Chapter 13

INSTRUMENTATION AND PERFORMANCE MONITORING

The design of coal refuse disposal facilities is governed by criteria for achieving desired levels of structural, geotechnical and hydraulic performance from initial startup through facility construction and operation to abandonment. To verify that the desired performance levels are being achieved, instrumentation should be installed and regularly monitored. Timely collection and review of instrumentation data can allow performance problems to be detected and addressed before unsafe conditions develop. This chapter discusses the factors that should be considered in planning a site-specific instrumentation program and the types of devices used for monitoring. Supporting discussion regarding the uncertainty associated with instrument measurements and types of instrument transducers and data acquisition systems is presented in Appendix 13A. Data typically monitored and the types of instrumentation most commonly used to monitor embankment performance at coal refuse facilities include:

- Vertical and lateral displacements at the ground surface using surface monuments
- Impoundment pool levels using staff gauges
- Piezometric levels and pore-water pressures in embankments and foundations using standpipe and vibrating-wire piezometers
- Surface water flow primarily from seepage and mine discharges using weirs
- Subsurface vertical and lateral displacements in situations of adverse conditions (e.g., settlement and slope deformation) using extensometers and inclinometers
- Meteorological conditions at or near the facility using weather stations (primarily rainfall gauges)

These and other instrumentation are discussed herein along with the ability to remotely monitor and efficiently process data from instruments.

13.1 INSTRUMENTATION PROGRAM PLANNING

Similar to instrumentation programs for other civil works projects, instrumentation program planning for a coal refuse disposal facility should follow a systematic approach with defined objectives. The process should follow a logical series of steps leading to preparation of construction plans and specifications that prescribe: (1) instrument types and installation methods, (2) performance and maintenance requirements, (3) data acquisition methods, (4) sampling intervals and reporting, and

(5) expected measurement ranges including appropriate action and hazard warning levels. This systematic approach, as defined by Dunnicliff (1997), should follow the steps presented in Table 13.1. The full benefit of an instrumentation program can best be realized if these steps are considered and carefully implemented. In doing so, the following adage by Ralph Peck (1972) can be realized,

> *"We need to carry out a vast amount of observational work, but what we do should be done for a purpose and done well."*

Monitoring the performance of coal refuse disposal facilities typically involves the measurement of deformations, piezometric levels, impoundment levels, seepage flows, and other site-specific parameters. The steps presented in Table 13.1 provide a rationale for determining the instrumentation and staffing requirements, establishing provisions for instrument maintenance, and identifying the use and benefit of monitoring results. Table 13.1 can be used as a design aid to focus attention on the important parameters and locations to be monitored and to avoid the use of instrumentation that may yield little value. Among the critical steps is No. 2 – defining performance questions that need to be answered. Performance questions arise from project or geotechnical conditions that could lead to instability or non-functionality of portions of the structure. Often, critical performance features such as an internal drain or suspect conditions such as a weak subsurface foundation layer beneath the facility or an observed seepage condition, may play a role. These critical or suspect conditions will then be the focus of performance questions related to instrumentation.

Some performance questions that are typically relevant for coal refuse disposal impoundments are summarized in Table 13.2. While this list includes common questions, each site will undoubtedly have unique features or conditions that may introduce other performance questions. At new facilities, the designer must rely on project information and engineering analyses and judgment to identify performance questions and select instrumentation. At existing facilities, where some performance data are available, the designer may identify suspect conditions such as observed seepage or deformation that may lead to more refined answers to the performance questions.

While impoundments are generally facilities where the consequences of non-performance are great, instrumentation should also be employed at non-impounding embankments and slurry cell facilities. Similar performance questions and suspect conditions should be evaluated as part of the identification of the need for and the types of instrumentation to be employed.

In selecting an instrument to measure a desired parameter within the project setting, consideration should be given to: (1) instrument error and uncertainty, (2) instrument type reliability and survivability relative to its expected application, and (3) possible integration of the instrument into a data acquisition system to facilitate data collection, processing, management and decision making. Discussion of the uncertainty associated with instrument measurements and the types of instrument transducers and data acquisition systems is presented in Appendix 13A.

13.2 MEASUREMENT TECHNIQUES

Instrumentation is typically installed at coal refuse disposal facilities to monitor movements and displacements, piezometric levels and pore-water pressures, and surface- and seepage-water flow and the hydrologic and operational factors that influence these flows. Instruments may also be installed to monitor miscellaneous factors such as soil pressure, vibration and shock, and internal temperatures. The following subsections discuss the significance of these measurements and instrumentation that can be used to provide the required data.

Selection of appropriate instrumentation depends on a variety of factors discussed in the previous sections of this chapter. In addition, instrument selection relates to whether performance monitoring

TABLE 13.1 INSTRUMENTATION PLANNING AND DESIGN STEPS

Step 1	**Define project conditions and mechanisms that control expected behavior** including subsurface conditions and stratigraphy, engineering properties of subsurface soil, rock and groundwater, environmental conditions and other factors that may affect the planned construction.
Step 2	**Define the performance questions that need to be answered.** For a coal refuse facility these might include: (1) What are the initial or current site conditions? (2) Is performance satisfactory during construction and facility operations? and (3) Is performance satisfactory during special loading conditions such as rapid drawdown or upstream construction?
Step 3	**Select the most important parameters to be monitored, magnitudes of change, and each type of instrumentation** considering parameter variations resulting from both cause and effect. For example, lateral slope displacements may result from elevated groundwater levels, and specific hazard warning levels can be determined. If a clear purpose cannot be defined, the need for instrumentation cannot be defended.
Step 4	**Identify staffing responsibilities for monitoring, interpreting and devising remedial action(s)** in terms of required labor and materials needed to respond to problem situations, including resources and reporting requirements.
Step 5	**Select instruments and locations** considering reliability for measurement of the desired parameter within the project site setting and the appropriateness of the location for measuring predicted behavior, compatibility with methods of analysis to be used, and device survivability. Other features that should be considered include in-service calibration, operator skill requirements, potential interference during construction, and location access during installation and reading.
Step 6	**Develop record of factors that may affect the measured data and establish procedures for controlling data quality** such as geologic conditions in the vicinity of the instrument, use of redundant instruments, regular examination of data for consistency, and in-service calibration checks.
Step 7	**Prepare instrumentation system report, budget and procurement specifications** summarizing Steps 1 to 6 and including sections on the contracting method and basis for instrument procurement and field instrumentation services.
Step 8	**Integrate instrumentation system report into the Operation and Maintenance Plan,** including data collection, processing, presentation, interpretation, reporting, calibration and maintenance.

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is required for a relatively short period of time up to a few years, or for a much longer time period up to and including the expected service life of the refuse facility.

13.2.1 Movements and Displacements

The performance of embankments can generally be evaluated by monitoring the movement of the embankment surface or configuration changes within the embankment and its foundation. For static loading conditions (i.e., no earthquake or blasting loads), movement can be determined by: (1) visual observation, (2) measurement of surface movements, and (3) measurement of internal movements. Table 13.3 provides an evaluation of each approach relative to complexity and cost, applicability, and limitations. Additional information is provided by Dunnicliff (1981), Hanna (1985), Bartholomew et al. (1987), Dunnicliff (1993) and USACE (1995c).

13.2.1.1 General Observations

Periodic surveying of monuments and instruments provides an effective means for observing the magnitude and rate of change of deformations at a coal refuse disposal facility during:

- Initial facility development and initial disposal operations
- Normal disposal operations

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TABLE 13.2 PERFORMANCE QUESTIONS FOR SLURRY IMPOUNDMENTS

Questions	Typical Instruments for Monitoring	Other Typical Measures for Monitoring Suspect Conditions
Embankment Conditions		
1. Where is the phreatic surface:		
a. in the refuse embankment?	Piezometers	
b. in the fine refuse deposit (e.g., when upstream construction is employed)?	Closed-System Piezometers	
2. What is the seepage rate?	*Weirs*	
3. What is the discharge rate from an internal drain?	Weirs	
4. Are embankment grades and alignments conforming to plans?	Survey Monument	*Survey Methods*
5. Are unacceptable deformations occurring: a. at the embankment surface? b. within the embankment?	Survey Monument	*Survey Methods* *Inclinometer*
6. Could unacceptable pore-water pressure develop due to the effects of the rate of fill placement, rapid drawdown, or earthquake loading?	Closed-System Piezometers	
7. Could unacceptable deformations develop due to the effects of the rate of fill placement, mine subsidence, rapid drawdown, or earthquake loading?	Survey Monuments *Extensometers*	*Survey Methods* *Inclinometer*
Foundation Conditions		
1. Could unacceptable deformations develop due to the presence of compressible foundation materials, subsidence from mining below the embankment or impoundment, or earthquake loading?	Survey Monuments *Extensometers*	*Geophysical Surveys*
2. Could unacceptable pore-water pressures develop due to the effects of rapid embankment construction, upstream construction over soft fine refuse, or earthquake loading?	Closed-System Piezometers	
3. Could unacceptable pore-water pressures develop due to the effects of an elevated reservoir level or an undetected pervious stratum?	Closed-System Piezometers	
Abutment Conditions		
1. Will excavation or natural slopes be stable: a. during construction? b. long term?	Survey Monuments	*Survey Methods*

TABLE 13.2 PERFORMANCE QUESTIONS FOR SLURRY IMPOUNDMENTS (Continued)

Questions	Typical Instruments for Monitoring	Other Typical Measures for Monitoring Suspect Conditions
2. Could unacceptable deformations or cracking develop due to subsidence from mining beneath the abutment or impoundment?	Survey Monuments *Extensometers*	
3. Could unacceptable pore-water pressures develop due to the effects of an elevated reservoir level or an undetected pervious stratum?	Open-Standpipe Piezometers	
Reservoir Level		
1. Is the water level in the impoundment at an acceptable level, and is there adequate freeboard?	Staff Gage	
Breakthrough Potential		
1. Could an unusual increase in seepage quantity or change in seepage quality from underground mine workings indicate a potential problem related to impoundment leakage or possible breakthrough?	Weir	
2. Could the level of water in underground mine workings have an effect on the impoundment or indicate possible breakthrough?	Observation Well	
Decant Works, Primary or Emergency Spillways		
1. Is the flow rate from the decant acceptable?	Weir	Pipe Discharge Measurement
2. Is the strain within the flexible decant conduit acceptable considering embankment loading and backfill support?	*Dial Gage* *Deflectometer* *Circumferential Survey*	*Camera*
3. Is there movement affecting the primary conduit spillway joints (or cracks) that could lead to separation?	*Dial Gage* *(Crack Monitor)*	
4. Is there movement affecting the lined emergency spillway joints (or cracks) that could lead to separation?	*Dial Gage* *(Crack Monitor)*	
5. Are the excavation slopes for the emergency spillway stable?	*Survey Methods* *Survey Monuments*	
Weather Conditions		
1. How do changes in measured facility performance (e.g., phreatic surface, flow from internal drains) relate to changes in weather conditions such as precipitation?	Precipitation Gage	Weather Station

Note: Instrumentation shown in italics is generally considered when adverse conditions are observed or suspected (e.g., seepage or movement).

