Chapter 4
Summary of Measurement Methods

4-1. Introduction

This chapter provides a brief summary of the measurement methods that are most frequently used to instrument embankment dams and levees. Methods for measuring piezometric pressure, deformation, total stress, temperature, seismic events, seepage, and water level are included. Methods for measuring joint movement, uplift pressure, strain and stress with load cells, strain gages, and concrete stress cells are structural parameter measurements which are outside the scope of this manual and are covered in EM 1110-2-4300. More detailed information of measurement methods is included in Dunnicliff (1988).

4-2. Instrumentation Measurement Methods

Most electronic instrumentation measurement methods consist of three components: a transducer, a data acquisition system, and a linkage between these two components. A transducer is a component that converts a physical change into a corresponding electrical output signal. Data acquisition systems range from simple portable readout units to complex automatic systems. Later in this chapter devices for measurement of various parameters are described. It will be seen that there is significant overlap among the various devices. For example, vibrating wire devices are used for measuring piezometric pressure, deformation, and total stress. To avoid repetition, this paragraph provides a brief description of some of the most frequently used devices. Users are warned to be wary of unproven new devices. New developments should be tested extensively, in the laboratory and field, before being accepted for incorporation as the sole measurement device in an embankment dam or levee. Other technologies such as vibrating strip capacitance and acoustics transducer may have potential but have not been sufficiently field-tested for geotechnical applications and are not discussed in this manual.

a. Pneumatic devices. Pneumatic devices are used for pneumatic piezometers, earth pressure cells, and liquid level settlement gages. Most modern devices are of the type shown in Figure 4-1, for which a measurement is made under a condition of no gas flow. The pressure *P* is the pressure of interest. An increasing gas pressure is applied to the inlet tube and, while the gas pressure is less than *P*, it merely builds up in the inlet tube. When the gas pressure exceeds *P*, the diaphragm deflects, allowing gas to circulate behind the diaphragm into the outlet tube, and flow is recognized using a gas flow detector. The gas supply is then shut off at the inlet valve, and any pressure in the tubes greater than *P* bleeds away, such that the diaphragm returns to its original position when the pressure in the inlet tube equals *P*. This pressure is read on a Bourdon tube or electrical pressure gage. Many detailed issues need to be considered when selecting a pneumatic device, including the sensitivity of the reading to diaphragm displacement, gas flow, tubing length and diameter, type of tubing, tubing fittings, gas, and pressure gage.

b. Vibrating wire devices. Vibrating wire devices are used in pressure sensors for piezometers, earth pressure cells, and liquid level settlement gages, and in numerous deformation gages. In a vibrating wire device a length of steel wire is clamped at its ends and tensioned so that it is free to vibrate at its natural frequency. As with a piano string, the frequency of vibration of the wire varies with the wire tension. Thus with small relative movements between the two end clamps of the vibrating wire device, the frequency of the vibration of the wire varies. The wire can therefore be used as a pressure sensor as shown in Figure 4-2. The wire is plucked magnetically by an electrical coil attached near the wire at its midpoint, and either this same coil or a second coil is used to measure the period or frequency of vibration. Frequency *(f)* is dependent on the bending of the diaphragm, hence on the pressure *P*. Many detailed issues need to be considered when selecting a vibrating wire device, including the method of clamping the wire, preventing corrosion or seepage, and pretreating the transducer to prevent significant zero drift. The attached wire is under near maximum tension at zero pressure. This tension applies the greatest demand on the clamping and annealing of wire, a condition that may cause creeping and slippage of the wire at the clamps, which results in a frequency reduction unrelated to strain. This is commonly known as drift of the baseline pressure or zero drift. With vibrating wire transducers undesirable effects involving signal cable resistance, contact resistance, electrical signal seepage to ground, or length of signal cable are negligible. Very long cable lengths are acceptable.

c. Electrical resistance strain gage devices.

(1) Electrical resistance strain gages have been used in many measurement devices. An electrical resistance strain gage is a conductor with the basic property that resistance changes in direct proportion to change in length. The relationship between resistance change ΔR and length change ΔL is given by the gage factor (*GF*), where

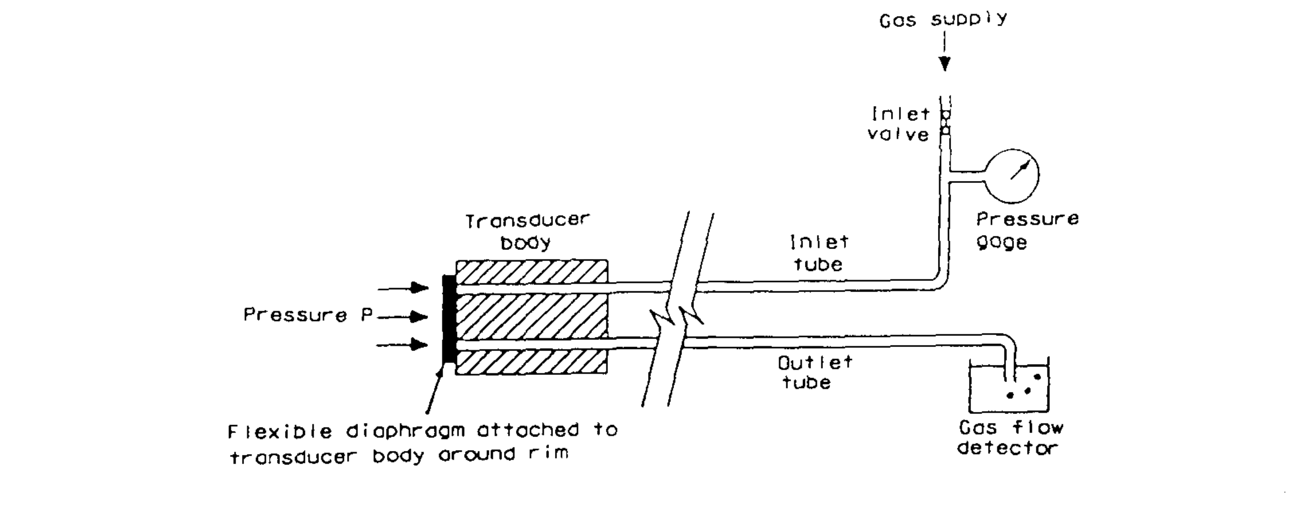

Figure 4-1. Schematic of pneumatic device (Dunnicliff 1988)

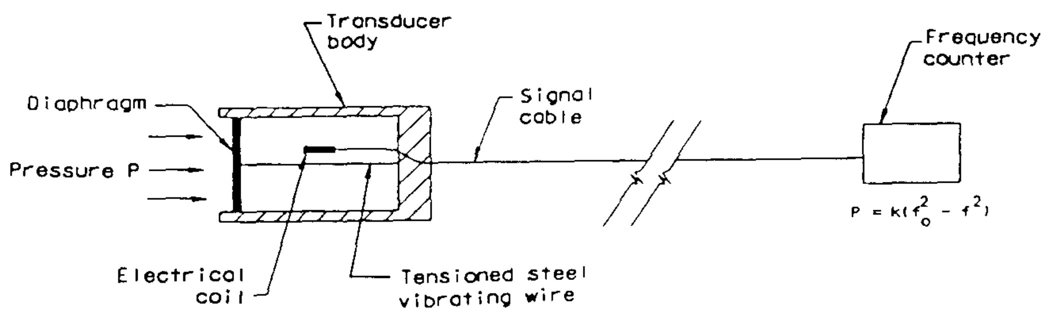

Figure 4-2. Schematic of vibrating wire pressure sensor (Dunnicliff 1988)

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} \times GF$$

Output from the gages is normally measured using a Wheatstone bridge circuit. Electrical resistance strain gages can be packaged as *bonded wire*, *unbonded wire* (Figure 4-3), *bonded foil* (Figure 4-4), and *weldable* gages.

(2) The measured resistance change can be strongly influenced by signal cable length, contact, moisture, temperature, and leakage to ground. However, correction for these influences can be made by measuring the resistance of the various system components (cable, contact, etc.) and subtracting the resistance from the total resistance. Various companies now manufacture low-current signal transducers (4- to 20-milliamp range) that are unaffected by resistance problems.

d. Electrical transducers for measuring linear displacement.

(1) A *linear variable differential transformer* (LVDT) (Figure 4-5) consists of a movable magnetic core passing through one primary and two secondary coils. An AC voltage is applied to the primary coil, thereby

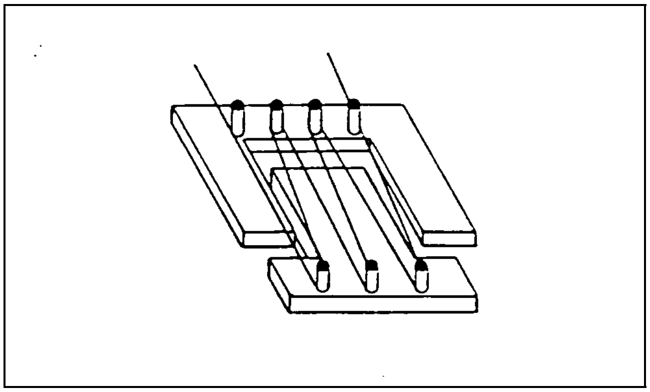

Figure 4-3. Schematic of unbonded wire resistance strain gage (Dunnicliff 1988)

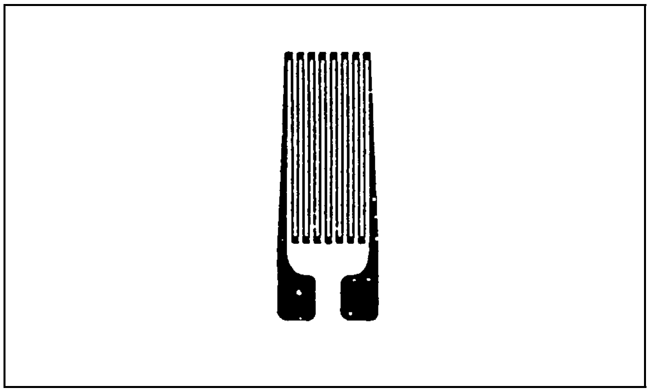

Figure 4-4. Uniaxial bonded foil resistance strain gage (Dunnicliff 1988)

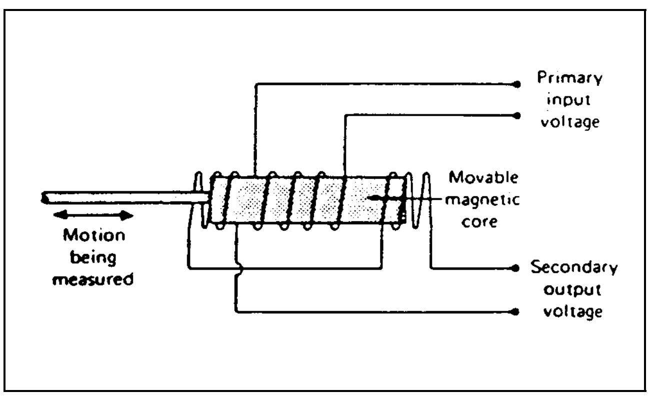

Figure 4-5. Schematic of linear variable differential transformer (LVDT) (Dunnicliff 1988)

inducing an AC voltage in each secondary coil, with a magnitude that depends on the proximity of the magnetic core to each secondary coil.

(2) A *direct current differential transformer* (DCDT) is similar to an LVDT, except that unwanted cable effects associated with LVDTs are avoided by using DC voltages, requiring miniaturizing the electrical circuitry and placing additional components within the transducer housing.

(3) A *linear potentiometer* is a device with a movable slider, usually called a wiper, that makes electrical contact along a fixed resistance strip. As shown in Figure 4-6, a regulated DC voltage is applied to the two ends of the resistance strip and the voltage or resistance between *B* and *C* is measured as the output signal. The voltage between *A* and *C* varies as the wiper moves from point *A* to point *B*.

