnetic core and each of the secondary coils. The displacement of the magnetic core can therefore be measured by measuring the changes in the voltages of the secondary coils.

The requirement of the AC power supply can be avoided by using DC power together with an amplitude regulator. Most LVDTs used in practice use this approach since it is often troublesome to get AC power supply in the field.
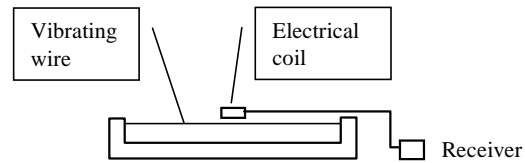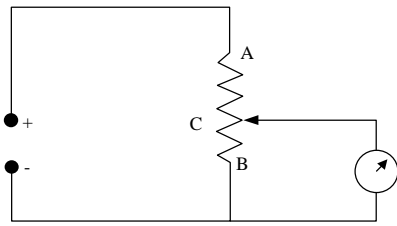
Potentiometer

A potentiometer consists of a fixed resistance strip and a movable slider that makes electrical contact along the resistance strip (Fig. 5). The measured resistance or voltage changes with the position of the contact point.

Vibrating wire transducers

A steel wire is clamped at its two ends (Fig. 6). The frequency of vibration of the wire changes with its tension. Small displacements between the ends of the wire can therefore be measured by measuring the frequency changes. The frequency of vibration of a tensioned wire in terms of the wire stress is (Hawkes and Bailey, 1973),
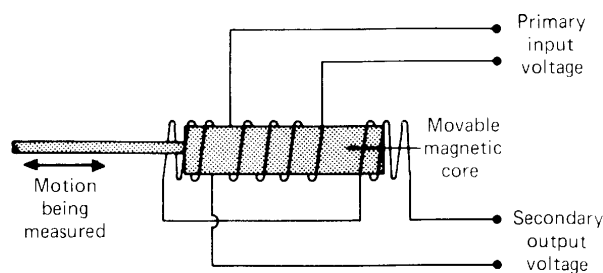
Figure 4 Schematic of a LVDT (after Dunnicliff, 1993)

Figure 5: Schematic of potentiometer   **Figure 6:** Schematic of vibrating wire transducer

$$f = \frac{1}{2L}\sqrt{\frac{\sigma g}{\rho}} \tag{2}$$

where, f is the natural frequency; L is the length of the vibrating wire; σ is the stress in the wire; ρ is the density of the wire material; and g is the acceleration due to gravity.

The electrical coil usually serves two purposes, plucking the wire and sensing the vibration of the wire in the same time. Some vibrating wire transducers can continuously carry out the measurement while the others measure only at discrete times.

Force Balance Accelerometer

Force balance accelerometer consists of a mass suspended in the magnetic field of a position detector (Fig. 7). When the mass is subjected to a force along its sensitive axis, it tries to move. The motion induces a current change in the position detector that is fed back to a restoring coil. The coil generates an electromagnetic force to the mass to balance the initiating force. The current change going through the restoring coil is measured from which the acceleration is calculated.
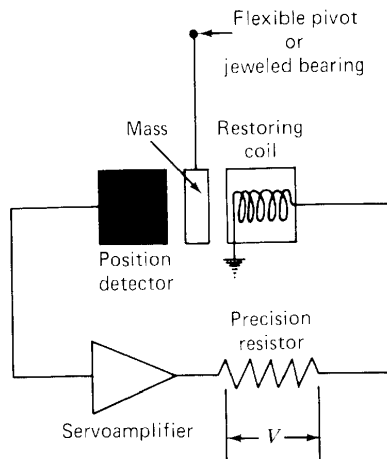
Figure 7 Schematic of a force balance accelerometer (after Dunnicliff, 1993)

There are many other types of electrical transducers, such as variable reluctance transducers and electrical levels. They will not be covered here due to the space limit.