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- Changes in the rate of disposal, in the physical characteristics of the fine and coarse coal refuse components, or in the phreatic or piezometric levels in the embankment
- Facility abandonment

Excessive movement or progressively increasing rates of movement can provide a warning of a potential failure and may indicate that modification of a facility operation is necessary.

Long-term periodic monitoring of surface movements provides an inexpensive record of embankment behavior. If changes due to natural phenomena or operations result in a reduction in stability not anticipated in the design, long-term records can provide a forewarning of impending distress. The potential value of surveyed records in relation to their cost justifies the installation of benchmarks and monuments for most types of refuse facilities, even if the instrumentation must be regularly monitored during the facility life and to abandonment.

TABLE 13.3 SUMMARY OF GENERAL METHODS FOR DETECTING EMBANKMENT MOVEMENTS AND DISPLACEMENTS

Technique	Complexity and Cost	Applicability	Limitations
Visual Observations	Low to Moderate	Normally used for monitoring general conditions to identify areas of potential distress where more detailed evaluation is required.	Surface cracking indicates the occurrence of displacements, but does not provide quantitative data.
Measurements of Surface Movements	Low to High	Reasonable costs and high accuracy provide desirable monitoring procedure for practically any condition. Should be routine practice for all facilities.	Surface movements can be very local without being significant to overall safety of facility.
Measurement of Internal Movements	Moderate to High	Necessary when cause of movements is important and surface measurements are not sufficient for interpretation.	Programs requiring complex instrument installation, monitoring and interpretation must be performed by an expert.

If a surface movement monitoring program is implemented primarily to develop long-term records of embankment behavior, the measurement points are usually located along representative cross sections perpendicular to the longitudinal axis of the embankment (e.g., at the toe, on benches, and at the top of slope along each section) and at readily accessible points on other facility structures. A limitation of conventional surveying techniques is that only movements at the surface are monitored. Observations at the surface are not always sufficient for determining if the movements are shallow and relatively unimportant or if they are associated with deeper, more significant conditions occurring within the embankment or its foundation. In the latter case, it may be necessary to install more sophisticated subsurface instrumentation such as inclinometers to better define the mechanism causing the movement and its location.

Optical level surveys (land surveys) are often the best method for monitoring vertical movements due to:

- Settlement resulting from consolidation of an embankment foundation or constituent materials
- Impending stability failure due to embankment movement or foundation deformations
- Surface subsidence from underground mining

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The order of accuracy required for land surveys depends on the total potential magnitude of movement, while the accuracy obtained is a function of the equipment and personnel employed and the reliability of benchmark datums used for control.

Monitoring of horizontal surface movements is useful for detecting conditions that may indicate impending instability or for verifying that such movements are not occurring. Preferably, identical reference points or monuments should be used for measuring both vertical and horizontal movements.

Instruments for measuring vertical displacements within an embankment or its foundation are useful when:

- Accurate settlement data are required for comparison to predicted embankment or foundation settlement.
- The integrity of an impervious core or internal drainage system is dependent on limiting the amount of settlement.
- Large settlements could affect drainage slopes and ditches after abandonment.
- A contractor is being paid for construction on a unit-price basis and the volume of material placed could significantly change based on the magnitude of settlement.
- A rigid structure is to be placed on an embankment at the completion of construction.
- The embankment was constructed over settled fine refuse or the embankment foundation is soft clay and potentially large settlements are a possibility.

The installation of internal settlement instrumentation is not generally recommended for routine refuse disposal embankment construction. However, several of the techniques discussed in the following section are relatively simple and inexpensive, and they may be considered when embankment settlement is important. The installation, monitoring and interpretation of data from these systems should only be undertaken under the supervision of a knowledgeable engineer.

Durability of the installed instrumentation is particularly important for systems placed in an embankment. Care in placement is critical, because instruments can often be irreparably damaged due to improper installation techniques. The high potential for corrosion at coal refuse facilities should always be considered, and plastic pipes are preferred over metal pipes unless it is known that high temperatures that might affect the long-term behavior of the plastic pipe could occur.

For all types of instrumentation, erroneous data are much more likely when vertical settlement is coupled with large horizontal movement. In such cases, instrumentation for measurement of both vertical and horizontal movements should be installed. The purpose of measurement of horizontal displacements within an embankment is normally to determine if there is instability and the depth at which movement is occurring or to verify that surface distortions due to creep movements do not have a deeper origin. Inclinometers are often used to determine the depth to the surface where movement is occurring prior to implementation of remedial measures so that the costly remedial effort is focused solely on the problem area.

Normally, sophisticated instrumentation is not required for newly-constructed refuse embankments designed in accordance with current engineering practice and constructed in conformance with detailed plans and specifications. Possible exceptions may include embankments:

- Located above populated areas.
- Constructed where site conditions do not permit access for the desired scope of exploration and testing, such as where steep slopes and/or dense ground cover limit access to drilling and sampling equipment.

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- Supported on a material that cannot be readily tested, such as settled fine refuse or soft, sensitive clay.
- Constructed over or adjacent to areas of past or active underground mining.
- Where dynamic loading is a critical consideration during design.

More sophisticated instrumentation is often used to investigate existing facilities where limited data relative to site conditions and construction practices (e.g., fill material characteristics) are available. The value of installing and monitoring the instrumentation must be carefully judged against the ability to interpret the data (i.e., the ability to recognize adverse conditions and distress). When internal movement instrumentation is required, the location and arrangement of instruments should be based on the judgment of an expert, and the installation and monitoring should be conducted under the direct supervision of an engineer or technician that is experienced with the equipment used.

Movements associated with dynamic loads (e.g., earthquake or nearby blasting) differ from those associated with static loads in that measurements must be taken during the occurrence of the dynamic condition. Generally, where earthquake considerations are important in the site selection process, potential dynamic displacements are estimated based upon seismic engineering analyses and no on-site measurements are involved. However, in the case of blasting, the amount of movement realized is dependent upon geologic conditions, the explosive material and blasting technique, and the location of the blast relative to the embankment. Often, blasting effects are minor and will not affect embankment stability. Exceptions are when blasting is very close to an embankment or other facility structure or rock abutment or the magnitude of the blast is unusually high. In these isolated cases, surface monitoring of resultant movements may be justified for verification that no significant damage to the refuse disposal facility has occurred. Instrumentation for this purpose is discussed in Section 13.2.4.2.

13.2.1.2 Movement Measurement Techniques

As listed in Table 13.4, Dunnicliff (1993) identifies the following as general categories of deformation measuring techniques:

- Surveying methods
- Surface extensometers
- Tiltmeters
- Probe extensometers
- Fixed embankment extensometers
- Fixed borehole extensometers
- Inclinometers

Descriptions of instrumentation associated with each of these deformation measurement techniques are presented in the following sections. Supplemental techniques for deformation measurement, including transverse-deformation gages, liquid-level gages, time-domain reflectometry, and fiber-optic gages are presented in Appendix 13A at the end of this chapter.

13.2.1.2.1 Surveying Methods

Surveying methods are generally used for monitoring the magnitude and rate of vertical and horizontal movement of the ground surface, structures, and accessible parts of subsurface instruments at construction sites (Dunnicliff, 1993). For many applications, these methods are adequate for performance monitoring, and instrumentation is used only if greater accuracy is needed or if subsurface movements need to be determined. When instrumentation is employed, surveying methods are often

TABLE 13.4 INSTRUMENT CATEGORIES FOR MEASURING MOVEMENTS

Category	H	V	A	R	S	U	Conditions for Use	Relative Complexity	Relative Cost	Applicability to Coal Refuse Disposal Facilities
Surveying Methods	●	●	●		●		Surface movements	Simple	Low to Moderate	Routine for all embankments.
Surface Extensometers • Crack gages • Convergence gages	●	●	●		●		Deformation between fixed points	Simple	Low	Usually limited to structure and rock movements, including subsidence monitoring.
Tiltmeters				●	●	●	Rotations on a surface	Simple	Low to Moderate	Usually limited to structure movements.
Probe Extensometers • Mechanical probe gages • Electrical probe gages • Probe extensometers with inclinometers	●	●	●			●	Displacement (usually vertical) between two or more points along a single axis	Moderate to complex	Moderate	Useful if settlement of soft foundation is critical; normally single settlement plates are adequate.
Fixed Embankment Extensometers • Settlement platform	●	●	●			●	Settlement at single depth. Practical for pre- or post-construction installation	Simple	Low	Useful if settlement of soft foundation is critical.
Fixed Borehole Extensometers • Single- and multi-point • Subsurface settlement points and rod gages	●	●	●			●	Displacement between two or more points along a single axis	Moderate to complex	Moderate	Useful if settlement of soft foundation or rock slopes is critical.
Inclinometers	●	●	●	●		●	Movement profiling in vertical, horizontal or inclined casings	Moderate	Moderate	Most commonly used method, but limited to zones where deformation profiles are needed or are a concern.
Transverse-Deformation Gages • In-place inclinometers	●	●	●			●	Movement profiling	Moderate to complex	Moderate to High	Useful only if automatic monitoring is planned.
Liquid-Level Gages • Single- and multi-point gages • Full-profile gages		●				●	Settlement of foundation or embankment fill	Moderate to complex	Moderate	Useful if settlement of soft foundation is critical.
Time-Domain Reflectometry	●	●	●		●	●	Movement detection at locations along cable axis	Moderate	Low to Moderate	Still evolving method, but shows excellent promise.
Fiber-Optic Sensors	●	●	●		●	●	Local deformation and strain measurements	Moderate	Moderate to High	Still evolving method, but shows excellent promise, especially for long-term monitoring applications.

Legend:
H = Horizontal deformation
V = Vertical deformation
A = Axial deformation
R = Rotational deformation
S = Surface deformation
U = Subsurface deformation

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used for locating the instruments relative to a reference datum. Table 13.5 summarizes the advantages, limitations, approximate accuracy, relative complexity, cost, and applicability to coal refuse disposal facilities of the various surveying methods identified by Dunnicliff (1993).

Optical Leveling

Most settlement surveys at construction sites are conducted using engineer's levels at second- or third-order accuracy. Second-order leveling surveys are generally confined to extending vertical control data over long distances. Second-order leveling involves limited sight distances (± 225 feet), balancing foresight and hindsight, careful plumbing of the level rod, and readings made on well-defined marks and stable turning points. Third order leveling surveys are used to establish vertical control and to maintain benchmarks for project control, construction survey control, topographic survey control and major structure points. Third-order leveling permits greater sight distances (± 300 feet), along with balancing foresight and hindsight, plumbing of the level rod, and readings made on well-defined marks and stable turning points. For the magnitude of elevation change typically of interest at coal refuse disposal facilities, a third-order survey is usually adequate.