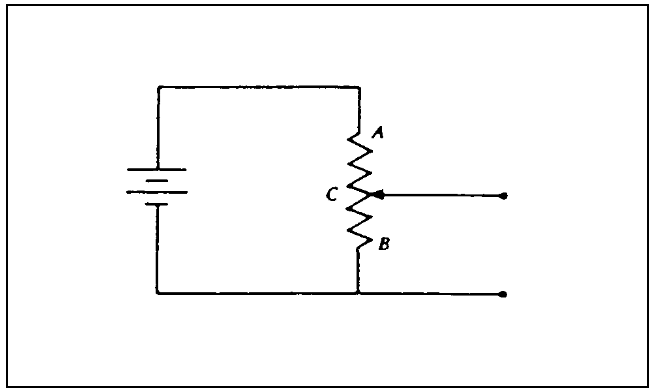

Figure 4-6. Schematic of linear potentiometer (Dunnicliff 1988)

(4) A vibrating wire transducer (paragraph 4-2*b*) can be adapted for measuring linear displacement by including a coil spring in series with the vibrating wire, thereby "softening" the system to give it adequate range, and providing the advantages of a frequency signal.

e. Other electrical systems.

(1) *Force balance accelerometers* are used as tilt sensors in inclinometers. The device consists of a mass suspended in the magnetic field of a position detector (Figure 4-7). When the mass is subjected to a gravity force along its sensitive axis, it tries to move, and the motion induces a current change in the position detector. This current change is fed back through a servo-amplifier to a restoring coil, which imparts an electromagnetic force to the mass that is equal and opposite to the initiating gravity force. The mass is thus held in balance and does not move. The current through the restoring coil is

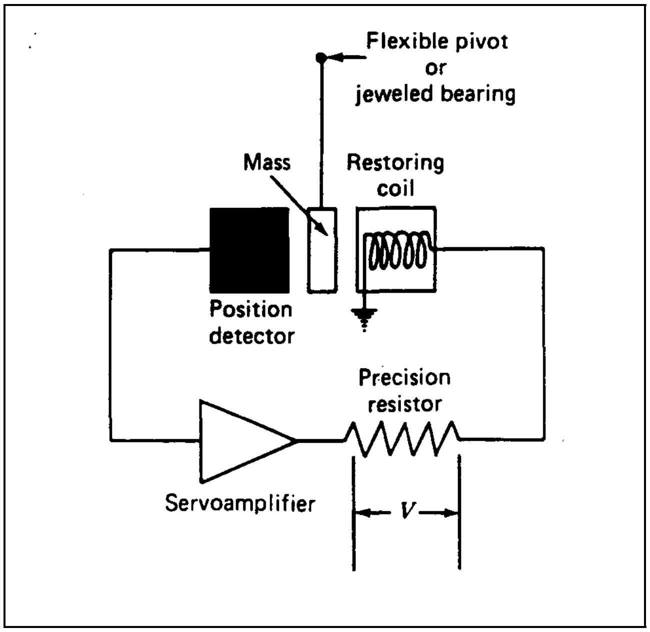

Figure 4-7. Schematic of force balance accelerometer (Dunnicliff 1988)

measured by the voltage across a precision resistor. This voltage is directly proportional to the input force.

(2) The *magnet/reed switch* system is used in probe extensometers. It is an on/off position detector, arranged to indicate when the reed switch is in a certain position with respect to a ring magnet, as shown in Figure 4-8. The switch contacts are normally open and one of the reeds must be magnetically susceptible. When the switch enters a sufficiently strong magnetic field, the reed contacts snap closed and remain closed as long as they stay in the magnetic field. The closed contacts actuate a buzzer or indicator light in a portable readout unit.

(3) *Induction coil transducers* are also used in probe extensometers. An electrical coil is powered to create a magnetic field around the coil. When this coil is placed inside a steel wire ring (with no external electrical connection), a voltage is induced in the ring, which in turn alters the current in the coil because its inductance changes. The current in the coil is a maximum when the coil is centered inside the ring; thus, by measuring current in the coil, the transducer can be used as a proximity sensor.

(4) *Sonic transducers* can be used to monitor water level in open standpipe piezometers and weir stilling basins. The transducer is mounted above the water surface. Sound pulses travel to the water surface and are reflected back to the transducer. Distance to the water surface is determined from the measured pulse time and the known velocity of sound waves, corrected for errors induced by temperature change.

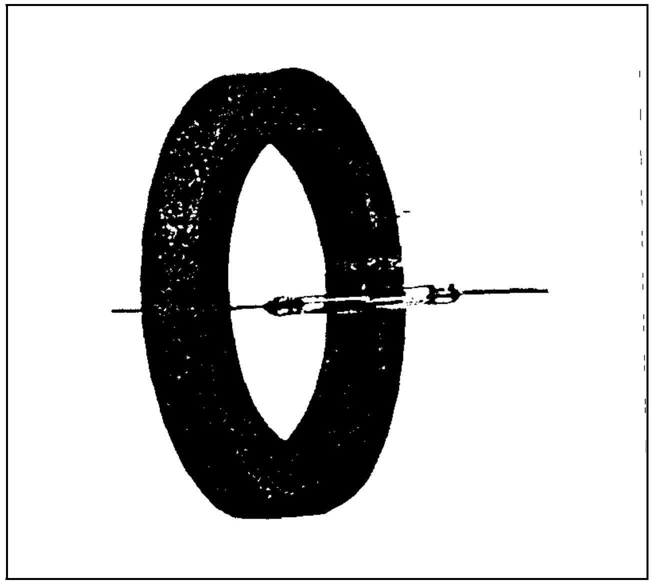

Figure 4-8. Magnet/reed switch (Dunnicliff 1988)

4-3. Measurement of Piezometric Pressure

Definitions of the terms groundwater level, *pore water pressure*, *pore gas pressure*, *piezometric level*, and other terms associated with measurement of piezometric pressure are given in Chapter 2. The most common device for measuring these parameters is the piezometer.

a. Applications. Applications for piezometers fall into two general categories: first, for monitoring the pattern of water flow and second, to provide an index of soil strength. Examples in the first category include determining piezometric pressure conditions prior to construction, monitoring seepage, and effectiveness of drains, relief wells, and cutoffs. In the second category, monitoring of pore water pressure allows an estimate of effective stress to be made, and thus an assessment of strength. Examples include monitoring dissipation of pore water pressure during consolidation of foundation and fill material and the effect of rapid drawdown. Applications for observation wells are very limited because they create a vertical connection between strata. Observation wells and various types of piezometers are described in the subsequent paragraphs, together with recommendations for their use. Under certain conditions piezometers may need to be protected against freezing.

b. Observation wells. Figure 4-9 shows a schematic of an observation well. The elevation of the water surface in the riser pipe is determined by sounding with a water level indicator.

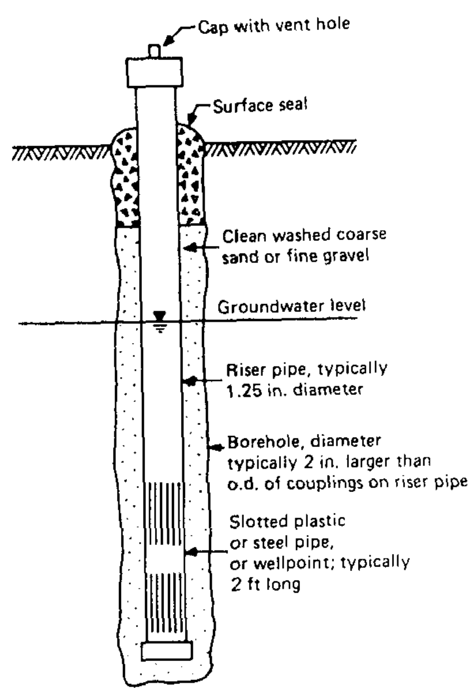

Figure 4-9. Schematic of observation well (Dunnicliff 1988)

c. Open standpipe piezometers. Figure 4-10 shows a schematic of an open standpipe piezometer (also known as a Casagrande piezometer) installed in a borehole. The components are identical in principle to components of an observation well, with the addition of subsurface seals which isolate the zone of interest. Readings can be made by sounding with a water level indicator, with a pressure transducer placed in the standpipe below the lowest piezometric level, or with a sonic transducer.

d. Twin-tube hydraulic piezometers.

(1) The twin-tube hydraulic piezometer is shown schematically in Figure 4-11. The piezometric elevation is determined by adding the pressure gage reading to the

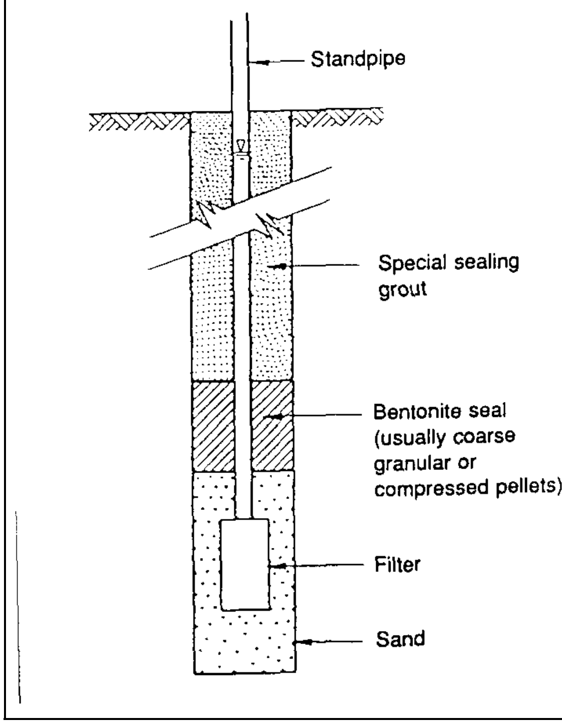

Figure 4-10. Schematic of open standpipe piezometer installed in a borehole (Dunnicliff 1988)

elevation of the pressure gages. If both plastic tubes are completely filled with liquid, both pressure gages should indicate the same pressure. However, if gas has entered the system (through the filter, tubing, or fittings) the gas will cause an inaccurate pressure reading on one or both gages. The gas must be removed by flushing. Dual gages therefore indicate the need for flushing and re-calibration.

(2) Twin-tube hydraulic piezometer systems have been developed in the United States by the U.S. Bureau of Reclamation and in England by Imperial College, London. Each system has been used widely in embankment dams throughout the world with variable success. The system developed in England appears to have a better success record than the system developed in the United States, and successful long-term use of twin-tube hydraulic piezometers requires close adherence to many proven details (Dunnicliff 1988).

e. Pneumatic piezometers. Pneumatic piezometers are based on the device shown in Figure 4-1. A filter is added to separate the flexible diaphragm from the material in which the piezometer is to be installed, and the

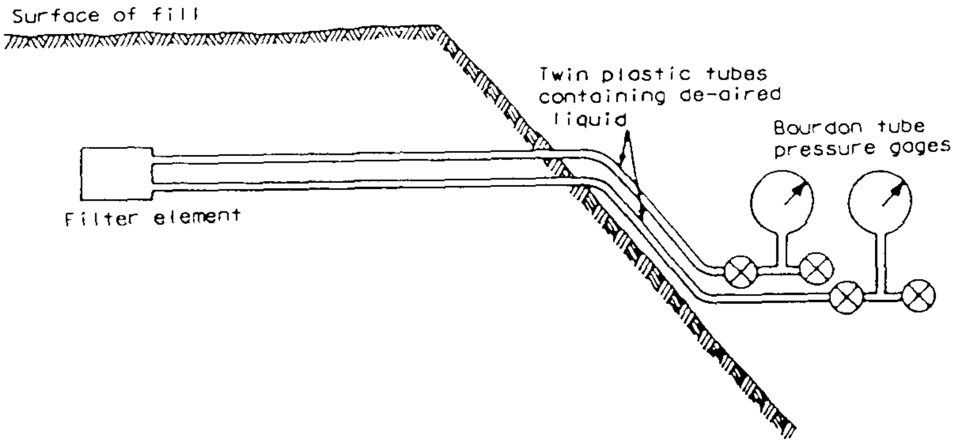

Figure 4-11. Schematic of twin-tube hydraulic piezometer installed in fill (Dunnicliff 1988)

installation arrangements can be similar to those shown in Figure 4-10. A special type of pneumatic piezometer is available for installation by pushing into foundation material, rather than by sealing as shown in Figure 4-10. The instrument shown in Figure 4-12 is applicable for monitoring consolidation pore water pressures below levees, in cases where vertical compression of the foundation material is large. The piezometer is pushed below the bottom of a borehole, and the borehole is filled with a soft bentonitic grout. Great care must be taken during installation to avoid damaging the lead connection to the sensor.

f. Vibrating wire piezometers. Vibrating wire piezometers are based on the pressure sensor shown in Figure 4-2. A filter is added, and permanent embedded installation arrangements can be similar to those shown for an open standpipe piezometer in Figure 4-10. Special heavy-walled versions are available for installation in compacted fills, the heavy wall ensuring that the instrument responds only to changes in pore water pressure, and not to total stresses acting on the housing. Special versions are also available, similar to the pneumatic piezometer shown in Figure 4-12, for monitoring consolidation pore water pressures below levees where vertical compression of the foundation material is large.

g. Electrical resistance piezometers. Electrical resistance piezometers, based on the strain gages shown in Figures 4-3 and 4-4, have been used in embankment dams and levees. The vent tubes have been known to block and invalidate readings as shown in Figure 4-13.