3 Instruments for Measurement of Deformations

There are a variety of geotechnical instruments that have been developed for deformation measurements. These include extensometers, inclinometers, tilt meters, pendulums and inverted pendulums.
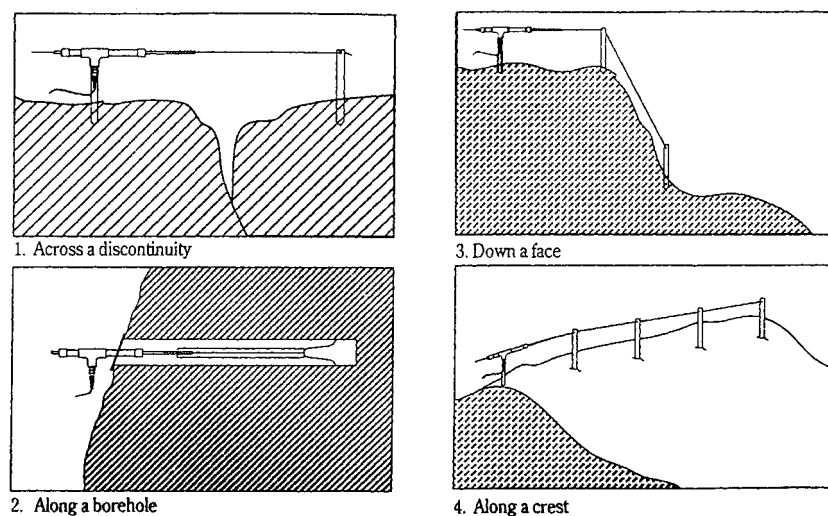
3.1 Extensometers

Extensometers are used to measure the relative movements between points (e.g., Caswell, 1992; Sheppard and Murie, 1992; Joass, 1993). They can be applied, e.g., to measure the movements across a crack, inside or on the surface of a slope, as shown in Fig. 8. Extensometers are made of various types of material, such as steel tapes and wires, tensioned or untensioned steel rods, and fiberglass, for different conditions of application. Extensometers usually use mechanical micrometers, electrical resistance and variable reluctance transducers.

Most extensometers currently in use have a digital readout. Readings can be taken by site personnel, or can be stored in an electronic data logger and transferred to a computer afterwards. A small number of mines have established telemetry systems in order to log and check the readings in real or near-real time.

Measurement ranges of the available extensometers vary from a few centimeters (crack meters) up to around 180 m (tensioned rod extensometers). Most in-wall extensometers extend to about 30-40 m. Accuracies of better than ± 0.1 mm can be achieved, though the effects of temperature and wind can have adverse impact on the accuracy of an individual reading.

Extensometers are commonly used for slope stability monitoring. They can be used either on the surface or inside a slope, and very easily linked to a data logger and alarm system. For example, for a typical open pit mine in Australia, 5 to 30 extensometers of various types are employed to monitor slopes formed in open pit mining.

1. Across a discontinuity

3. Down a face

2. Along a borehole

4. Along a crest

Figure 8 Typical applications of extensometers (Courtesy of Geotechnical Systems Australia Pty. Ltd.)
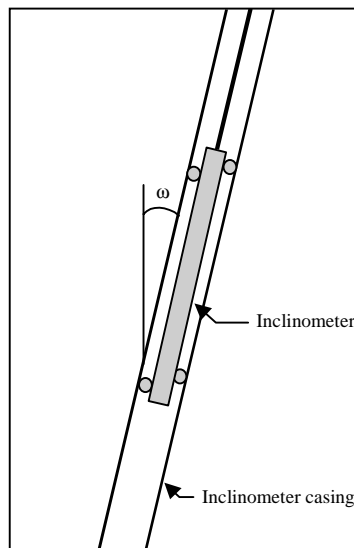
Figure 9: Profile measurement with inlinometers

3.2 Inclinometers

Inclinometers are used to measure the subsurface lateral displacement of soil or rock. An electrical probe is usually lowered through a guide casing to the base of a near vertical borehole (see Fig. 9). The probe is then pulled up while the inclination information of the probe in two orthogonal planes is registered at certain intervals. From this information, profiles of the borehole in the two planes can be derived and reviewed graphically. The lateral displacements of the borehole can be determined by comparing the measured profiles of the borehole obtained at different times. Boreholes of up to 200 m in depth can be measured using inclinometers.