An important requirement for measuring horizontal movements is the establishment of reference monuments away from the embankment being monitored that are known to be fixed against horizontal movement and are convenient for the method of measurement used. This requirement may be difficult in many coal mining areas where natural slopes are steep with resulting downhill creep of the surface soils and where surface strains from nearby mine subsidence may be present. Where possible, reference monuments should be placed on flat natural ground or on bedrock by excavating holes in the soil/rock and backfilling them with concrete. For monuments in soil, the depth should extend below the maximum depth of frost penetration. Where assurance of undisturbed location is not possible for the primary reference monuments used for routine monitoring, they should be closed into a larger survey traverse or triangulation network for occasional checking of their locations. The large traverse should preferably have at least two permanent monuments in an area minimally susceptible to movement, such as adjacent to a highway in a broad valley bottom that does not overlie coal seams. Additional discussion of monuments and benchmarks is provided at the end of this section.

Trigonometric Leveling

Trigonometric leveling uses electronic distance measuring (EDM) equipment to measure the slope distance from the survey instrument to a prism on the surveyed location and to calculate the elevation and horizontal position of the surveyed location. The angle between the horizontal and surveyed location can be measured using a semi-precise (6-arc-second) or a precise (1- or 2-arc-second) theodolite.

Distance Measurement by Taping

Distance measurement by taping is probably the easiest measurement technique for horizontal movements because it requires only the use of a steel tape. When a known fixed point can be located in the direction of anticipated movement, this procedure consists of measuring the distance between the fixed reference and the monuments of interest. Typical corrections for sag, temperature and slope should be applied in order to obtain accurate measurements. The limitations of tape measurement should not preclude its use, because it may be the only means for locating lost reference points covered by deep snow or inadvertently buried by refuse placement.

Electronic Distance Measurement

Except for distances less than about 200 feet, distance measurement by taping has been replaced by EDM equipment. EDMs are used to directly measure the distance change or lateral position change

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by triangulation. EDMs make use of electromagnetic radiation (or lasers) to measure the distance between the instrument and a reflector prism.

Theodolite and Scale

Offsets from baseline using a theodolite and scale are measurements at a right angle to a baseline. These surveys are typically used for grade control for embankments and roadways. Laser beam leveling and offsets provide a faster and more accurate alternative to optical leveling.

Total Station Survey

Total station instruments combine electronic distance measurement, digital theodolites and microprocessors to simultaneously measure slope length and angle, calculate horizontal and vertical distance, and display the results in real time. Typically, a reflector prism is manually positioned at locations of interest, and the data are recorded and processed by the total station. This technology can provide real-time monitoring of predetermined points through use of one or more automated total stations combined with multiple-prism targets, a data acquisition system, and software interfaces. For this application, prism targets are mounted on the surface of the features to be monitored and are programmed into the routine of the total station. The survey frequency can vary (typically every two to five minutes) depending on the number of targets programmed into the total station's routine. Each automated total station can monitor up to about 100 prism targets.

Traverse Lines and Triangulation

Traverse lines and triangulation are conventional survey techniques that have been used for decades. Their improved accuracy in recent years is due to the use of more precise equipment used to measure distance (EDMs) and angles (theodolites) between reference control points. A traverse is used to determine change in lateral position through measurement of successive distances and angles. If a traverse returns to its starting point, the sum of the interior angles of the enclosed polygon can be calculated and adjusted for measurement errors. Triangulation can also be used to determine change in lateral position. This is accomplished by accurately measuring a baseline offset from the surveyed locations and the angles between the ends of baseline and the surveyed locations, as illustrated in Figure 13.1. Then by periodic re-sighting on the surveyed locations from the ends of the baseline, changes in lateral position can be calculated, assuming the baseline is located on stable ground.

Airborne Mapping Systems

Airborne methods include photogrammetric and LIDAR mapping systems. Photogrammetry is a remote-sensing technology in which geometric properties of objects are determined from photographic images. Photogrammetric methods can be used to record movement of hundreds of survey points at one time and thus provide an overall pattern of deformation, but the accuracy is affected by weather conditions, baseline measurements and interpreter skill.

Light Detection and Ranging (LIDAR) is a remote sensing system used to collect topographic data and develop topographic maps. LIDAR consists of a laser imaging device, an inertial navigation system, a GPS receiver and a computer. The technology can be used to map and determine coordinates of dense patterns of ground points, which can be used to develop an image of the ground surface. The data can be used to produce digital elevation models (DEMs) and subsequently topographic maps. When LIDAR is used, weather conditions must be monitored because the flights cannot be flown during times of rain or fog, as the water vapor in the air could cause the laser beams to scatter and give false readings.

Global Positioning System (GPS)

The GPS consists of a constellation of 24 satellites. Each satellite orbits the Earth twice a day at an altitude of about 12,500 miles and continuously transmits information on specific radio frequencies

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TABLE 13.5 SURVEYING METHODS

Method	Advantages	Limitations	Approximate Accuracy	Relative Complexity	Cost	Applicability to Coal Refuse Disposal Facilities
Elevations by optical leveling	Fast, particularly with self-leveling equipment Uses widely available equipment	First order leveling requires high-grade equipment and careful adherence to standard procedures	Third order: ± 0.05 ft $\sqrt{\text{miles}}$ Second order: ± 0.025 to 0.033 $\sqrt{\text{miles}}$ First order: ± 0.012 to 0.020 $\sqrt{\text{miles}}$	Simple	Low to Moderate	Routine for all embankments
Trigonometric leveling	Long range; fast and convenient; can be done simultaneously with traversing	Accuracy is influenced by atmospheric conditions; requires a very accurate measurement of zenith angle	Third order: ± 0.05 ft $\sqrt{\text{miles}}$ Second order: ± 0.025 to 0.033 $\sqrt{\text{miles}}$	Simple for 3rd Order; Moderate for 2nd Order	Low for 3rd Order; Moderate for 2nd Order	Routine for all embankments
Distance measuring by taping	Direct measurements	Requires clear, relatively flat surface between measuring points and reference datum; movement can only be measured in one direction; monuments must be located along a straight line with ready access between points; tape should be checked frequently against standard; except for short measurements, taping has been replaced by EDM.	Third order: ± 0.0033 to 0.0016 of distance between instrument and surveyed location Second order: ± 0.00005 – 0.00002 of distance First order: ± 0.000003 of distance	Simple	Low to Moderate	Routine for all embankments
Electronic distance measurement (EDM)	Long range; fast and convenient; very accurate.	Accuracy is influenced by atmospheric conditions	For distance: ± 0.001 to 0.03 ft For lateral position change by triangulation: ± 0.005 to 0.03 ft	Simple to Moderate	Low to Moderate	Routine for all embankments
Offsets from baseline using theodolite and scale	Direct measurements	Requires baseline unaffected by movement	± 0.001 to 0.005 ft	Simple	Low to Moderate	Routine for all embankments

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TABLE 13.5 SURVEYING METHODS (Continued)

Method	Advantages	Limitations	Approximate Accuracy	Relative Complexity	Cost	Applicability to Coal Refuse Disposal Facilities
Laser beam leveling and offsets	Faster than conventional optical methods; readings can be made by one person	Seriously affected by air turbulence, humidity, and temperature differential; requires curvature and refraction corrections beyond about 200 ft	± 0.01 to 0.03 ft	Simple	Low	Routine for significant embankments
Traverse lines	Useable where direct measurements are not possible	Accuracy decreases as number of legs in traverse increases; traverse should be closed if possible	± 0.00003 to 0.000007 of distance between instrument and surveyed location	Simple	Low to Moderate	Routine for significant embankments
Triangulation	Useable where direct measurements are not possible; baseline can be located to avoid active construction areas	Requires accurate measurement of angles and baseline length	± 0.00003 to 0.000001 of distance between instrument and surveyed location	Moderate	Low to Moderate	Routine for significant embankments
Photogrammetric methods	Can record movement of hundreds of potential points at one time for determination of overall deformation pattern	Weather conditions can limit use; interpretation requires specialist; for good accuracy the baseline should not be less than one-fifth of the sight distance	± 0.0002 to 0.00001 ft	Complex	Expensive	Non-routine for significant embankments
Global positioning system (GPS)	Operates with little attention from personnel; can be set to trigger a warning device; very accurate; does not require line of sight; measurements can be made in almost any weather condition	Requires open sky line of sight	Static and Relative Positioning: ± (0.016 ft + 1ppm) Requires 10 to 30 minutes observation per point depending on method of survey and whether single or dual frequency receiver is used.	Complex	Moderate to Expensive	Non-routinge for significant embankments

Note: $\sqrt{\text{miles}}$ = square root of distance in miles

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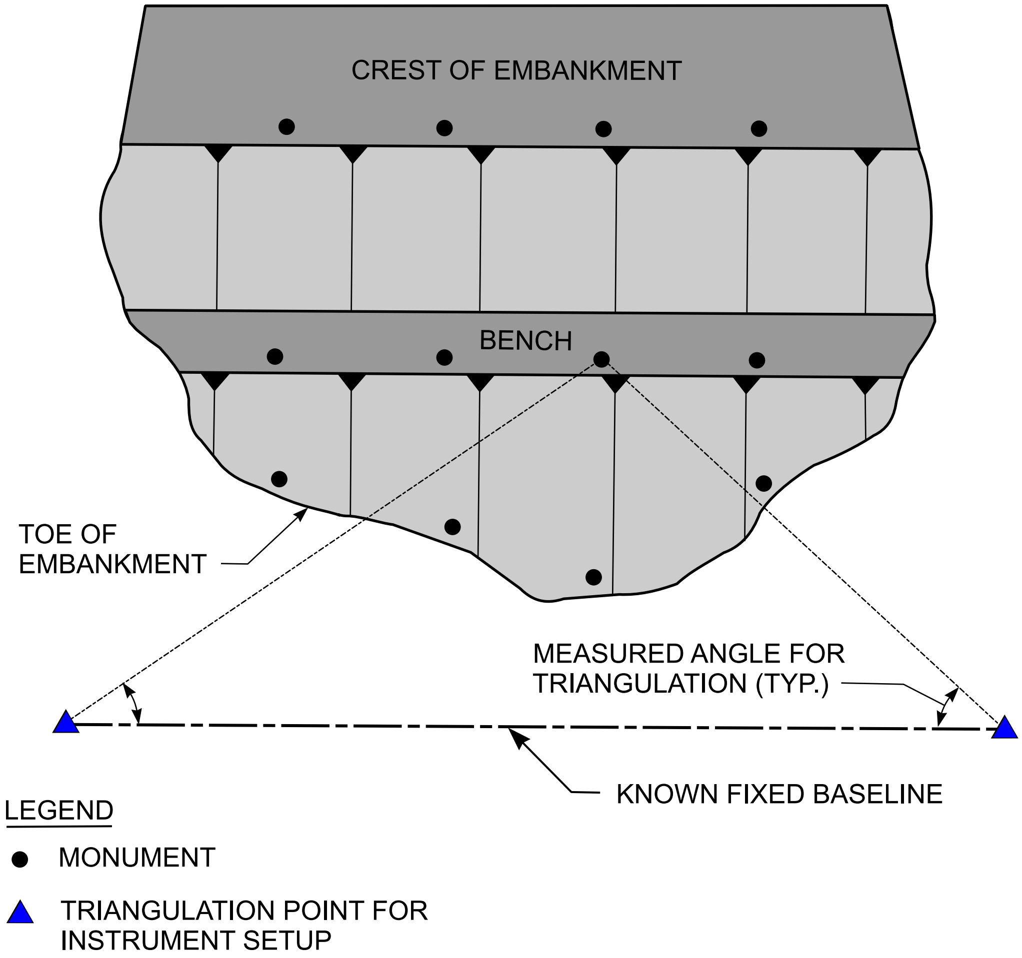