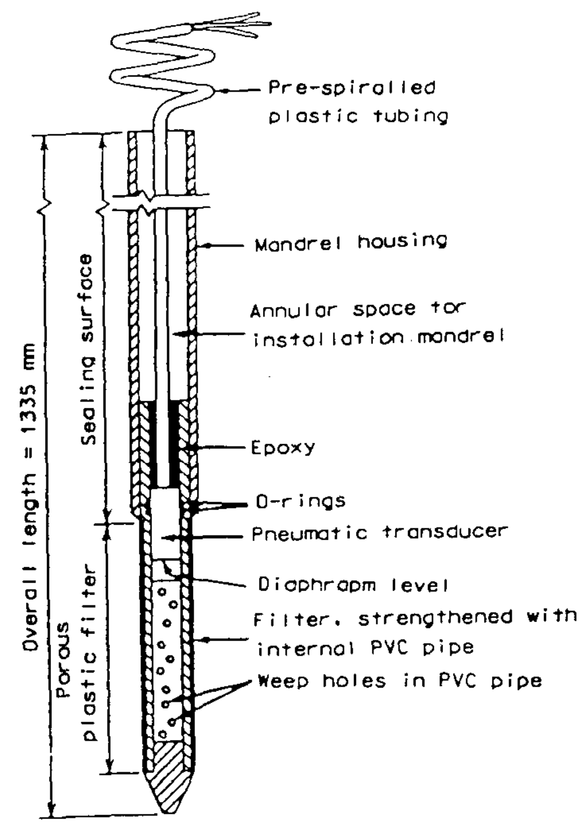

Figure 4-12. Pneumatic piezometer for installation by pushing in place below bottom of a borehole in very soft clay (Dunnicliff 1988)

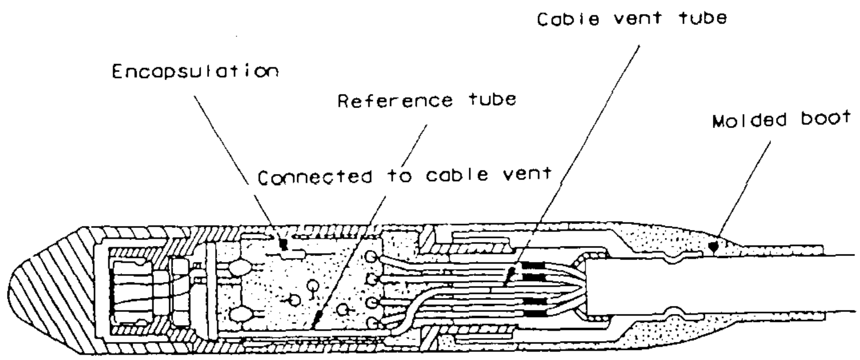

Figure 4-13. Fully encapsulated submersible pressure transducer (courtesy of Druck, Inc.)

h. Type of filter. All piezometers include an intake filter. The filter separates the pore fluid from the structure of the soil in which the piezometer is installed and must be strong enough to avoid damage during installation and to resist the total stresses without undue deformation. Filters can be classified in two general categories: *high air entry* and *low air entry.*

(1) Filters keep fluids in equilibrium by balancing the pressure differential with surface tension forces at the gas/water interface. The smaller the radius of curvature of the *menisci* at the interface, the larger can be the pressure difference between water and gas. Since the minimum radius of curvature of the *menisci* is dictated by the pore diameter in the filter, the finer the filter, the greater can be the pressure differential. The *air entry value* or *bubbling pressure* of the filter is defined as the pressure differential at which blow-through of gas occurs. Thus, a filter with a high air entry value (or high bubbling pressure) is a fine filter that will allow a high pressure differential before blow-through occurs.

(2) Low air entry filters are coarse filters that readily allow passage of both gas and water, and should be used for all piezometer types that are installed in saturated soils and for open standpipe piezometers installed in unsaturated soils. Typical low air entry filters have a pore diameter of 0.02-0.08 mm, 20-80 microns (0.001-0.003 in.), and air entry values range from 3-30 kPa (0.4 to 4.0 lb/in.^{2}). Filters should be saturated when installed. They can readily be saturated with water prior to installation by soaking or by passing water through the pores.

(3) High air entry filters are fine filters that must be used when piezometers (except open standpipe piezometers) are installed in unsaturated soil, such as the compacted core of an embankment dam, with the intent of measuring pore water pressure as opposed to pore gas pressure, in an attempt to keep gas out of the measuring system. These filters typically have a pore diameter of 0.001 mm, 1 micron (4×10^{-5} in.) and an air entry value of at least 100 kPa (15 lb/in.^{2}). Saturation of high air entry filters requires a much more controlled procedure, entailing removal of the filter from the piezometer, placing the dry filter in a container, and applying a vacuum. The filter should then be allowed to flood gradually with warm de-aired water.

i. Recommended instruments for measuring piezometric pressure in saturated soil. Advantages and limitations of instruments for measuring piezometric level are summarized in Table 4-1.

(1) Reliability and durability are often of greater importance than sensitivity and high accuracy. Therefore, the designer's intent for the use of the instrument is crucial to the selection of the type of instrument. The fact that the actual head may be in error by 300 mm (1 ft), as a result of time lag, may not matter in some cases, provided the piezometer is functioning properly. Piezometer installations with transducers may require corrections for barometric pressure if high accuracy is needed.

(2) As indicated in paragraph 4-3*a* and Table 4-1, observation wells should be used only rarely. For measurement of piezometric pressure in saturated soil, an open

Table 4-1
Instruments for Measuring Piezometric Pressure

Instrument Type	Advantages	Limitations[a]
Observation well	Easy installation Field readable	Provides vertical connection between strata and should only be used in continuously permeable strata
Open standpipe piezometer	Reliable Long successful performance record Self-de-airing if inside diameter of standpipe is adequate Integrity of seal can be checked after installation Can be used to determine permeability Readings can be made by installing pressure transducer or sonic sounder in standpipe	Time lag can be a factor Subject to damage by construction equipment and by vertical compression of soil around standpipe Extension of standpipe through embankment fill interrupts construction and may cause inferior compaction Possible freezing problems Porous filter can plug owing to repeated water inflow and outflow
Twin-tube hydraulic piezometer	Buried components have no moving parts Reliable when maintained Long successful performance record When installed in fill, integrity can be checked after installation Piezometer cavity can be flushed Can be used to determine permeability Short time lag Can be used to read negative pore water pressures	Application generally limited to long-term monitoring of pore water pressure in embankment dams Elaborate terminal arrangements needed Tubing must not be significantly above minimum piezometric elevation Periodic flushing is required Possible freezing problems Attention to many details is necessary
Pneumatic piezometer (Embedded)	Short time lag Calibrated part of system accessible Minimum interference to construction; level of tubes and readout independent of level of tip No freezing problems	Requires a gas supply Installation, calibration, and maintenance require care
Vibrating wire piezometer (Embedded)	Easy to read Short time lag Minimum interference to construction; level of lead wires and readout independent of level of tip Lead wire effects minimal Can be used to read negative pore water pressures No freezing problems	Potential for zero drift (Special manufacturing techniques required to minimize zero drift[b]) Need for lightning protection should be evaluated
Electrical resistance piezometer (Embedded)	Easy to read Short time lag Minimum interference to construction; level of lead wires and readout independent of level of tip Can be used to read negative pore water pressures No freezing problems	Potential lead wire effects unless converted to 4 to 20 milliamps Errors caused by moisture and corrosion are possible Need for lightning protection should be evaluated

[a] Diaphragm piezometer readings indicate the head above the piezometer, and the elevation of the piezometer must be measured or estimated if piezometric elevation is required. All diaphragm piezometers, except those provided with a vent to the atmosphere, are sensitive to barometric pressure changes. If piezometer pipes, tubes, or cables are carried up through fill, there will be significant interruption to construction and the probability of inferior compaction.

[b] See Dunnicliff (1988)

Source: Dunnicliff (1988)

standpipe piezometer is the first choice and should be used when applicable. Limitations associated with extending the standpipe through embankment fill normally prevent their use within the fill of an embankment dam or levee (see paragraph 6-4). When any of these limitations are unacceptable, a choice must be made among the remaining piezometer types.

(3) For short-term applications, defined as applications that require reliable data for a few years (for example during the typical construction period), the choice is generally between pneumatic and vibrating wire piezometers. The choice will depend on the factors listed in Table 4-1, on the user's own confidence in one or the other type, and on a comparison of cost of the total monitoring program.

(4) For long-term applications, selection criteria are similar, but because of their basic simplicity and reliability, twin-tube hydraulic piezometers and Casagrande piezometers have become attractive options.

(5) For monitoring consolidation pore water pressures below levees, in cases where vertical compression of the foundation material is large, the push-in pneumatic or vibrating wire piezometers (paragraphs 4-3*e* and 4-3*f*) are good choices. Push-in versions of open standpipe piezometers are also available.

(6) When the economics of alternative piezometers are being evaluated, the *total* cost should be determined, considering costs of instrument procurement, calibration, installation, maintenance, monitoring, and data processing. The cost of the instrument itself is rarely the controlling factor and should never dominate the choice.

j. Recommended instruments for measuring pore water pressure in unsaturated soil. If the pores in a soil contain both water and gas, such as in the compacted clay core of an embankment dam or in an organic soil deposit, the pore gas pressure will be greater than the pore water pressure (Chapter 2). In fine-grained soils the pressure difference can be substantial, and special techniques are required to ensure measurement of pore water pressure rather than pore gas pressure. For all piezometer types other than open standpipe piezometers, these techniques include use of high air entry filters, saturated as described in paragraph 4-3*h*, with the filter in contact with the unsaturated soil. Intimate contact will not be achieved if the filter is on the flat end of a cylindrical piezometer; the filter must be on the side or on a conical end. The piezometer should not be installed in a sand pocket.

(1) Piezometer selection criteria are similar to those given in paragraph 4-3*i* for saturated soil. For short-term applications, the choice will generally be among open standpipe, pneumatic, and vibrating wire piezometers.