In practice it is usual to extend a borehole into stable ground in order to have a common reference point to compare borehole profiles for determining displacements. Inclinometers can also be placed permanently at important locations to log data continuously. In this situation the inclinometer is acting as a tilt meter.

Servo-accelerometers are usually used as the sensors in an inclinometer probe. Very high resolutions can be achieved with these devices. For example, a sensitivity of ± 0.02 mm per 500 mm casing is offered by the 50325M model of Slope Indicator's Digitilt sensor. The system accuracy of the inclinometer is around ± 6 mm per 25 m of casing.

Inclinometers are ideal to measure the lateral displacements occurring within a slope. However, it is difficult to fully automate the process of measurement with inclinometers.

A significant number of open pit mines in Australia employ inclinometers for pit deformation measurements (e.g., Joass, 1993), although there are fewer applications of inclinometers than extensometers.

3.3 Tilt meters and Electrolevels

Tilt meters are available for measuring the rotational deformation at specific locations on a structure. For example, Applied Geomechanics produces an electronic clinometers with

specified resolutions of 1.75 - 0.01 microradian (0.36 - 0.002 arc seconds). However the high cost of these instruments mean that they are not widely adopted.

3.4 Pendulums and Inverted Pendulums

A pendulum (Fig. 10 (a) achieves a plumb line by using a weight at the lower end of a wire. A near vertical duct is required to set up the system. The weight is usually kept in a liquid (such as oil) tank to stabilise the pendulum. The relative horizontal movement between the anchor point and the lower ground can be determined by reading the scales in two orthogonal directions. Inverted pendulum uses a float in a liquid tank to keep the wire tensioned and vertical (Fig. 10(b)). The relative horizontal movement between the anchor point and the ground surface is determined by reading the scales located on the ground surface. Inverted pendulums are more suitable for situations where access to the bottom end of the system is not readily available. The instruments are commonly used in embankment dam deformation monitoring (e.g., Marsland, 1973).

Pendulums and inverted pendulums can offer an accuracy of +0.5 mm by using a steel measuring scale or +0.03 mm by using travelling vernier microscopes (Dunnicliff, 1993). The reading process can also be automated by using some sensing devices such as an optical vision system.
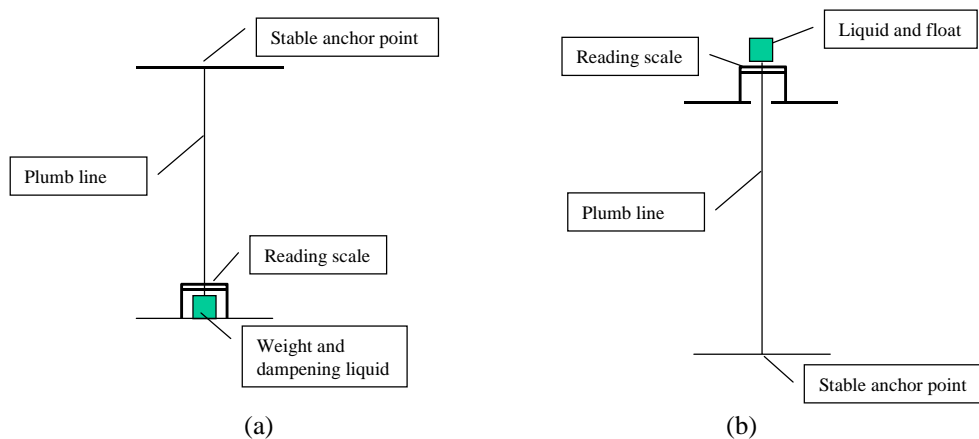

Figure 10: Schematic of pendulum (a) and inverted pendulum (b)

4 Instruments for Measurement of Load, Stress and Strain

Instruments for measuring load, stress and strain all rely on the use of transducers to sense the usually small extensions or compressions caused by the load or by the deformation of the monitored object.