FIGURE 13.1 LOCATION OF MONUMENTS USING TRIANGULATION

to ground-based receivers. Using sophisticated receivers and data-analysis techniques, receiver positions can be determined. The GPS satellites continuously transmit an estimate of their position, digital codes, and a precise time signal. A GPS receiver uses an internal clock and the codes to determine the distances to at least 4 satellites. Distance is calculated by multiplying the time it takes the radio signals to reach the receiver times the speed of light. Knowing where the satellites are located when signals are transmitted, the receiver calculates its position. GPS equipment is becoming more reliable, cheaper, faster, and easier to use compared to conventional instruments. New hardware, field procedures and software have also been developed to assist users in data collection and processing. GPS equipment is now used for a wide range of monitoring applications.

A stable reference datum is required for all survey measurements pertaining to deformation. A benchmark is a reference datum for vertical movements and a horizontal control station or reference monument is a reference datum for horizontal movements. As a minimum, the datum benchmark should be placed in the ground, on a structure or on a rock outcrop in such a manner that the effects of weather (frost heave) or equipment travel will not alter its position. It should also be located well away from the embankment area so that increased earth loads or water pressures in the embankment do not significantly change the ground elevation at the benchmark. Where rock is shallow, an excavated hole to rock with concrete backfill and an embedded brass pin reference point is normally acceptable. When rock is deep, the most reliable benchmark consists of a steel rod installed inside a casing placed through overburden into bedrock. The rod should be isolated from the casing by nylon spacers, and the casing should be provided with a protective cover, as shown in Figure 13.2. Because the outer casing may be disturbed or compressed due to settlement of the surrounding material, the

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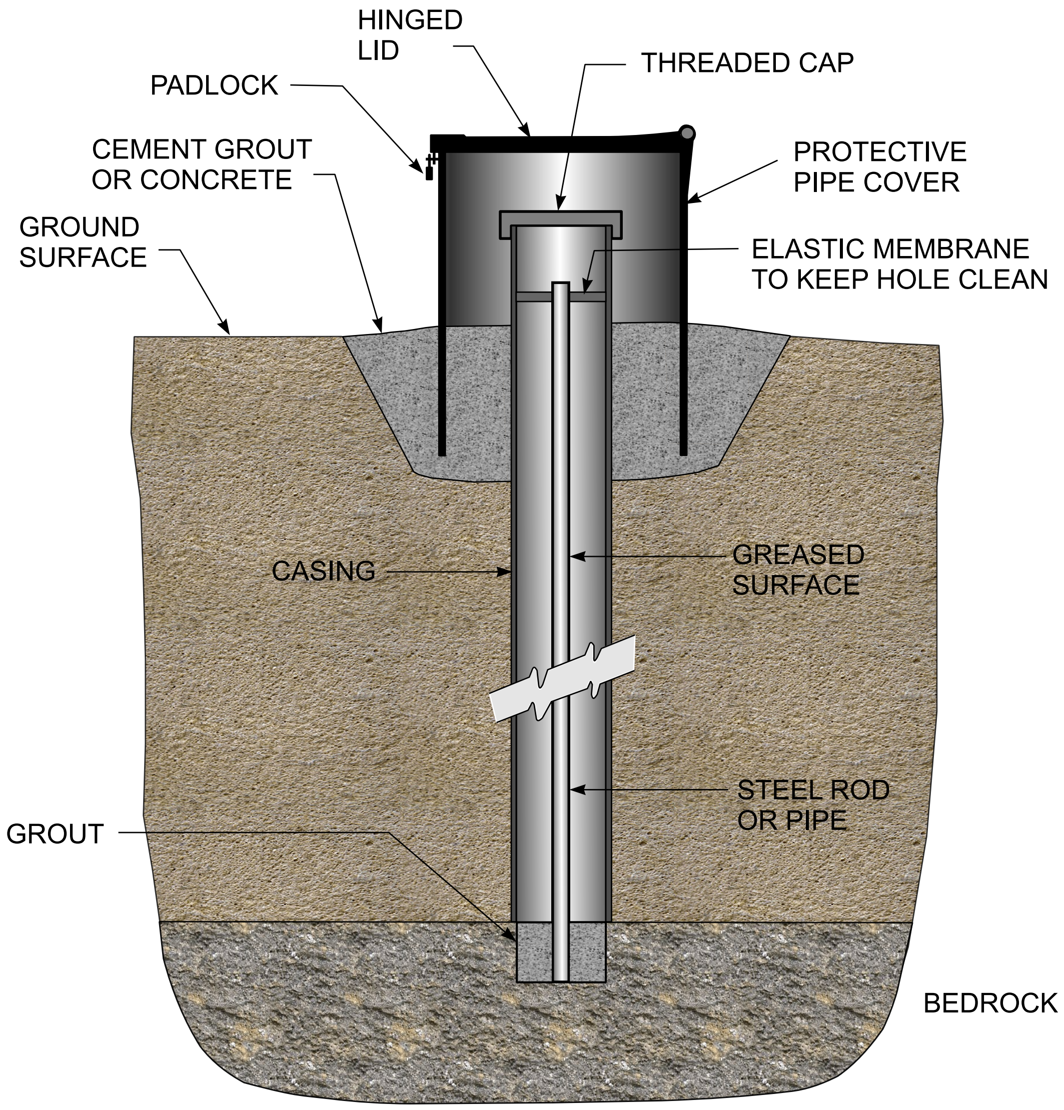
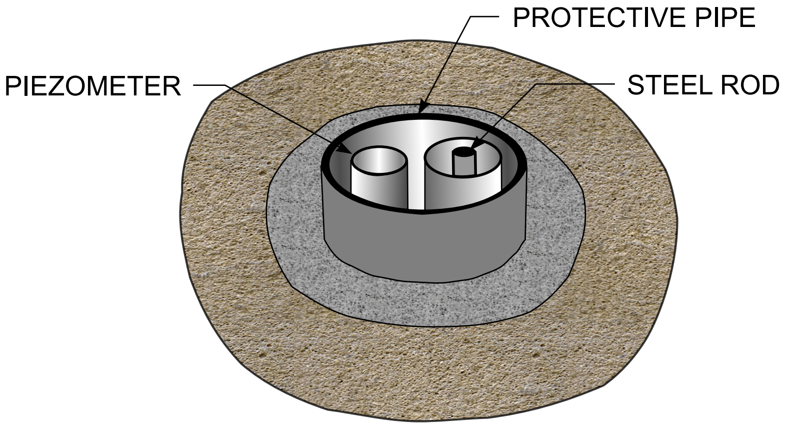


13.2a TYPICAL ARRANGEMENT



13.2b ROCK BENCHMARK IN COMMON

FIGURE 13.2 EXAMPLE OF BENCHMARK IN ROCK

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benchmark should be placed on the top of the inner rod, which is isolated from the movement of the casing. The protective cover will prevent damage due to material becoming wedged between the inner rod and the casing or due to vandalism.

In areas with nearby mining activity, associated movements of the ground surface may occur on adjacent hillsides (both surface heave and subsidence have been observed to occur for horizontal distances of more than several hundred feet from the nearest point of mining), so it may be necessary to construct a benchmark in a deep hole so that mining in the coal seam does not affect the benchmark. If the depth of mining is such that the cost of constructing a deep benchmark is prohibitive, a project benchmark should be established and should be periodically checked against other benchmarks in the region. In all cases, a minimum of three datum benchmarks should be established for periodic checking. These benchmarks should be located on opposite sides of the facility and in locations where they will not be affected by weather or subsidence conditions.

Reference points or monuments where surface settlement monitoring is desired can range from stakes or rods driven into the ground to carefully installed concrete cylinders. Examples are shown in Figure 13.3. In all cases, the point of measurement must be clearly identified so that the same location is used each time. Brass or steel rods or pipes set in concrete or rock or chiseled/painted crosses are suitable.

Except for rapidly established and very short-duration monitoring programs, driven rods should be avoided because this type of arrangement can be easily disturbed. If used, the minimum depth of embedment should be at least two feet, and the maximum extension above grade should be one foot or less to minimize tilting or bending of the rod. Also, because settlement points are often located in areas of high equipment activity, they should be well marked with stakes and flags to minimize loss and disturbance. Where loss of a monument would reduce the extent or accuracy of an important survey, up to twice the number believed necessary may be installed. The monument shown on Figure 13.3c can be used where surface creep is significant and conditions at depth (e.g., below the frost line or in rock or stable strata below the ground surface) better represent slope performance.

13.2.1.2.2 Surface Extensometers

Surface extensometers are devices used to monitor changes in distance between two points at the ground surface or on a structure (Dunnicliff, 1993). Surface extensometers are usually referred to as crack gages or convergence gages. Crack gages are used to monitor tension cracks behind slopes, across a joint or fault in a rock mass, or in concrete structures. Convergence gages have been used to measure the displacement between two surface monuments as part of the monitoring of ground surface strain induced by longwall mining near an impoundment. Mechanical crack gages include pins and tape, pins and steel ruler or caliper, pins and mechanical extensometer, and grid crack monitors. For each of these devices, the pins or grid crack elements are anchored on opposite sides of the discontinuity, and the distance between the anchored elements is measured periodically to determine the change in separation. Each of these types of surface extensometer is inexpensive and has a precision ranging from ± 0.01 to ± 0.1 inches. The principal limitation of mechanical crack gages is the relatively short span length between the pins. Additional details related to surface extensometers are provided in Dunnicliff (1993).