(2) For long-term applications the longevity of filter saturation is uncertain because gas may enter the filter by diffusion. The compacted fill in an embankment dam may remain unsaturated for a prolonged period after the reservoir is filled, and in fact the fill may never become permanently saturated by reservoir water. Increase of water pressure causes air to go into solution, and the air is then removed only when there is enough flow through the fill to bring in a supply of less saturated water. The pressure and time required to obtain saturation depend on the soil type, degree of compaction, and degree of initial saturation. Pore gas pressure may therefore remain significantly higher than pore water pressure for a substantial length of time, perhaps permanently. Pneumatic and vibrating wire piezometers therefore cannot be relied upon for monitoring long-term pore *water* pressures. However, twin-tube hydraulic piezometers allow for flushing of the filter and cavity with de-aired liquid, thereby ensuring that pore *water* pressure continues to be measured. The choice for long-term reliable measurement of pore water pressure is therefore between open standpipe and twin-tube hydraulic piezometers.

4-4. Measurement of Deformation

Instruments for measuring deformation can be grouped in the categories listed in Table 4-2. Definitions of each category, together with an indication of typical applications, are given below.

a. Surveying methods. Surveying methods are used to monitor the magnitude and rate of horizontal and vertical deformations of the surface monuments on and at the toes of embankment dams and levees. When subsurface deformation measuring instruments are installed, surveying methods are also often used to relate instrument measurements to a reference datum.

(1) Surveying methods include optical leveling, taping, traverse lines, measuring offsets from a baseline, triangulation, electronic distance measurement, trigonometric leveling, photogrammetric methods, and the satellite-based global positioning system. Details are beyond the scope of this manual and are included, together with additional references, in Dunnicliff (1988).

Table 4-2
Categories of Instruments for Measuring Deformation

Category	Type of Measured Deformation					
	↔	↕	⤢	○	—̇	—̣
SURVEYING METHODS Optical and other methods Benchmarks Horizontal control stations Surface measuring points	•	•	•		•	
PROBE EXTENSOMETERS Mechanical probe gages Electrical probe gages Combined probe extensometers and inclinometer casings	•	•	•			•
FIXED EMBANKMENT EXTENSOMETERS Settlement platforms Buried plates Gages with electrical linear displacement transducers	•	•	•			•
SUBSURFACE SETTLEMENT POINTS		•				•
FIXED BOREHOLE EXTENSOMETERS Single-point extensometers Multipoint extensometers	•	•	•			•
INCLINOMETERS Probe inclinometers In-place inclinometers	•	•	•	•		•
LIQUID LEVEL GAGES Single-point gages Full-profile gages		•				•

Key: ↔ horizontal deformation
↕ vertical deformation
⤢ axial deformation (↔ or ↕ or in between)
○ rotational deformation
—̇ surface deformation
—̣ subsurface deformation

Source: Dunnicliff (1988)

(2) All surveying methods must be referenced to a stable reference datum: a *benchmark* for vertical deformation measurements and a *horizontal control station* for horizontal deformation measurements. Great care must be taken to ensure stability of reference datums, for example by installing deep benchmarks (below frost depth) in boreholes drilled to an immovable stratum.

(3) Surface measuring points (points on the surface that are used for survey observations, and that may move) must be stable and robust points that will survive throughout the project life, and must be isolated from the influence of frost heave and seasonal moisture changes. Figure 4-14 shows a typical measuring point for monitoring settlement on the surface of an embankment dam.

b. Probe extensometers. Probe extensometers are defined in this manual as devices for monitoring the changing distance between two or more points along a

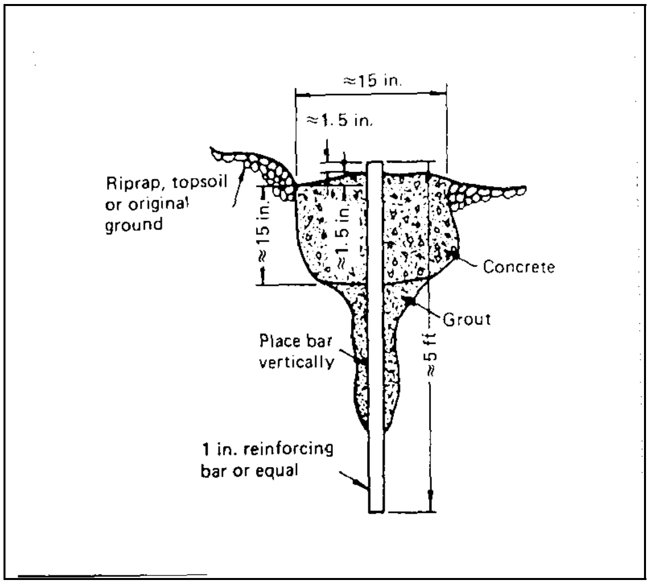

Figure 4-14. Measuring point for monitoring settlement on surface of embankment dams

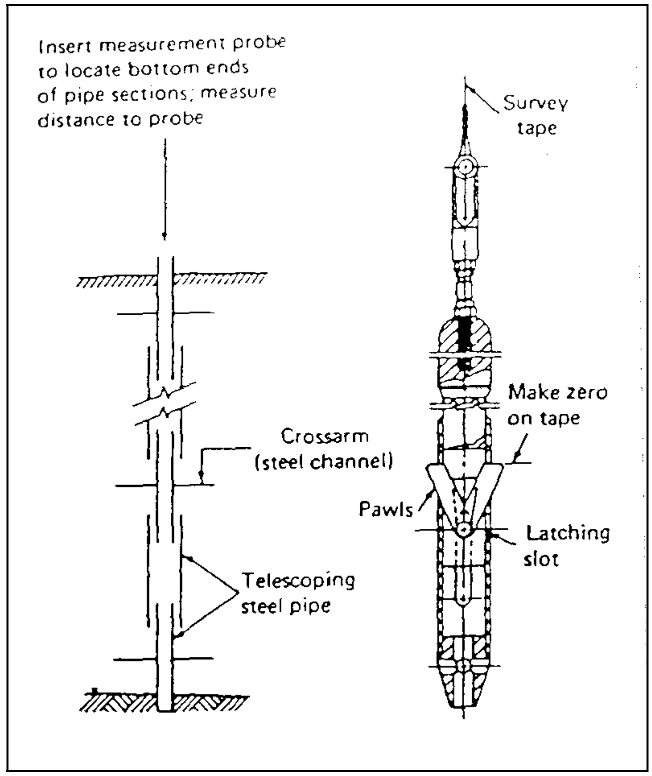

Figure 4-15. Crossarm gage: (a) Schematic of pipe arrangement and (b) measurement probe

common axis, by passing a probe through a pipe. Measuring points along the pipe are identified mechanically or electrically by the probe, and the distance between points is determined by measurements of probe position. For determination of absolute deformation data, either one measuring point must be at a location not subject to deformation, or its position with respect to a reference datum must be periodically determined by surveying methods. The pipe may be vertical, providing measurements of settlement or heave, or may be horizontal, providing lateral deformation measurements, for example in downstream shells of embankment dams.

(1) Probe extensometers are used for monitoring vertical compression of the fill or foundations of embankment dams and levees. Four types of probe extensometers are described below.

(2) The *crossarm gage* was developed by the U.S. Bureau of Reclamation for installation during construction of embankment dams. As shown in Figure 4-15, it consists of a series of telescoping pipe sections with alternate sections anchored to the embankment by horizontal steel channel crossarms. The crossarms ensure that the pipes move together an amount equal to compression of the intervening fill. Depths to the measuring point at the lower end of each interior pipe are sounded by a probe with spring-loaded sensing pawls, lowered on a steel tape. The probe is lowered just beyond each interior pipe in turn and raised until the pawls latch against the lower end. On reaching the bottom of the pipes, the pawls retract and lock within the body of the probe. The crossarms limit the application to embankments, because the gage cannot be installed in boreholes in foundation material. It is therefore applicable only for new construction.

(3) A *mechanical probe*, similar to the measurement probe shown in Figure 4-15(b), can be lowered within telescoping inclinometer casing (paragraph 4-4*f*) to determine the depths to bottom ends of casing sections. In embankments, the casing is forced to follow the pattern of soil compression by attaching settlement collars to its outside. Settlement collars are not possible for borehole installations; thus, the telescoping of casing in boreholes will not necessarily conform with soil compression, and data may not be correct.

(4) The *induction coil gage* consists of an embedded telescoping pipe surrounded by steel rings or plates at the required measuring points. The reading device consists of a primary coil housed within a probe and an attached signal cable connected to a current indicator. Readings

are made by traversing the probe along the pipe and noting the tape graduation when output current is a maximum. A schematic of a commercial version is shown in Figure 4-16. As will be seen from the figure, borehole installations require that the grout must be very carefully selected to ensure that the measurement system deforms axially in exact conformance with the soil, and this is often not possible when there are variable strata or where vertical compression is large, such as in levee foundations. When the gage is installed horizontally in the downstream shell of an embankment dam, with steel plates around a telescoping pipe, it is referred to as a *horizontal plate gage*. This arrangement can be used only when drainage is provided downstream of the core. As an alternative to the probe, multiple transducers can be connected by rods and left in place within the pipe, and inched along the pipe to take readings, thereby increasing measurement accuracy.

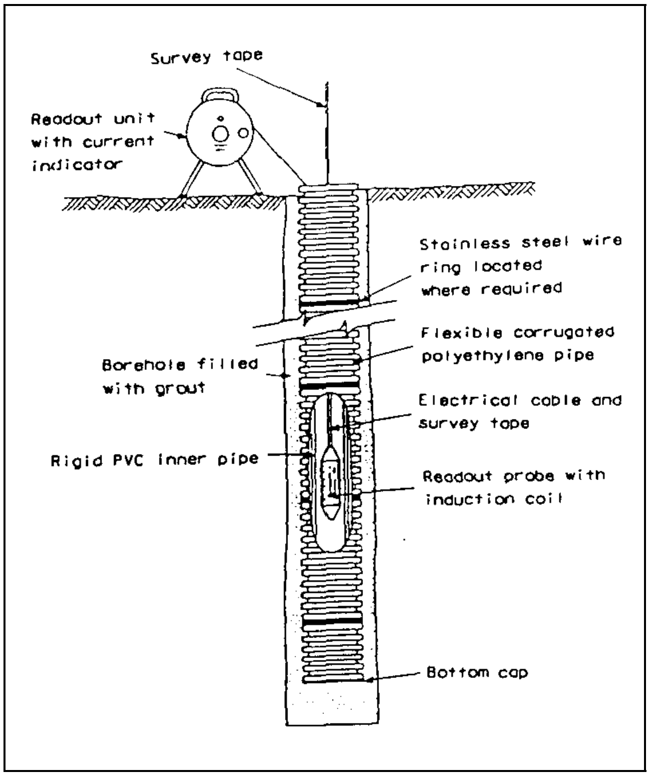

Figure 4-16. Schematic of Slope Indicator Company sondex probe extensometer installed in a borehole (Dunnicliff 1988)

(5) The *magnet/reed switch gage* is based on the transducer shown in Figure 4-8, arranged as in Figure 4-17. The *spider magnets* have spring anchors that ensure conformance with soil deformation, hence allowing the gage to be used where vertical compression is large.

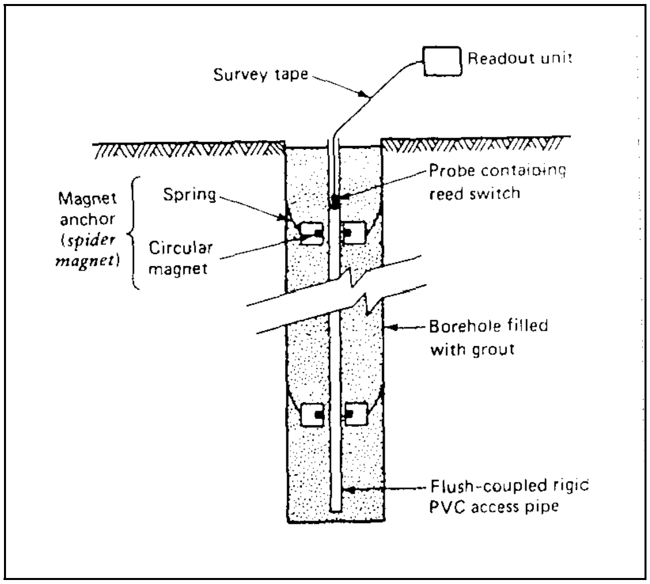

Figure 4-17. Schematic of probe extensometer with magnet/reed switch transducer, installed in a borehole (Dunnicliff 1988)

c. Fixed embankment extensometers. Fixed embankment extensometers are defined in this manual as devices placed in embankment fill as filling proceeds for monitoring the changing distance between two or more points along a common axis without use of a movable probe. They are used for monitoring settlement, horizontal deformation, or strain. Three types are described below.