Load cells, also referred to as dynamometers, are usually interposed in a structure in such a way that the structural forces pass through the cells. Depending on the types of transducers used in the load cells, there are, e.g., mechanical load cells that use dial gages, hydraulic load cells that have a flat liquid-filled chamber connected to a pressure transducer, electrical resistance load cells that rely on electrical resistance strain gages, vibrating wire load cells that use vibrating wire transducers. Most of the load cells have an accuracy of about 2-10% FS. Load cells are widely used to monitor loads in testing piles, rockbolts and drilled shafts.
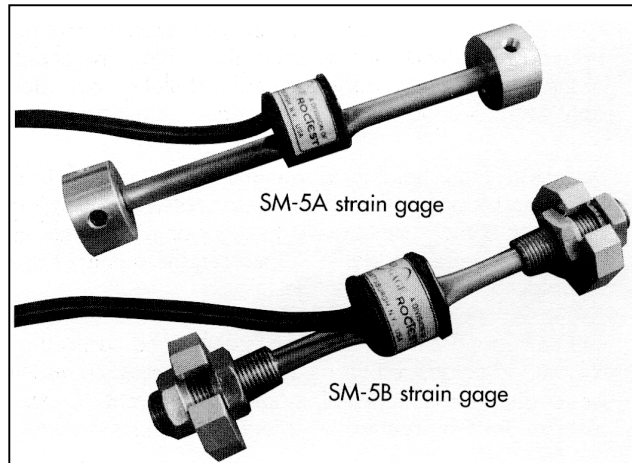
Figure 11 Vibrating wire strain gages (courtesy of Rocktest Ltd., Quebec, Canada)

Strain gages are often attached to the surface of a structure or embedded within the structure. There are also mechanical, vibrating wire and electrical resistance strain gages beside some other specially designed ones. There are also different designs within each category. For example, there are five basic types of electrical resistance strain gages: bonded wire resistance strain gage, unbonded wire resistance strain gage, bonded foil resistance strain gage, semiconductor resistance strain gage, and the weldable resistance strain gage. The measurement ranges, sensitivities and accuracies of the strain gages vary from one design to another.

Stress in soils or rocks can be measured using pressure cells and stressmeters that use, e.g., vibrating wire transducers. It is also common to measure stresses directly by measuring deformations.

Fig. 11 shows the SM-5 series of vibrating wire strain gages from Rocktest Ltd. The resolution of the instruments is 0.1 μstrain with a measurement range of 3,300 μstrains.

## 5 Instruments for Measurement of Ground Water Level and Pore Water Pressure

Ground water level can usually be measured through the use of a standpipe (Fig. 12). Various instruments that are based on the use of mechanical, electrical, acoustic and pressure sensing gages can be used for this purpose. The commonly used ones include steel tape, electrical dipmeter, audio reader, and piezometers.

Piezometers are instruments for the measurement of ground water pressures. They are usually used in an open standpipe, sealed in filled embankment, or driven into ground. The central part of a piezometer is a pressure gage, either a mechanical, electrical, hydraulic or pneumatic transducer. Therefore, we have the vibrating wire piezometers, twin-tube hydraulic piezometers, pneumatic transducers, electrical resistance piezometers, etc.

Multipoint piezometers can also be used to measure water pressures in different strata of the ground. Fig. 13 shows an example of such an arrangement.

Piezometers are commonly used in monitoring slopes, dams and underground constructions. For example, a large number of piezometers have been installed in slopes in HK. Hillman (1993) and Joass (1993) presented examples of using piezometers in monitoring open pit