13.2.1.2.3 Tiltmeters

Tiltmeters are used for monitoring changes in inclination or rotation at the ground surface or on a structure in either a horizontal or vertical plane (Dunnicliff, 1993). A tiltmeter consists of a gravity-sensing device that is sealed in a housing. Some tiltmeters are fixed in place, and others are portable and can be used to monitor multiple locations by mounting on a fixture that is permanently attached to the monitoring location. The most common types of tiltmeters have an accelerometer transducer,

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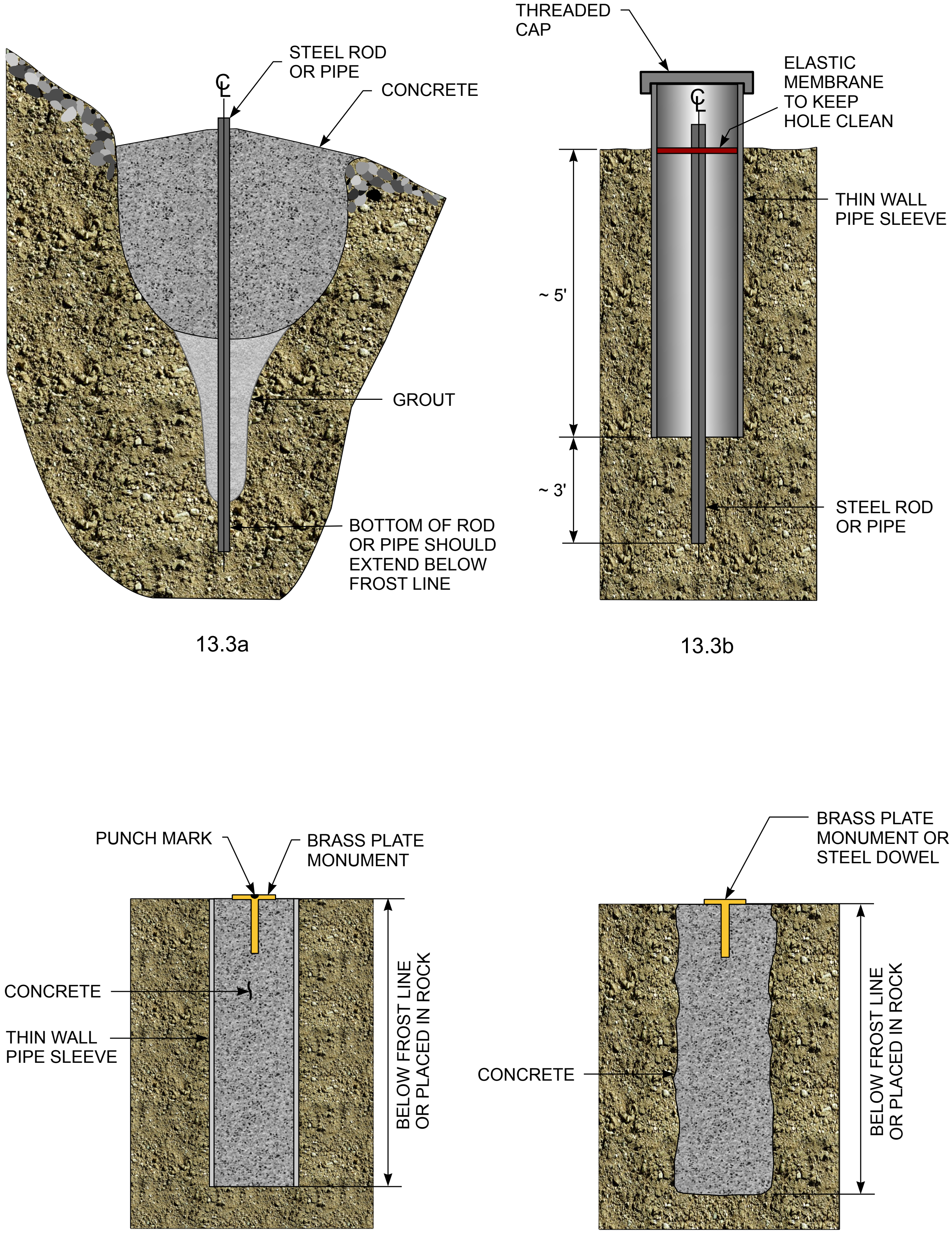

13.3a

13.3b

13.3c

13.3d

FIGURE 13.3 TYPICAL MONUMENT INSTALLATIONS

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but devices with mechanical, vibrating wire and electrolytic transducers are also available. The typical range of accelerometer-type tiltmeters is ± 30° from horizontal or vertical; the precision is typically ± 50 arc-seconds; and the temperature sensitivity is typically in the range of 2 to 3 arc-seconds/°F (Dunnicliff, 1993).

13.2.1.2.4 Probe Extensometers

Probe extensometers are used to monitor changes in distance between two or more locations along a common axis by passing a probe through a pipe (Dunnicliff, 1993). As the probe passes through the pipe, it mechanically or electrically detects the measuring locations, and the distance between them is determined by physical measurement of the probe positions. If an exact measurement of probe location is required, one measuring point must be accessible so that its location relative to a reference datum can be determined by surveying methods. Depending on project requirements, the pipe may be vertical for measurement of settlement or heave, horizontal for measurement of lateral displacement, or inclined. Dunnicliff (1993) provides a complete summary of probe extensometer types, their advantages, limitations and approximate accuracy.

The most commonly used probe extensometers are:

- Gage with current-displacement induction coil
- Magnetic reed switch gage
- Combined probe extensometers and inclinometer casing

Induction-coil transducers are described in Appendix 13A.2.4.6. When used as a probe extensometer, the device consists of a series of steel rings attached to and surrounding a telescoping or corrugated plastic pipe and a reading device consisting of a primary coil housed in a probe that is attached to a signal cable and current indicator. The pipe is installed in a borehole and backfilled. When the probe is inserted into the pipe, the steel rings can be located because the current indicator displays a maximum value at each ring location. The measurements enable determination of the distance between each ring, and a series of measurements over time permit determination of rate of deformation between the rings. Information related to installation, measurement precision and typical applications is provided in Dunnicliff (1993).

The magnetic reed switch gage is described in Appendix 13A.2.4.5. When used as a probe extensometer, the device consists of a series of circular magnetic anchors surrounding a rigid or telescoping plastic pipe. The pipe is installed in a borehole and backfilled. When the probe is inserted into the pipe, the magnetic anchors are located and their position measured as the coupled oscillator in the probe is activated at each ring location.

The Sondex system consists of a probe, a signal cable, a cable reel with a built-in voltmeter, and a number of stainless steel sensing rings. A survey tape is typically connected to the probe. The sensing rings are fixed to a continuous length of corrugated plastic pipe that is installed coaxially with inclinometer casing or access pipe. The annulus between the corrugated pipe and the borehole wall is grouted. The corrugated pipe and its sensing rings settle with the surrounding ground. To obtain measurements, the operator draws the probe through the access pipe. A buzzer sounds when the probe is near a ring, and the voltmeter indicates peaks when the probe is aligned with a ring. The operator refers to the survey tape and records the depth of the ring. A sensitivity adjustment allows operation adjacent to steel pipes, piles, or other metal objects. Settlement and heave can be calculated by comparing the depth of each ring to its initial depth.

Several types of probe extensometers can be used in conjunction with inclinometer casing in a vertical borehole to permit measurement of both horizontal and vertical deformations in one installation. Increx

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and Sondex are examples of this type of probe extensometer. The Increx system consists of a number of brass rings that are positioned at one-meter intervals along an inclinometer casing. The probe is positioned to successively take readings between each pair of rings. Periodic surveys are compared to the initial survey to determine changes in the distance between rings. If the distance has increased, extension has occurred; if the distance has decreased, compression has occurred. Movements can be referenced to the deepest ring, if it is located in stable ground, or the top of the casing can be optically surveyed. The systems can measure changes as small as 0.001 mm with an accuracy of ± 0.01 mm/m. A schematic illustration of a probe extensometer is provided in Figure 13.4.

13.2.1.2.5 Fixed Embankment Extensometers

Fixed embankment extensometers are devices placed in an embankment fill during construction to monitor changes in distance between two or more points along a common axis without a movable probe. They are used to measure settlement, horizontal deformation or strain (Dunnicliff, 1993). The most common type of fixed embankment extensometer is a settlement platform. A settlement platform consists of a square plate or anchorage to which a riser is attached. If the fill height exceeds about 25 feet, the riser should be isolated from the surrounding fill by an outer pipe within which the riser can move freely. As the height of fill increases, the riser and outer pipe are raised by adding additional pipe lengths. Movements of the settlement platform can be monitored by optical survey of elevation of the top of the riser. A schematic illustration of a settlement platform is provided in Figure 13.5. Settlement platforms are easy to construct, but they are easily damaged during construction as fill is placed and compacted near them. This problem can be avoided by using liquid- level gages, as described in Appendix 13A.3.2.