(1) *Settlement platforms* can be used for monitoring the settlement of levee foundation material. A settlement platform consists of a square plate of steel, wood, or concrete placed at a known elevation on the original ground surface, to which a riser pipe of known elevation is attached (Figure 4-18). Optical leveling measurements to the top of the riser provide a record of plate elevations. Although a simple and frequently used device, the riser pipe tends to interfere with fill placement, and can readily be damaged if not protected.

(2) A *buried plate* is identical to the steel or concrete base plate of a settlement platform, and its use overcomes problems associated with the coupled riser pipe. To take an elevation reading on the plate, a vertical borehole is drilled, jetted, or augered from an accurately surveyed surface position, the plate located, and a depth measurement made. An accurate record must of course be made of the initial location of the plate in plan and elevation, and the plate must be large and level.

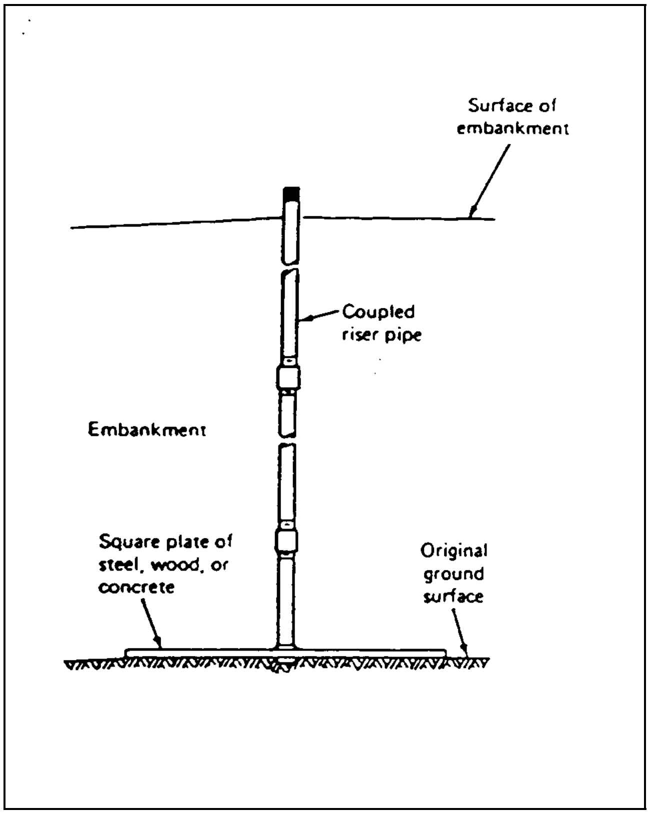

Figure 4-18. Typical settlement platform (Dunnicliff 1988)

(3) Gages with electrical linear displacement transducers (Figure 4-19) are used for monitoring horizontal strain in embankment dams. The transducers can be any of the types described in paragraph 4-2*d*.

d. Subsurface settlement points. Subsurface settlement points are used for monitoring consolidation settlements in embankment and foundation material. The device consists essentially of a riser pipe anchored at the bottom of a vertical borehole and an outer casing to isolate the riser pipe from downdrag forces caused by settlement of soil above the anchor. Settlement of the anchor is determined by measuring the elevation of the top of the riser pipe, using surveying methods. Figure 4-20 shows one example.

e. Fixed borehole extensometers.

(1) *Fixed borehole extensometers* are defined in this manual as devices installed in boreholes in soil or rock for monitoring the changing distance between two or more points along the axis of a borehole, without use of a

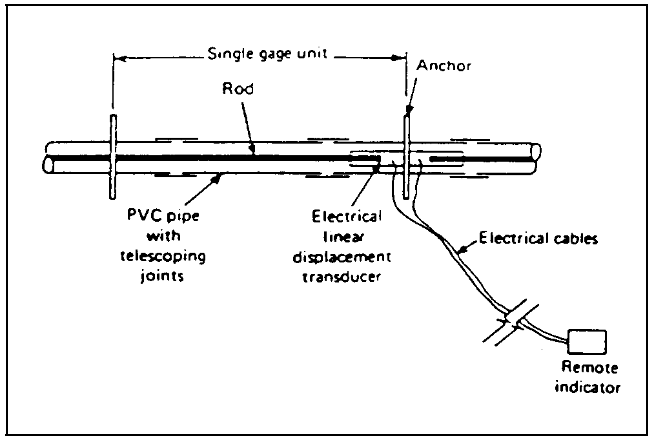

Figure 4-19. Schematic of fixed embankment extensometer with electrical linear displacement transducers (Dunnicliff 1988)

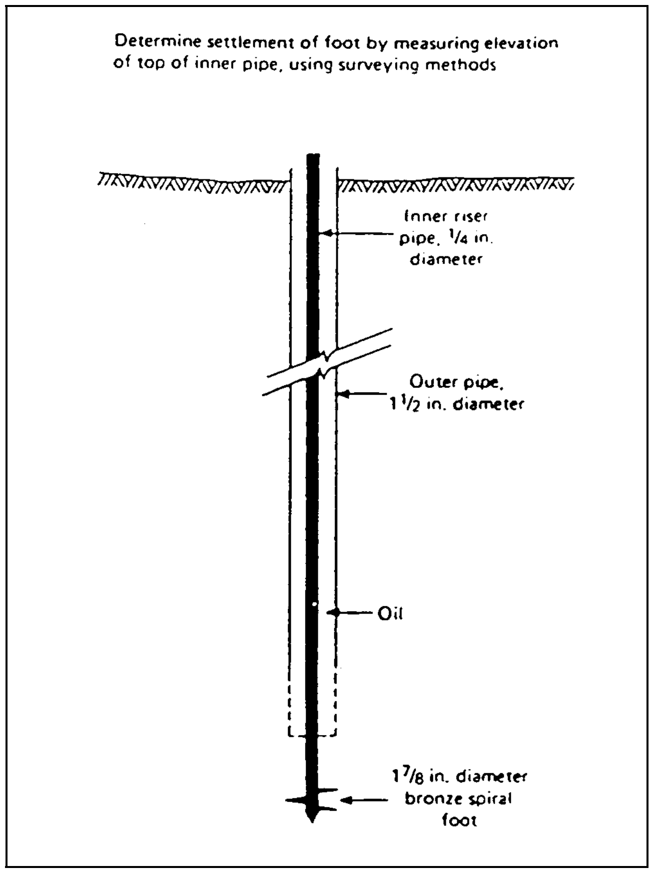

Figure 4-20. Schematic of spiral-foot subsurface settlement point (Dunnicliff 1988)

movable probe. When the location of one measurement point is determined with respect to a fixed reference datum, the devices also provide absolute deformation data.

(2) Many types of fixed borehole extensometers are available, the primary variables being anchor type, SPBX or MPBX, transducer type, and extensometer head. A typical application is monitoring deformations behind the faces of excavated slopes. The operating principle is shown in Figure 4-21. The distance from the face of the collar anchor to the end of the rod is measured using either a mechanical or an electrical transducer (paragraph 4-2*d*). The device shown is a single-point borehole extensometer (SPBX), but several downhole anchors can be located in a single borehole, each with an attached rod from the downhole anchor to the collar anchor, to create a multipoint borehole extensometer (MPBX). MPBXs are used to monitor the deformation or strain pattern along the axis of an appropriately oriented borehole, for example, so that potential failure zones can be located and dangerous deep-seated movements separated from surface spalling.

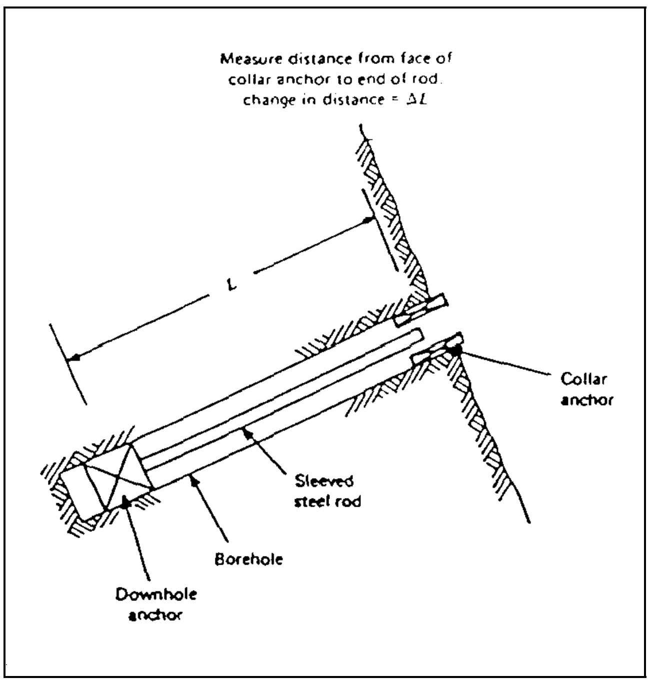

Figure 4-21. Operating principle of fixed borehole extensometer (Dunnicliff 1988)

f. Inclinometers. Inclinometers are defined as devices for monitoring deformation parallel and normal to the axis of a flexible pipe by means of a probe passing along the pipe. The probe contains two gravity-sensing transducers (usually a force balance accelerometer, as shown in Figure 4-7) designed to measure inclination with respect to the vertical. The pipe may be installed either in a borehole or in fill, and in most applications is installed in a near-vertical alignment, so that the inclinometer provides data for defining subsurface horizontal deformation.

(1) Typical applications for inclinometers include monitoring the extent and rate of horizontal movement of embankment dams and levees, both in the fill and foundation, and monitoring slope stability. As shown in Figure 4-22, an inclinometer system consists of four components: a guide casing, a portable probe, a portable readout unit, and a graduated electrical cable. Guide casings, made of ABS (acrylonitrile/butadiene/styrene), are provided by the inclinometer manufacturer and are available in various sizes, are suitable for most applications, and are available with telescoping couplings for installations where significant vertical compression is expected. Aluminum alloy casing has been used, but several instances of total corrosion within a few months have been reported, and its use is not recommended.

(2) After installation of the casing and surveying of its tip location, the probe is lowered to the bottom and an inclination reading is made. Additional readings are made as the probe is raised incrementally to the top of the casing, providing data for determination of initial casing alignment. The differences between these initial readings and a subsequent set define any change in alignment. Provided that one end of the casing is fixed from translation or that surface translation is measured by separate means, these differences allow calculation of absolute horizontal deformation at any point along the casing.

(3) Inclinometer casing can also be installed horizontally in the downstream shells of embankment dams, providing data for determining vertical deformation.