mine slopes. Little (1973) described test results of using hydraulic, electrical and pneumatic piezometers in dam monitoring.
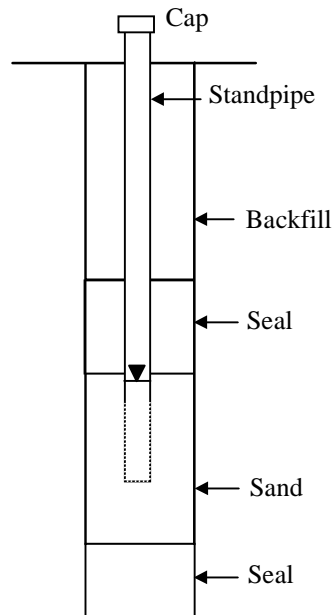
Figure 12 Open standpipe for ground water level and water pressure measurement
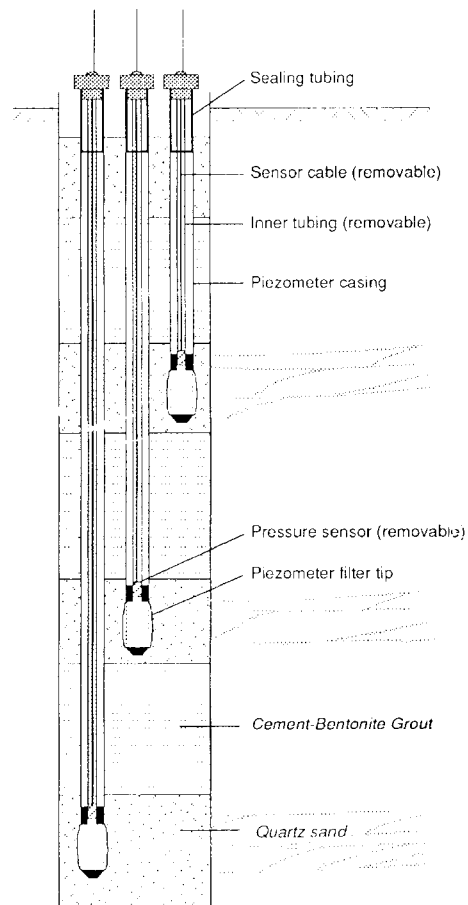
Fig. 13 Schematic of a multipoint piezometer (courtesy of Sol Experts, Zurich)

6 Comparison with Geodetic Methods

When compared with geodetic methods for structural monitoring, geotechnical instruments have the following advantages:
a) Whist geodetic methods are usually limited to deformation measurement, geotechnical instruments can determine many other types of useful parameters such as load, stress and ground water pressure beside deformation measurement.
b) Most geodetic methods can only measure "surface deformations", or in another word the deformations at places where the operator can access or at least can see. Geotechnical instruments are not limited by this. This feature of geotechnical instruments make them very useful for such applications as slope monitoring where information on the deformation inside a slope is often more important.
c) Most geotechnical instruments can output electrical signals and therefore be easily linked to an automatic monitoring system. A number of such systems have been demonstrated (e.g., Chrzanowski and Kurz, 1982; McAuey and Smith, 1983; Ding, et al., 2000).
d) Very high measurement accuracy can often be achieved using geotechnical instruments.

Geotechnical instruments also have their limitations:
a) Most deformation measurement instruments such as extensometers and inclinometers can only measure relative displacements within limited ranges.
b) Most geotechnical instruments need careful and sometimes complicated and expensive installations by experienced personnel before they can be used. The time delay in installation can also be lengthy. Besides, if an instrument malfunctions, it may be difficult to get it repaired or replaced. Therefore the reliability of a geotechnical instrument is a very important factor to consider when choose the instrument.
c) If manual reading mode is used, the operator often need to physically get to the site each time when data is collected.

It is often advantageous to integrate the two types of monitoring techniques in practical applications.

7 Conclusions

There are basically two main types of techniques for structural monitoring, the geodetic and the geotechnical techniques. This paper has provided an overview of the currently available geotechnical instruments used for structural monitoring. The principals of the basic transducers used in geotechnical instrumentation, the various types of geotechnical instruments and their applications, as well as the advantages and disadvantages of geotechnical instruments when compared with geodetic methods have been discussed. It has been seen from the discussions that geodetic and geotechnical techniques are complementary in many aspects and it is often advantageous to integrate the two in practical applications.

Acknowledgements

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