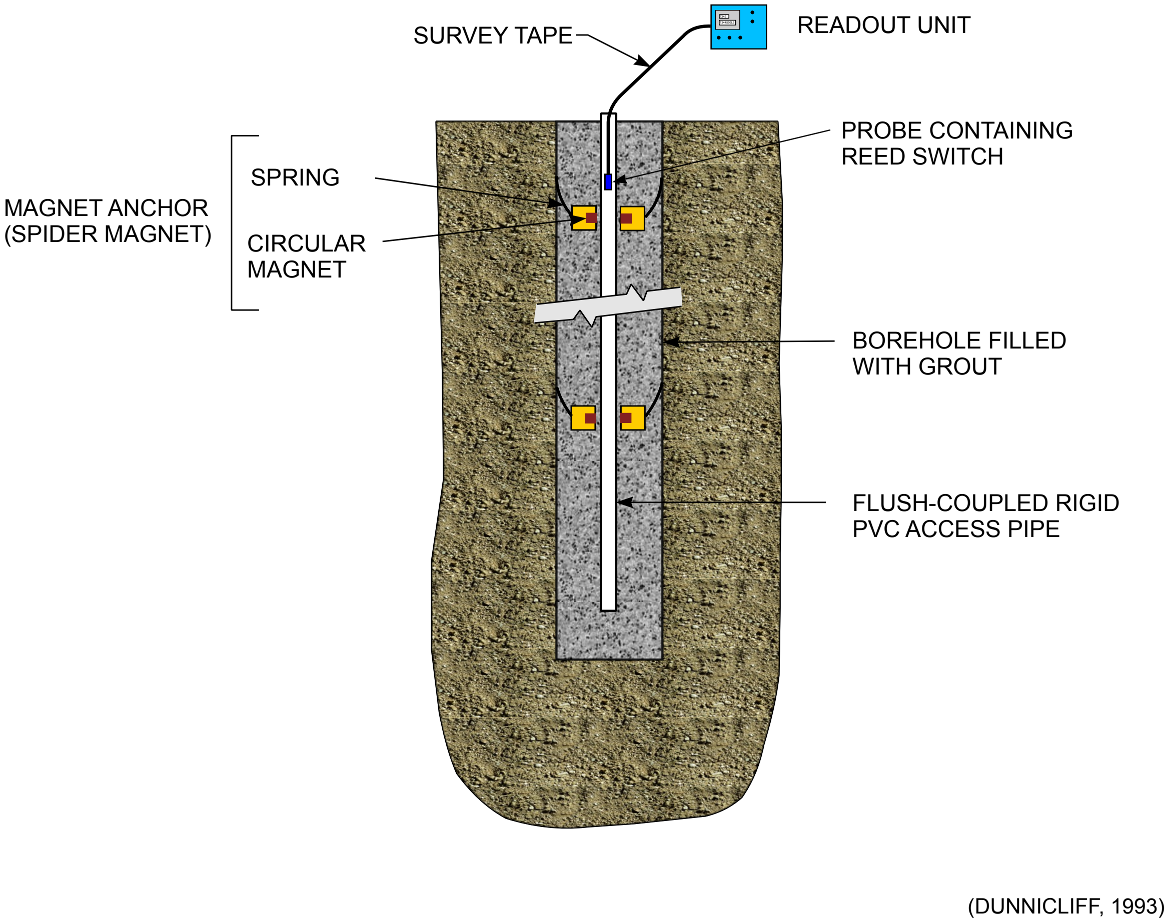
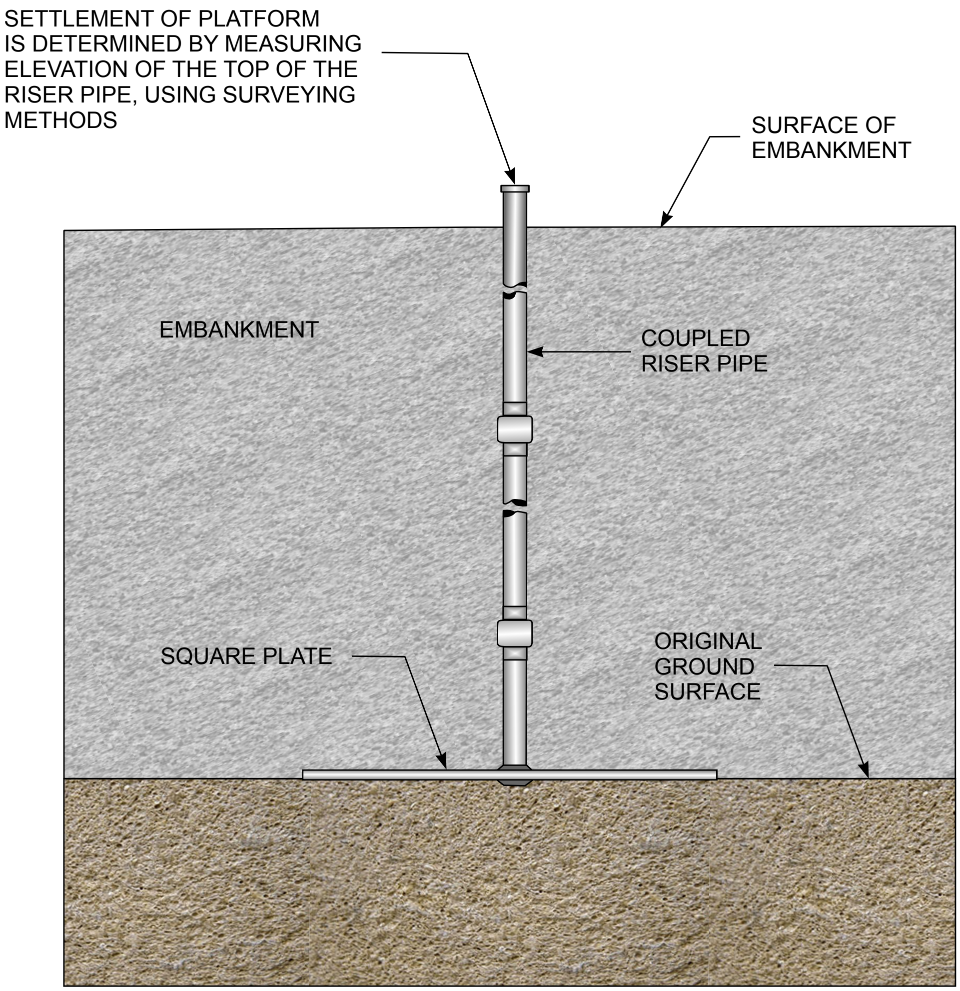


FIGURE 13.4 PROBE EXTENSOMETER



(DUNNICLIFF, 1993)

FIGURE 13.5 SETTLEMENT PLATFORM

Tensioned-wire gages and fixed embankment extensometers with Linear Variable Differential Transformers (LVDTs) have been used to monitor horizontal displacements in an embankment fill (Dunnicliff, 1993). These devices have been largely replaced by probe or in-place inclinometers (Section 13.2.1.2.7) installed in a vertical borehole.

13.2.1.2.6 Fixed Borehole Extensometers

Fixed borehole extensometers are devices without moveable probes installed in boreholes in soil or rock and used to monitor the change in distance between two or more points along the borehole axis (Dunnicliff, 1993). If measurement of the exact deformation at a specific location is required, one end of the extensometer must be fixed in stable ground or it must be accessible for optical survey. Fixed borehole extensometers can be used to monitor deformations behind rock slopes, foundation settlements, the progression of subsidence above underground mines, and heave at the base of open-cut excavations. A schematic illustration of a fixed borehole extensometer is provided in Figure 13.6.

The distance between the end of the rod and the face of the collar anchor can be measured using either a mechanical device (e.g., dial gage) or electrical transducer (e.g., LVDT). The device illustrated in Figure 13.6 is a single-point borehole extensometer (SPBX). A multiple-point borehole extensometer (MPBX) consists of several downhole anchors within a single borehole along with a rod and measur-

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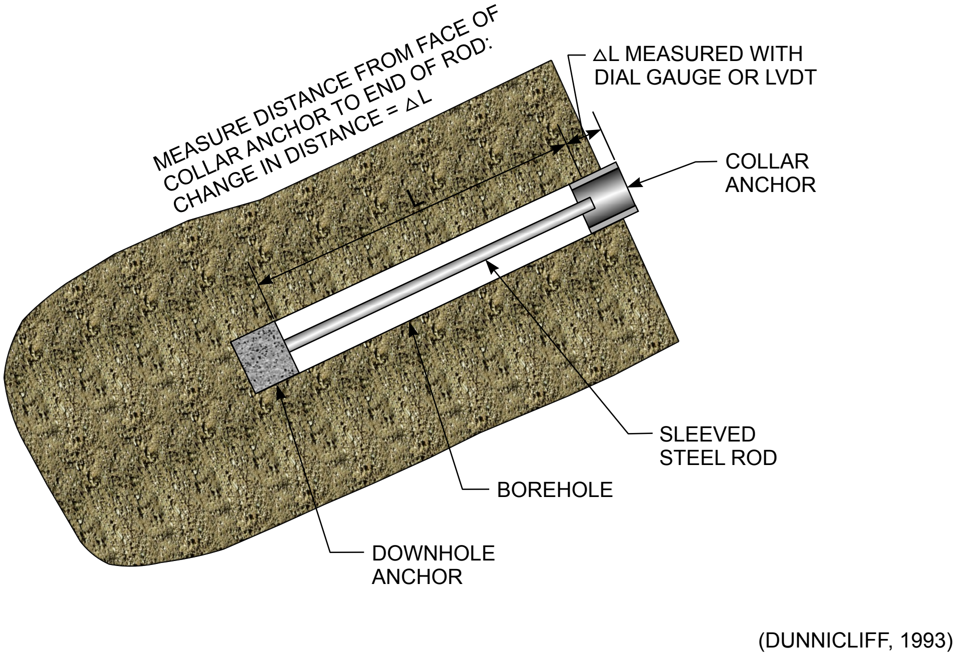


FIGURE 13.6 FIXED BOREHOLE EXTENSOMETER

ing device for each. MPBXs allow the measurement of deformation or strain patterns over the length of the borehole so that potential failure or large deformation zones can be identified. Fixed borehole extensometers can be manufactured to meet site-specific requirements. The principal feature differences include choice of rod or tensioned wire attached to the downhole anchor, downhole anchor type (i.e., mechanical, hydraulic or groutable), SPBX or MPBX, transducer type and extensometer head. Dunnicliff (1993) provides guidance for selecting among these options for particular applications. The accuracy of the device depends on the type of mechanical or electrical transducer used to measure change in the anchor location.

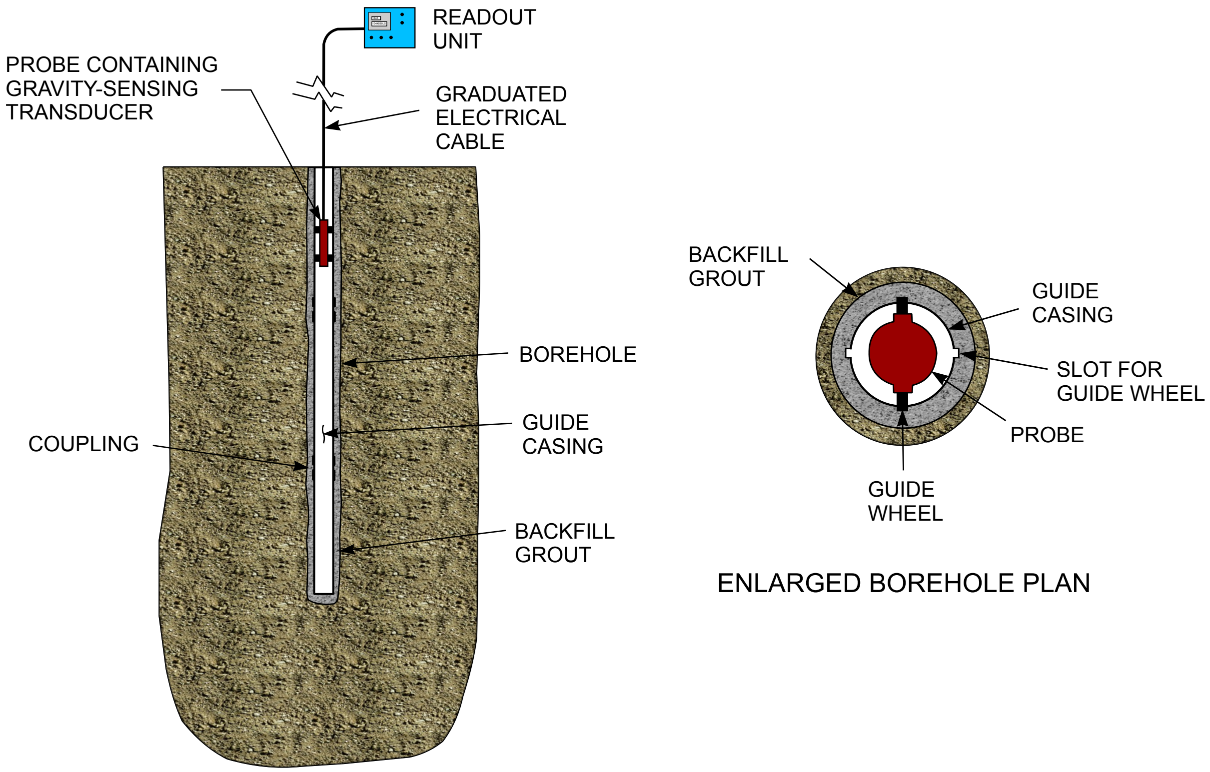
13.2.1.2.7 Inclinometers

Inclinometers are devices used for monitoring displacements normal to the axis of a pipe by passing a probe along the pipe (Dunnicliff, 1993). They can be used to determine the depth and profile of lateral displacement above and below a slide plane such as in a distressed slope. A gravity-sensing transducer in the probe measures inclination with respect to vertical. Normally the probe is inserted into a vertical or inclined borehole to measure lateral displacements in landslide zones or structures, but probes are available for use in horizontal pipe for obtaining profiles beneath embankments and structures.