(4) In-place inclinometers operate in the same guide casing as conventional probe-type inclinometers, but a series of gravity sensing transducers are left in place in the casing. When compared with conventional inclinometers, advantages include more rapid reading, an option for continuous automatic reading, and an option for connection to a console for transmission of data to remote locations or for triggering an alarm if deformation exceeds a predetermined amount. Disadvantages include greater complexity and expense of the hardware, environmental (water) damage protection for the electronics, and the inability to confirm data quality by using the inclinometers "check-sum" procedure. In-place inclinometers are

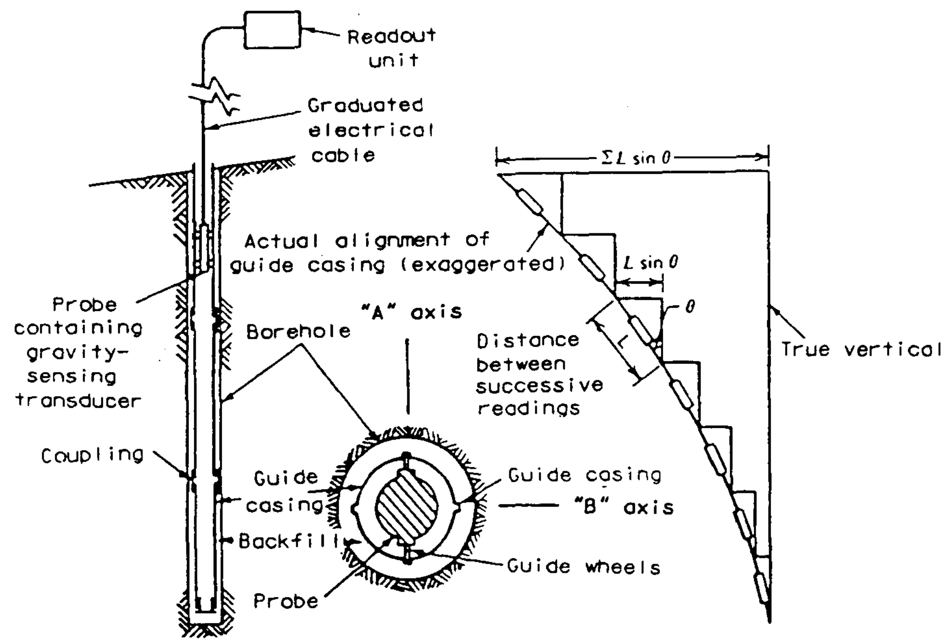

Figure 4-22. Principle of inclinometer operation (Dunnicliff 1988)

most advantageous when placed so that they span a previously defined shear zone.

g. Liquid level gages. Liquid level gages are defined in this manual as instruments that incorporate a liquid-filled tube or pipe for determination of relative vertical deformation. Relative elevation is determined either from the equivalence of liquid level in a manometer or from the pressure transmitted by the liquid.

(1) The primary application for liquid level gages is monitoring settlements within the foundation or fill of embankment dams and levees. In general, they are alternatives to vertical probe extensometers, settlement platforms, and subsurface settlement points, allowing installation to be made without frequent interruption to normal fill placement and compaction, and minimizing the potential for instrument damage.

(2) In general, liquid level gages are sensitive to liquid density changes caused by temperature variation, to surface tension effects, and to any discontinuity of liquid in the liquid-filled tube. Precision claimed by the manufacturers of these instruments is sometimes unrealistic, and the various sources of error must be minimized. Gages can be categorized as *single-point gages* and *full-profile gages*.

(3) The simplest single-point gage is shown in Figure 4-23. The gage is normally read by adding liquid to the liquid-filled tube at the readout station, causing overflow in the cell such that the visible level at the readout station stabilizes at the same elevation as the overflow point. The vent tube is essential to maintain equal pressure on both surfaces of liquid, and the drain tube is needed to allow overflowed liquid to drain out of the cell.

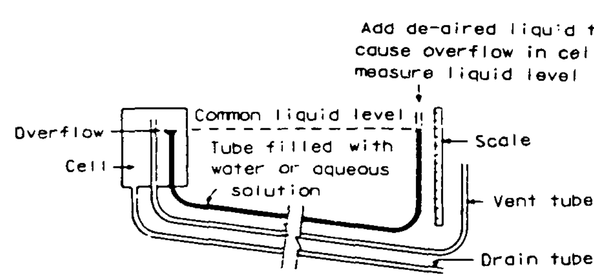

Figure 4-23. Schematic of overflow liquid level gage with both ends at same elevation (Dunnicliff 1988)

(4) Other types of single-point liquid level gages are arranged such that the readout station can be either at a

higher or lower elevation than the cell. Figure 4-24 shows an example of the first configuration. The upper surface of the liquid column is at a known elevation at the readout location; therefore, relative elevation of the transducer and reservoir can be determined from the pressure measurement and liquid density. Experience has shown that, despite using de-aired liquid in these instruments, continuity of liquid can rarely be maintained, causing reading errors. Improved versions are available, in which the entire liquid-filled part is backpressured with gas. By recording the measured pressure and backpressure as the backpressure is increased, the point at which any discontinuities are forced into solution can be determined, and this source of error is eliminated.

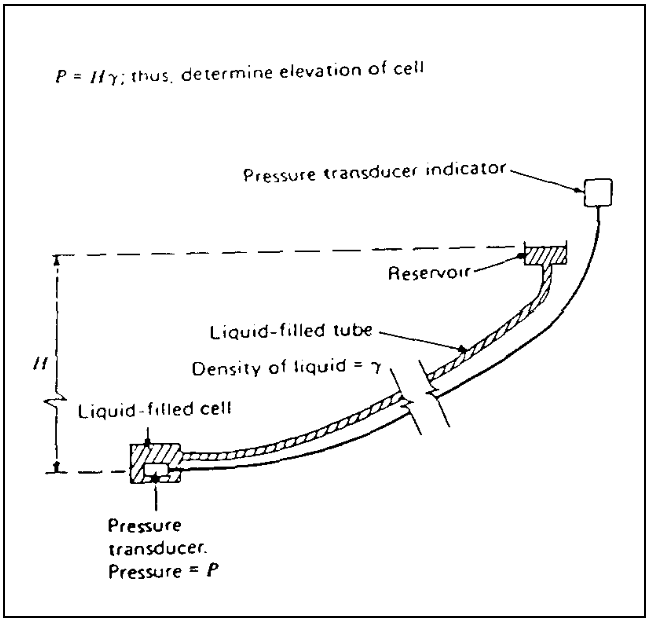

Figure 4-24. Schematic of liquid level gage with pressure transducer in cell, with readout unit higher than cell (Dunnicliff 1988)

(5) Most full-profile gages consist of a near-horizontal plastic pipe and an instrument that can be pulled along the pipe. Readings are made at points within the pipe, and the entire vertical profile can be determined. Differences in vertical profile with time provide data for determination of vertical deformation. The only application for this type of gage is in the downstream shells of embankment dams. The most frequent use has been as part of a *horizontal plate gage*, requiring installation of a near-horizontal telescoping pipe in the downstream shell. Horizontal deformation measurements are made by passing an induction coil probe extensometer (paragraph 4-4*b*) along the pipe, and vertical deformation measurements are made with a full-profile gage, based on the principle shown in Figure 4-23.

(6) Another version of full-profile gage, the *double fluid settlement gage*, has been successfully used to monitor vertical deformation along a continuous loop of nylon tubing installed throughout various zones in embankment dams, including the core, transition zones, and both shells. The gage is shown in Figure 4-25.

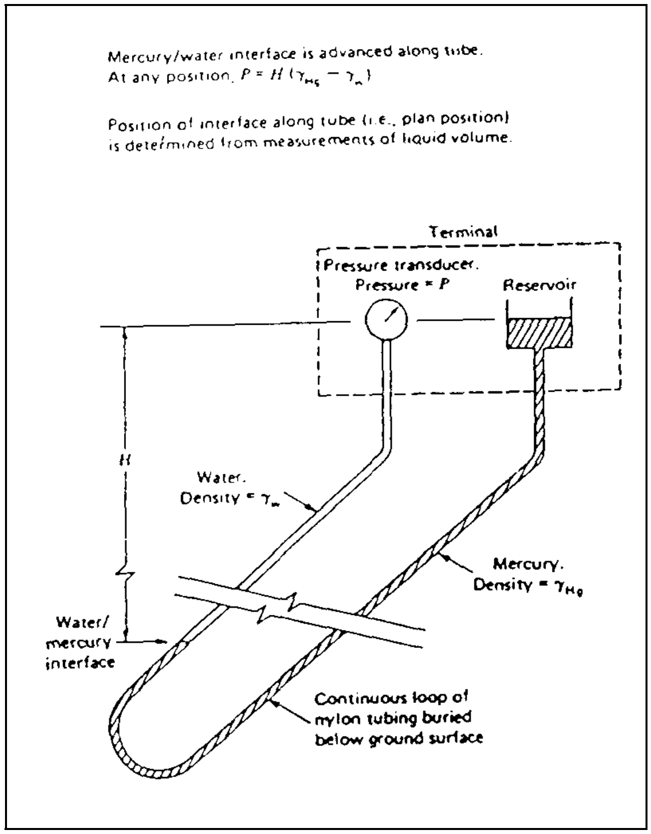

Figure 4-25. Schematic of double fluid settlement gage (Dunnicliff 1988)

h. Recommended instruments for measuring deformation of embankment dams and levees. Table 4-3 summarizes suitable instruments. The choice among the various possibilities depends on site-specific considerations and on a comparison of cost of the total monitoring program.

4-5. Measurement of Total Stress

Total stress measurements in soil fall into two basic categories: measurements within a soil mass and measurements at the face of a structural element. In this manual the terms *embedment earth pressure cells* and *contact* *earth pressure cells* are used for the two basic categories, respectively.

a. Applications. Embedment earth pressure cells are installed within fill, for example, to determine the distribution, magnitude, and direction of total stress within an embankment dam. Applications for contact earth pressure cells include measurement of total stress against retaining walls and culverts. The primary reasons for use of earth pressure cells are to confirm design assumptions and to provide information for the improvement of future designs; they are usually inappropriate for construction control or other reasons.

b. Embedment earth pressure cells. Attempts to measure total stress within a soil mass are plagued by errors, because both the presence of the cell and the installation method generally create significant changes in the free-field stress. It is difficult and expensive to match the elastic modulus of the earth pressure cell to that of an individual soil. It is also very hard to place the cell under field conditions so that the material around the cell has the same modulus and density as the surrounding soil or rockfill, and with both faces of the cell in intimate contact with the material. It is also very difficult and costly to perform a truly representative calibration in the laboratory to determine the cell response or calibration factor. Therefore, it is usually impossible to measure total stress with great accuracy.

(1) There are two basic types of embedment earth pressure cells: *diaphragm cells* and *hydraulic cells*. Examples of the two types are shown in Figure 4-26.

(2) Numerous factors affect measurements, including the ratio of cell thickness to diameter (aspect ratio), the ratio of soil stiffness to cell stiffness, cell size, and field placement effects. The accepted field installation procedure involves compacting fill with heavy equipment, installing the cells in an excavated trench, and backfilling

Table 4-3
Suitable Instruments for Measuring Deformation of Embankment Dams and Levees

Measurement	Suitable Instruments	Additional Instruments for Special Cases
Vertical deformation of embankment surface, and ground surface at and beyond toe of embankment	Optical leveling Trigonometric leveling Satellite-based system Benchmarks	
Horizontal deformation of embankment surface, and ground surface at and beyond toe of embankment	Electronic distance measurements Triangulation Satellite-based system Horizontal control stations	
Vertical deformation below surface	Single-point and full-profile liquid level gages Double fluid settlement gages Horizontal plate gages Horizontal inclinometers Benchmarks	Settlement platforms[a] Buried plates Subsurface settlement points[a] Probe extensometers with induction coil or magnet/reed switch transducers, installed vertically[a]
Horizontal deformation below surface	Horizontal plate gages Probe inclinometers[a] Horizontal control stations	Fixed embankment extensometers with vibrating wire linear displacement transducers In-place inclinometers[a]

[a] If carried up through fill, there will be significant interruption to construction and the probability of inferior compaction. If inclinometer casing is used in an embankment dam, it should be installed within the filter zone, not within the core.