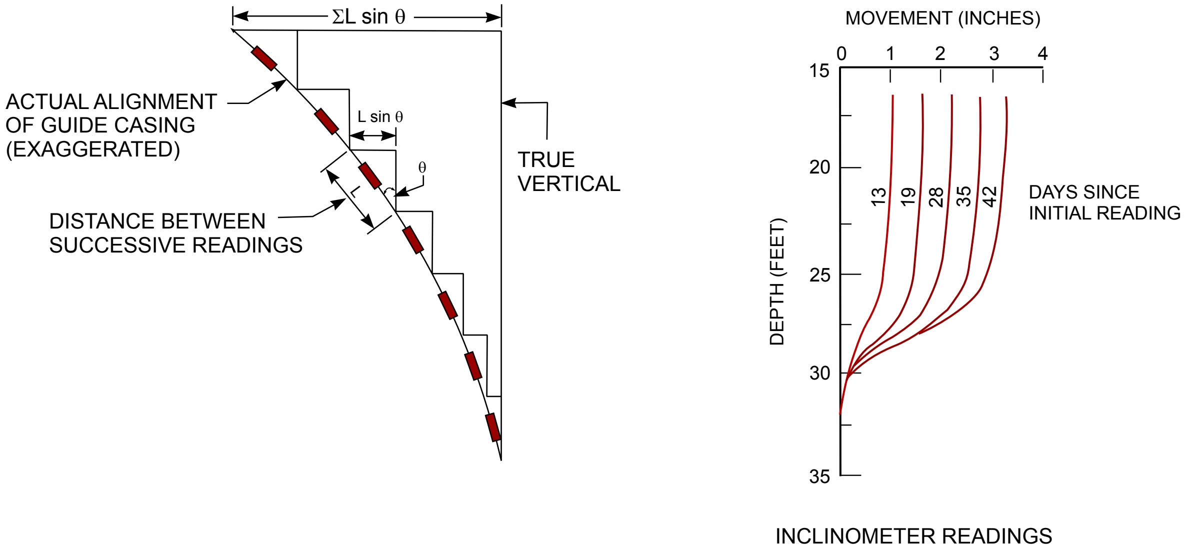
Inclinometer systems have four primary components:

- A probe casing with tracking grooves that is permanently installed in a borehole (vertical or inclined application) or trench (horizontal application)
- A probe with a pair of wheel carriages housed in steel to confine the gravity-sensing transducer
- A portable readout for power supply and measurement of probe inclination
- A graduated electrical cable connecting the probe and readout unit

Figure 13.7 shows a schematic representation of the operation of an inclinometer for vertical and near- vertical applications. The inclinometer casing is installed and grouted along its full length into a borehole so that one pair of the four orthogonal grooves in the casing is normal to the displace-



13.7a INSTRUMENT AND CASING ARRANGEMENT



13.7b DISPLACEMENT COMPUTATION

13.7c LOCATION OF PLANE OF MOVEMENT

(DUNNICLIFF, 1993)

FIGURE 13.7 INCLINOMETER OPERATION

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ments being measured. Normally the casing is installed to a depth that provides fixity. Measurements are made by lowering the probe along the pair of grooves normal to the desired direction of movement observation to the bottom of the casing and then incrementally raising the probe and measuring probe inclination at each interval. Once the uppermost reading is made, the probe is removed from the casing, rotated 180 degrees to reverse the orientation of the probe in the casing, lowered to the bottom of the casing, and the measurement process is repeated at the previous depth intervals. Reversal of the inclinometer is performed in order to eliminate or minimize the effects of errors due to long-term drift of the gravity-sensing transducers. If a fixed base is not achieved, the top of the inclinometer casing must be surveyed each time measurements are taken so that measurements from one time interval can be compared to another. Dunnicliff (1993) provides additional details on inclinometer type; operation and calibration; casing types and installation; and data collection, processing and interpretation. The reported precision for inclinometers is: ± 0.05 to 0.5 inches per 100 feet for force-balance accelerometer transducers, ± 0.02 to 1 inch per 100 feet for bonded resistance strain gage transducers, and ± 0.1 to 0.5 inches per 100 feet for vibrating wire transducers (Dunnicliff, 1993).

13.2.2 Piezometric Levels and Pore-Water Pressures

Knowledge of the piezometric levels and pore-water pressures in foundations and embankment cross sections is important for safe operation of coal refuse disposal facilities. Elevated piezometric and pore-water pressure levels can be a pre-failure indicator of general and localized instabilities in foundation soils, downstream embankment slopes, upstream embankment slopes (due to failure of fine refuse following pushouts or upstream construction), and temporary excavations in soil or rock. Commonly used techniques for measuring piezometric levels and pore-water pressures are discussed in this section and are summarized in Table 13.6. Valuable additional information related to groundwater monitoring instrumentation is provided by Dunnicliff (1981), Hanna (1985), Bartholomew et al. (1987), Dunnicliff (1993) and USACE (1995c).

Pore-water pressure and its significance relative to embankment fill and coal refuse behavior are discussed in Section 6.5.7. Monitoring of pore-water pressures may be important for controlling construction and maintaining embankment or foundation stability. Devices for measuring pore-water pressure (piezometers) operate by admitting water through openings or a porous element, while restricting inflow of fine particles, such that the pore-water pressure can be determined from the elevation of water in the piezometer or by a pressure gage.

13.2.2.1 Piezometer Types

Piezometers generally fall into two categories: open system (e.g., observation wells and open standpipes) and closed system (e.g., pneumatic, vibrating-wire, and electrical-resistance). Both types have application at coal refuse disposal facilities.

Open observation wells are not selectively screened and thus provide limited information. For open standpipe piezometers, a screen or filter is placed in the zone of interest and sealed off so that only the sensing zone will be monitored. Water rises in the open piezometer to an elevation corresponding to the piezometric head in the zone being monitored. Measurement of piezometric head is typically accomplished using an electrical water level meter.

Closed-system installations such as vibrating-wire, pneumatic or electrical piezometers respond more quickly to changes in pore pressure because no significant flow of water is necessary. Also, these types of piezometers can be monitored remotely. While these devices have some reliability problems over long time periods, they can perform acceptably if they are properly selected for the applications required and environmental conditions encountered. Rapid response time is necessary when an embankment is constructed over a saturated and sensitive foundation material that could fail if excess pore pressures develop during construction and temporarily exceed those assumed in design. Table 13.6 summarizes

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TABLE 13.6 INSTRUMENTS FOR MEASURING GROUNDWATER PRESSURE

Instrument Type	Advantages	Limitations
Observation well	Can be installed by drillers without full-time participation of geotechnical engineering personnel	Provides undesirable vertical connection between strata so results can be misleading; should rarely be used
Open-standpipe piezometer	Reliable; long successful performance record; self de-airing if inside diameter of standpipe is adequate; seal integrity can be checked after installation; can be converted to diaphragm piezometer; can be used for ground-water sampling and permeability measurements	Long lag time; subject to damage during construction; extension of standpipe through embankment fill interrupts construction and leads to poor compaction; porous filter can plug due to repeated in- and out-flow; push-in versions subject to several potential errors
Pneumatic piezometer	Short lag time; calibrated part of system is accessible; minimum interference to construction; level of lead wires and readout independent of tip level; no freezing problems	Attention must be paid to many details during instrument selection; push-in versions subject to several potential errors
Vibrating-wire piezometer	Easy to read; short lag time; minimum interference to construction; level of lead wires and readout independent of tip level; lead wire effects minimal; can be used to read negative pore pressures; no freezing problems	Special manufacturing required to minimize zero shift; need for lightning protection should be evaluated; push-in versions subject to several potential errors
Electrical-resistance piezometer	Easy to read; short lag time; minimum interference to construction; level of lead wires and readout independent of tip level; suitable for dynamic measurements; can be used to read negative pore pressures; no problems with freezing in cold weather	Low electrical output; lead wire effects; errors caused by moisture, temperature and electrical connections are possible; long-term stability is uncertain; need for lightning protection should be evaluated; push-in versions subject to several potential errors

(ADAPTED FROM DUNNICLIFF, 1993)

the advantages and limitations associated with various types of piezometers, and Figure 13.8 presents guidance regarding the approximate response times for various types of open- and closed-system piezometers as a function of the hydraulic conductivity of the soil surrounding the sensing zone. As shown in the figure, the response time to achieve 90 percent equilibration increases with decreasing hydraulic conductivity and with increasing volume of the sensing zone. Methods for estimating the response time are presented in Terzaghi and Peck (1967).

13.2.2.2 Observation Wells

Observation wells are not selectively screened in a specific formation. Thus, they will usually not provide useful information unless they are located in a single aquifer near the surface. While observing the water level in an open or cased borehole with an electrical water level meter, measuring tape and weight, or similar device is relatively easy, the measured water level may represent the contribution of many soil layers. Therefore, it is generally not possible to distinguish between pressures occurring at different elevations. Observation wells should only be used when relatively homogeneous embankment/foundation materials are present, and generally open-standpipe piezometers are preferred.