Source: Dunnicliff (1988)

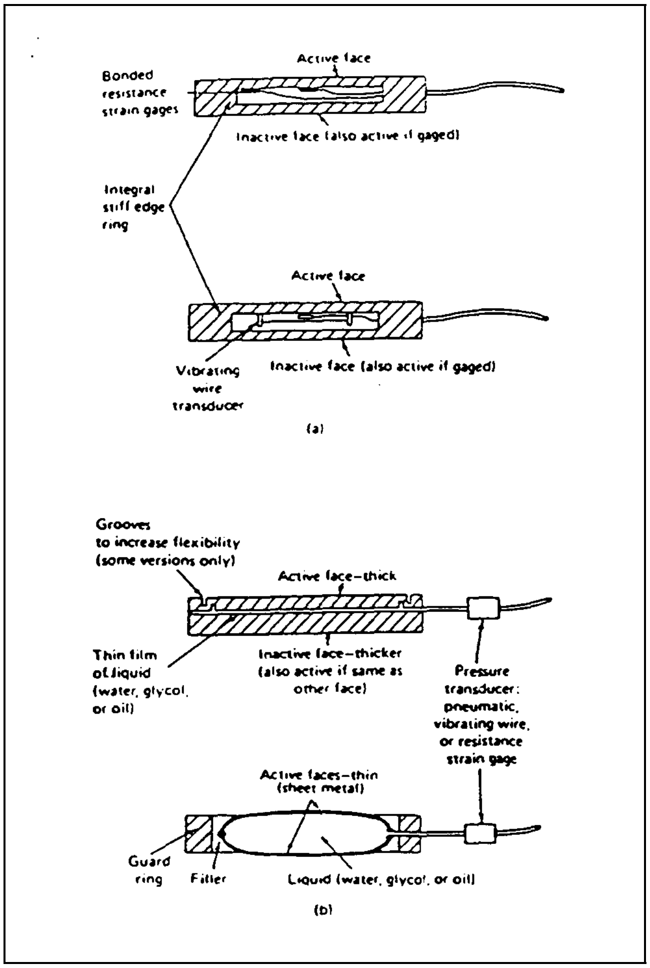

Figure 4-26. Basic types of earth pressure cell: (a) diaphragm cells and (b) hydraulic cells (Dunnicliff 1988)

around and over them by hand tamping or light machine. The probability is high that cells are therefore surrounded by a zone of soil with greater compressibility than the remainder of the fill, that imposed stresses are therefore redistributed by arching, and that substantial under-registration occurs.

(3) Experience has shown that hydraulic cells are less subject to error than diaphragm cells. Diaphragm cells are designed and calibrated for a uniformly distributed load on the active faces, and point loads, stress nonuniformities, or arching will cause significant errors. Hydraulic cells are also subject to errors from these causes but to a lesser extent than diaphragm cells. The best choice appears to be a hydraulic cell with aspect ratio less than 1/15, thick active faces, grooves in the faces as shown in Figure 4-26(b), and a thin layer of liquid. The grooves help to minimize the effect of nonuniform loading on the faces of the cell and lateral stress effects.

c. Contact earth pressure cells.

(1) Measurements of total stress against a structure are not plagued by so many of the errors associated with measurements within a soil mass, and it is possible to measure total stress at the face of a structural element with greater accuracy than within a soil mass. However, cell stiffness and the influence of temperature are often critical. The primary needs are to install the sensitive face of the cell exactly flush with the surface of the structural element, and to ensure that the cell does not create a "soft spot." Again, a grooved hydraulic cell with a thick active face and a thin layer of liquid appears to be the best choice.

(2) Contact cells may be subjected to a condition that does not exist for embedment cells. As concrete in the structural element cures, its temperature increases, and the temperature of the cell is therefore increased. The possibility therefore exists for the cell to expand, pushing the weak concrete away from the cell and, when the concrete takes its initial set and cools, for the cell to cool, contract, and uncouple itself from the surrounding concrete. In this condition the cell would not be responsive to subsequent stress changes. It is therefore preferable to construct the cell with one steel plate approximately 0.5 in. (13 mm) thick and to place that plate against the concrete, thereby ensuring that any expansion occurs outward.

4-6. Measurement of Temperature

Applications for measurement of temperature fall into two general categories. For example, during attempts to detect seepage and to monitor changes in the seepage pattern in an embankment dam, temperatures are monitored internally within the embankment. Second, when a transducer itself is sensitive to temperature change, then a thermal correction to measured data may be required.

a. Types of instruments. Three types of instruments are most frequently used for remote measurement of temperature: thermistors, thermocouples, and resistance temperature devices (RTDs). The name *thermistor* is derived from *therm*ally sensitive res*istor*. A thermistor is composed of semiconductor material that changes its resistance very markedly with temperature. A *thermocouple* is composed of two wires of dissimilar metals, with one end of each wire joined together to form a measuring junction. At any temperature above absolute zero, a small voltage is generated between the wires at the other end. This voltage is proportional to the difference in temperature of the measuring junction and the temperature of the cold junction. *Resistance temperature devices* depend on the principle that change in electrical resistance of a wire is proportional to temperature change. The wire is usually mounted on a postage-stamp-sized backing or wound on a small-diameter coil.

b. Recommended instruments for measuring temperature. All three types of instruments are suitable for remote measurement of temperature, the choice depending on the application. Comparisons are given in Table 4-4. All three types have wide temperature range and rapid response to temperature changes.

4-7. Measurement of Seismic Events

The outdated concept that seismic instrumentation of embankment dams and reservoir sites is only a research tool has given way to the modern concept that seismic instrumentation is necessary for moderate-to-high hazard dams in seismic areas. It is also desirable in traditionally nonseismic areas. With the advent of digital seismic equipment, it can now be an integral part of a dam safety program in each CE district. The digital earthquake data can be gathered by site personnel and district personnel by the use of a portable computer. When the digital instrument is installed with a modem and telephone line then remote access from several offices is available. Servicing parameters such as battery voltage, memory available, functional test of accelerometers and the number of events recorded are available to check the integrity of the instrument from a remote location. Software for time history display and for full analysis makes data reporting quick and easy. Digital accelerographs can be part of other data acquisition systems: for example, a trigger device for piezometer recordings or for a slope stability study during an earthquake, a telephone calling system to report an earthquake event, or a multirecorder installation to study the response of an intake tower.

a. Seismic instrumentation. Three types of recording devices are popular today. They are (1) accelerograph, (2) seismic acceleration alarm device (SAD), and (3) nonelectronic peak accelerograph recorder. Typically three accelerographs and one peak accelerograph recorder are installed per site. The SAD is installed where a display of peak acceleration is required immediately

Table 4-4
Comparison of Instruments for Remote Measurement of Temperature

Feature	Thermistor	Thermocouple	Resistance Temperature Device (RTD)
Readout	Digital ohmmeter or multimeter	Thermocouple reader	Wheatstone bridge with millivolt scale
Sensitivity	Very high	Low	Moderate
Linearity	Very poor	Fair	Fair
Accuracy	High	Moderate	Very high (but may be reduced by lead wire effects)
Stability	Excellent	Good	Excellent
Type of lead wire	Two-conductor	Special (bi-metal)	Three-conductor
Repairability of lead wire	Straightforward	Less straightforward (can cause errors)	Straightforward
Applicability for instrument temperature corrections	Preferred	Possible	Possible
Suitability for automatic data acquisition	Fair	Excellent	Good

Source: Dunnicliff (1988)

following an earthquake. For all USACE facilities, the SAD is supplied by the USACE Waterways Experiment Station (WES).

b. Accelerograph. An accelerograph measures acceleration triaxially at the location the instrument is anchored to the structure. These accelerations are mutually perpendicular and are called vertical, longitudinal, and transverse. All instruments at the structure are aligned in the same direction usually with the longitudinal axis parallel with the long axis of the dam. Accelerographs are available in analog and digital models. It is recommended that digital instruments be installed and connected to a modem and telephone line. Typically the three accelerographs are located on the center of the crest, on one of the rock abutments and on downstream rock, a minimum distance of “three heights of the dam” from the toe of the structure. A short, lightweight shelter anchored to a thin concrete pad is recommended for housing the accelerographs (Figure 4-27). The instrument is powered by 12-volt batteries, and it is necessary to have AC power and a trickle charger to maintain peak battery capacity.

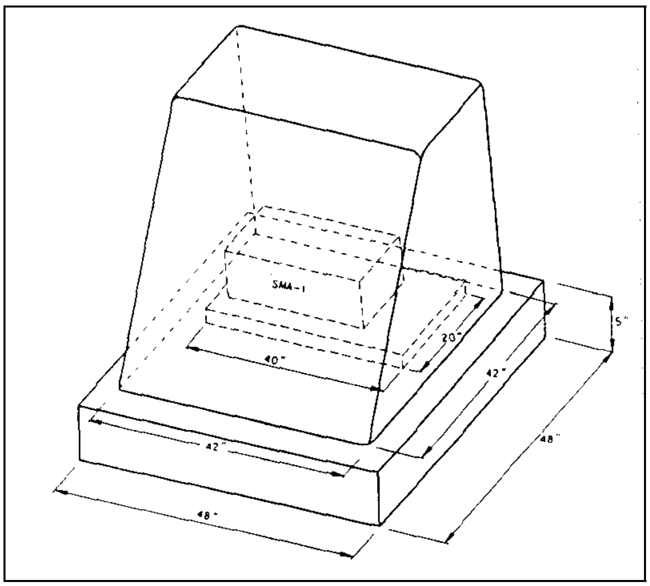

Figure 4-27. 41-2 shelter on a concrete pad for housing accelerograph

(1) Analog accelerograph. The analog instrument records data on 70-mm film which must be recovered under low light conditions and chemically processed to develop the film. A component diagram of an analog accelerograph is shown in Figure 4-28. The film roll is 15.24 m (50 ft) in length and can normally record 25 earthquake events. Full-scale recorder range is 1.0 g. Recording scales larger than 1.0 g are available. The analog earthquake data are optically digitized, and the computer- generated tape is processed with mainframe computer software at WES for data analysis and reporting.

(2) Digital accelerographs. The digital instrument continuously digitizes the three internal force balance accelerometers and stores data in solid state memory. A component diagram of a digital accelerograph is shown in Figure 4-29. When an earthquake event triggers the instrument, sensed by the three internal accelerometers, the pre-event data are saved plus the data occurring during the earthquake and post-event data following cessation of the motion. Digital data are saved with a file number and header information. The digital instrument will return to digitizing accelerometer data until another earthquake event occurs and another data file is saved. Full-scale recorder range is 1.0 g. Depending upon memory size, 512K bytes is standard, approximately 20 minutes of recording time is available. The data files are downloaded locally by an RS-232 connection to a portable computer or to a remote computer by modem and telephone. Personal computer software is provided with each instrument to display the data for each internal force balance accelerometer in time history plot format and to read the associated header information as shown in Figure 4-30. Computer software is also available for more detailed analysis processing, for example, single and double integration and spectrum analysis.

c. Seismic acceleration alarm device (SAD). The SAD stores and displays a vertical acceleration peak level in a wall-mounted unit easily read by site personnel. The display increments are 0.05 g and it has a range from 0.05 g to 0.5 g. The unit can be connected, by a relay closure, to a remote alarm, annunciator panel, telephone dialer, or recorder. The SAD is AC powered with a battery backup.

d. Peak accelerograph recorder (nonelectronic). The peak accelerograph recorder senses and records acceleration peaks triaxially. These accelerations are mutually perpendicular and are called vertical, longitudinal, and transverse. It is a self-contained passive device requiring no external power or control connections with a sensitivity as low as 0.01 g. The records are scratched permanently on metal plates or magnetized strips of recorder tape. The triaxial plates or tapes are read with an optical loupe and a calibration factor is applied to obtain peak acceleration levels. Full-scale recorder range is 2.5 g. Typically, one peak accelerograph recorder is co-located with an accelerograph at the crest station for redundancy and events greater than 1.0 g.

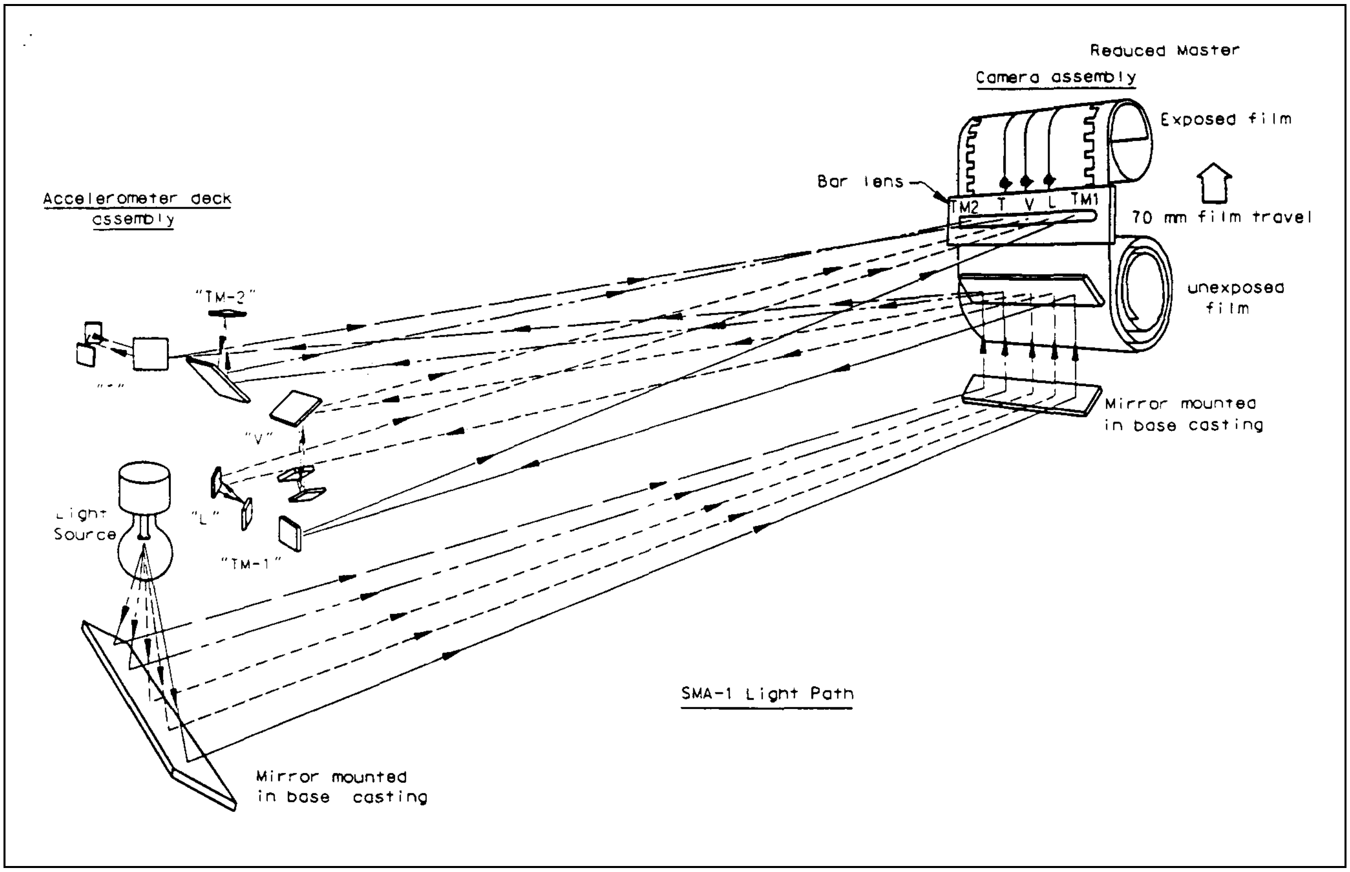

Figure 4-28. Analog/accelerograph component diagram (courtesy of Kinemetrics, Inc., Pasadena, CA)

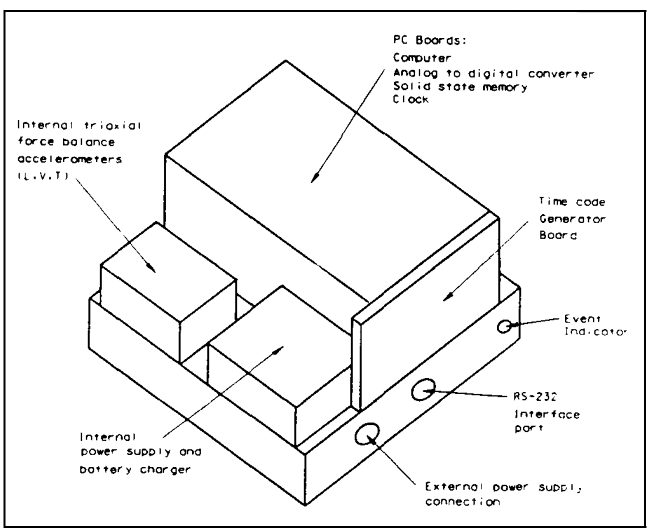

Figure 4-29. Digital accelerograph component diagram

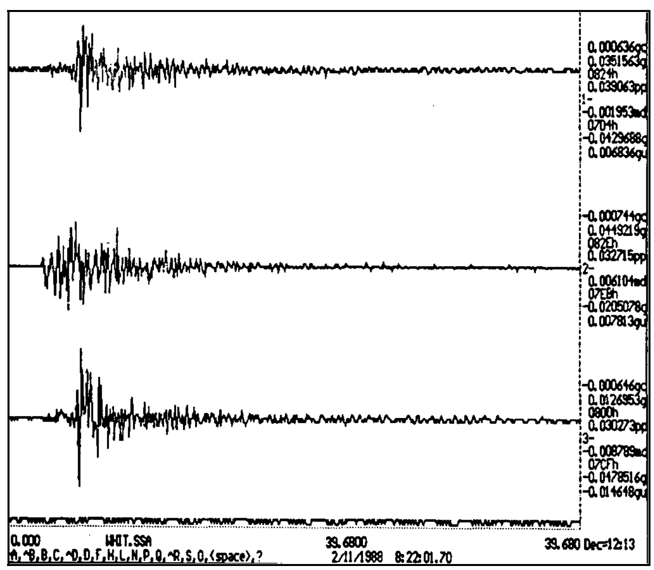

Figure 4-30. Digital accelerograph data plot

e. Strong-motion instrumentation program (SMIP). In 1973 the issuance of ER 1110-2-103 essentially required instrumentation of all USACE dams that exist within seismic risk zones 2, 3, and 4 (ER 1110-2-1806). ER 1110-2-103 also established the WES Strong-Motion Instrumentation Program (SMIP) and its responsibilities. WES provides assistance to each CE district and division by reviewing each structure's installation plan to assure conformance with HQUSACE policy, by maintaining records of instrument locations and servicing, by providing instrumentation services personnel for installation and maintenance of CE instruments, by gathering, processing, and analyzing earthquake records obtained, and by furnishing copies of records and reports to the district concerned. WES reviews and evaluates new instruments and assists districts in the selection and purchasing of needed equipment. (Information about SMIP is provided in an annual engineer circular for Corps-wide distribution.)

4-8. Measurement of Seepage Emerging Downstream

a. Introduction. Seepage measuring devices are used in embankments to measure amounts of seepage through, around, and under the embankment. Monitoring the seepage that emerges downstream is essential to assessing the behavior of a dam during first filling. The first indication of a potential problem is often given by an observed change of seepage rate. Also monitoring the solids content in the seepage water can provide important information. Observations of seepage rate can be correlated with measurements of piezometric pressure, and be used to examine the effectiveness of drains, relief wells, and cutoffs. Seepage measurements are often made during the operating life of a dam to monitor long-term performance. Relief wells, drainage outlets, channels, and ditches are common measuring points of seepage. Some seepage-measuring methods commonly used are discussed in this chapter. These devices and others are described in detail in U.S. Bureau of Reclamation publications (1984, 1987).

b. Weirs. Seepage flows are often measured with weirs that have regular shaped overflow openings, such as V-notch, rectangular, trapezoidal, etc. The seepage rates are determined by measuring the vertical distance from the crest of the overflow opening to the water surface in the pool upstream from the crest. The measurement is then used to compute the flow rate, by reference to tables for the size and shape of the weir. The critical parts of weirs are easily inspected and cleaned, and any improper operations can easily be detected and corrected quickly. Weir flows are often measured by monitoring the water level in the weir stilling basin. Methods of water level monitoring include a staff gage, gas purge pressure transducers, submerged pressure transducers, chart recorders, shaft-encoders, sonic transducers (paragraph 4-2*e*), and force transducers. Figure 4-31 shows a useful version of a weir with force transducers, manufactured by Geonor, Norway. Criteria for design of weir stilling basins include adequate length, prevention of false readings by blockage, and protection from freezing.

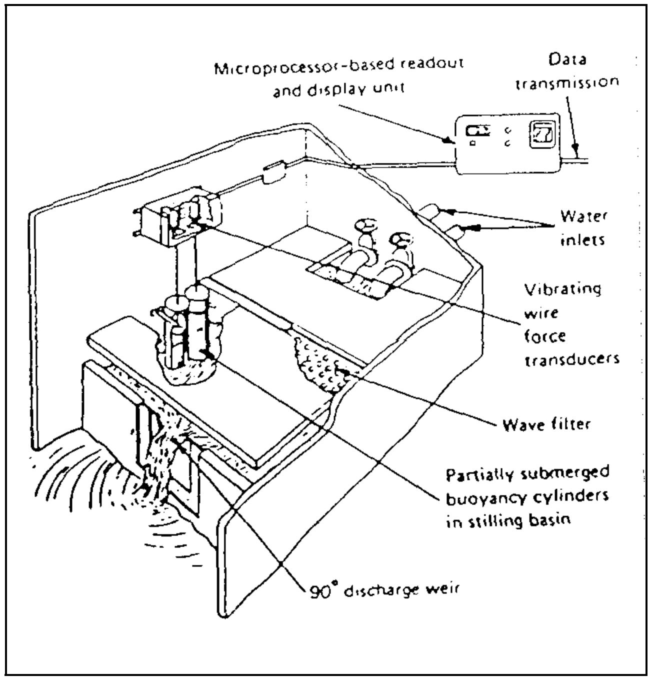

Figure 4-31. Remote-reading weir for monitoring leakage quantities (courtesy of GEONOR, Inc.)

c. Parshall flumes. Parshall flumes are specially shaped open-channel-flow sections that can be installed in channels or ditches to measure flow rate. The constricting throat of a flume produces a differential head that can be related to flow rate. Methods of water level monitoring are the same as those for weirs. Criteria for design of flume approaches include adequate length, alignment, prevention of false readings by blockage, and protection from freezing.

d. Calibrated catch containers. When occasional measurements of low flows are required, the flow can be diverted into a container of known volume, and the filling time measured.

e. Velocity meters. Several different types of velocity meters are available commercially, from WES, and from the Missouri River Division Laboratory. Their methods of operation vary. Some use the pitot tube principle, others include propeller-type devices, acoustic flowmeters, and electromagnetic current indicators. Most of these devices can be used to measure the flow in pipes or in open channels. Also available is a portable velocity meter which operates on the principle of electromagnetic velocity determination. This device can be used for measuring water velocity in pipes or in open channels, which is then converted to flow.

f. Thermotic surveys/thermal monitoring. Flowing groundwater, of even minor magnitude, influences near-surface soil temperatures to a measurable extent. Thermotic techniques are particularly useful in identifying zones or paths of high permeability and piezometric flow concentrations within fractured rock and surficial deposits. Although these techniques do not replace borings or conventional instrumentation, they can make other monitoring activities more accurate and economical by directing the location of more quantitative investigation methods such as boreholes and pump tests.

g. Precipitation gages. Precipitation can directly affect seepage measurements and should be measured and evaluated with any seepage measurement data. There are numerous precipitation gages available commercially and their selection should be based on the specific site conditions.

h. Water level gages. The difference in head between the reservoir and tailwater levels of a dam, or the riverward water level and the landward side of a levee, provides the potential for seepage through, around, or under the embankment. Therefore, these water levels should be measured and evaluated with any seepage measurement data. There are numerous chart recorders, encoders, manometers, and pressure transducers available commercially and their selection should be based on the specific site conditions. Pressure transducers that can be used to measure these water levels parallel techniques used to measure piezometric pressure and are discussed in paragraph 4-3.