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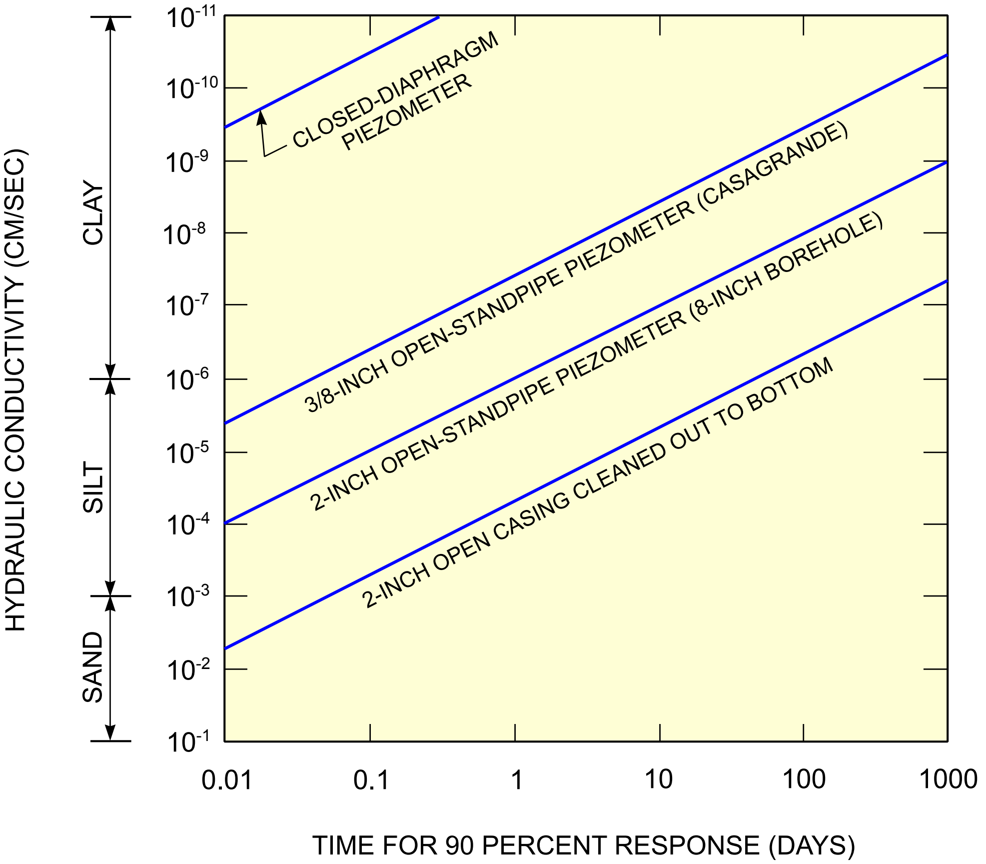

(ADAPTED FROM TERZAGHI AND PECK, 1967)

FIGURE 13.8 APPROXIMATE RESPONSE TIME FOR VARIOUS TYPES OF PIEZOMETERS

13.2.2.3 Open-Standpipe Piezometers

The disadvantages of observation wells can be overcome using open-standpipe piezometers with sensing elements that are sealed in the zones where pore-water pressures are needed. Open-standpipe piezometers are suitable for a wide range of hydraulic conductivities and may even be acceptable in low hydraulic conductivity conditions where there is little concern for rapid changes in excess pore pressure. It is the most common type of piezometer used in coarse refuse embankment stages.

This type of piezometer is normally installed in a borehole supported by temporary casing or a string of hollow-stem augers. The casing or internal diameter of hollow-stem augers should be of a size to permit placement of the backfill around the piezometer pipe, usually at least twice the diameter of the piezometer. When the desired depth is reached, small-diameter plastic pipe with slotted-pipe or other type of screen at the appropriate interval is inserted into the temporary casing or augers, and the casing or augers are extracted while the plastic pipe is held in place. Traditionally, as the casing or augers are extracted, the annulus between the pipe and borehole walls is backfilled with granular material around the sensing zone, a bentonite seal is placed above the sensing zone, and a cement-bentonite grout is placed above the bentonite seal to the ground surface. Many designers perceive that a bentonite seal is needed to protect the sand from being disturbed during grouting. However, if the sand zone is saturated, a well-designed grout with a creamy consistency will only penetrate the sand a few inches (Mikkelsen, 2002). Therefore, an alternative and simpler procedure for backfilling open-standpipe piezometers is to grout the annulus above the sand zone with cement-bentonite grout to the ground surface. The grout should be placed using a tremie pipe to avoid bridging of

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materials in small-diameter holes or for placement at a substantial depth below the water table. Table 13.7 presents a typical mix design for cement-bentonite grout for medium-to-hard-soil and soft-soil applications.

The sensing zone where pore pressure measurements are desired is typically a section of slotted pipe or an attached porous element for keeping granular filter material and soil/refuse from entering the piezometer. If a slotted zone is used, the slots should be sized using the criterion:

$$\text{Slot Width} \leq 0.5\, D_{85} \text{ of surrounding material} \qquad (13\text{-}1)$$

where:

D_{85} = the soil particle size on a grain-size plot for which 85 percent of the soil sample by weight is smaller.

A schematic illustration of an open standpipe piezometer is provided in Figure 13.9.

Open-standpipe piezometers are often constructed using 2-inch-inside-diameter, flush-coupled, Schedule 80 PVC or ABS pipe with either cemented or threaded couplings that permit easy passage of an electrical or mechanical reading device for measuring the water level. When cemented couplings are used, one end of each pipe length should be machined as male and the other as female so that the coupling can be connected using a solvent cement. When threaded couplings are used, they should be self-sealing so that a watertight connection is achieved without any sealer. Smaller-diameter pipe may be used (a minimum diameter of 1 inch is recommended for operation of water level measurement equipment), but that may limit the ability to flush the piezometer or to conduct other measurements such as falling-head hydraulic conductivity tests or to obtain water samples. As the annulus around the standpipe is backfilled, the pipe should be maintained as straight as possible to avoid difficulty in lowering measuring devices to determine the level of the water surface.

In addition to using slotted PVC pipe in sensing zones, manufactured porous piezometer screens that admit water but not particulate matter may be used. The two most frequently used types are metal well points commonly used for shallow dewatering and porous tips specially made for piezometers, such as the Casagrande-type piezometer tip. In fine-grained deposits where electrolytic action may bring about formation of gas that can increase the lag time of a system or where water chemistry may cause corrosive damage, the use of nonmetallic piezometer tips is advisable. The Casagrande-type

TABLE 13.7 CEMENT-BENTONITE GROUT MIX

Materials	Grout for Medium to Hard Soils(1)		Grout for Soft Soils(2)	
	Weight	Ratio by Weight	Weight	Ratio by Weight
Water	30 gal	2.5	75 gal	6.6
Portland Cement	94 lb (1 sack)	1	94 lb (1 sack)	1
Bentonite(3)	25 lb (as required)	0.3	39 lb (as required)	0.4

Note:
1. The 28-day compressive strength of this mix is about 50 psi, similar to very stiff to hard clay. The modulus is about 10,000 psi.
2. The 28-day compressive strength of this mix is about 4 psi, similar to very soft clay.
3. Water and cement should be mixed prior to the addition of bentonite; sufficient bentonite (as required) should result in a smooth, thick mixture like thick cream or pancake batter.

(MIKKELSEN, 2002)

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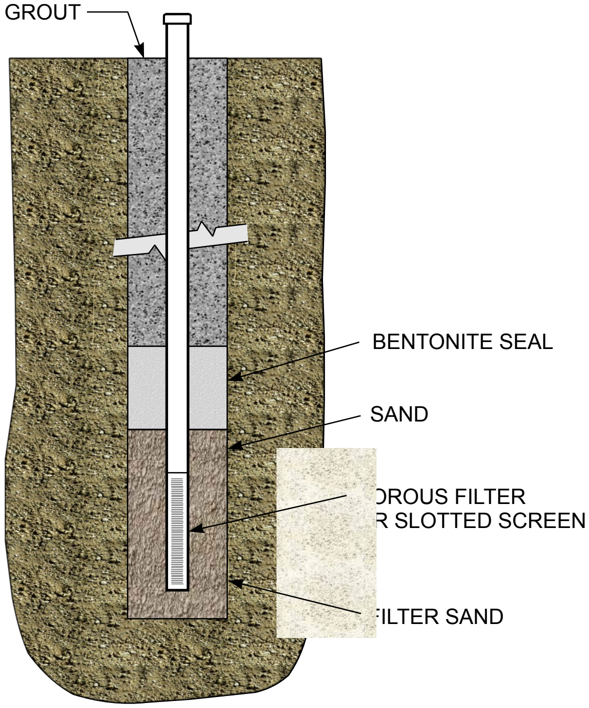

(DUNNICLIFF, 1993)

FIGURE 13.9 OPEN-STANDPIPE PIEZOMETER/OBSERVATION WELL

piezometer tip, for example, consists of a one- to two-foot-long porous ceramic tube that can be connected to various sizes of riser pipe.

Continuous experienced supervision should be provided in order to maximize the potential for successful piezometer installation. Because of continuing construction activities at coal refuse embankments and the long service life, it is common to encounter loss of functionality or damage to piezometers, leading to a need for repair or replacement. At critical locations, particularly where access may be a concern, multiple installations should be considered.

Following the installation of an open-standpipe piezometer, measurements should be taken to verify that the piezometer is functioning as expected, and the top should be protected against accidental damage or vandalism. The hydraulic response of open standpipe piezometers can be checked by:

- Bailing or evacuating water from within the piezometer riser pipe and letting groundwater re-enter through the sensing zone (rising-head test)
- Adding water to the piezometer riser pipe and letting water flow out from the piezometer sensing zone (falling-head test)
- Inserting a solid rod into the standpipe and forcing water flow out from the piezometer sensing zone (slug test)

Selection of a method to check piezometer response depends on the depth of the sensing zone below the ground surface and the availability of an adequate supply of clean water to conduct a rising- or falling-head test. In general, rising- or falling-head tests are conducted when the groundwater level is shallow and clean water is readily available. If the water level is deep (greater than 50 feet) and/or an adequate water supply is not available, a slug test is typically used. ASTM D 4043, “Standard Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques,” should be followed for selection of suitable methods for checking the hydraulic response of open-

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standpipe piezometers. Care should be taken in using the results of slug tests to determine hydraulic conductivity of coarse-grained soils. Herzog (1994) reports that four commonly used methods to determine hydraulic conductivity in coarse-grained soils can yield results that differ by up to two orders of magnitude. By contrast, in fine-grained soils, the analytical method used to interpret slug tests typically results in consistent values of hydraulic conductivity.

If the material in which the piezometer tip is located is relatively permeable, these tests can often be conducted shortly after installation, because the flow into or out of the piezometer should occur rapidly. The procedure simply consists of: (1) reading the water depth; (2) changing the depth by bailing, adding water or inserting a slug; and (3) periodically reading the depth to determine the time required to return to the original measured level. Much greater care is required when the piezometer tip is located in a low-hydraulic-conductivity material and the flow of water is slow. In this situation, the test should be delayed until the system stabilizes following installation. Then only slight changes in level should be made; otherwise, the time for stabilization may interfere with required readings for which the piezometer was installed in the first place. A piezometer is considered to be developed when repeated testing results in nominal sediment detection in the sensing zone and when rising or falling head tests produce consistent results. Once operational, response tests should be conducted whenever the accuracy of readings from a piezometer is in doubt (e.g., readings are inconsistent with readings from other piezometers).

Figure 13.8 provides guidance regarding the approximate response times for various types of open- and closed-system piezometers as a function of the hydraulic conductivity of the soil surrounding the sensing zone of the piezometer. As shown in the figure, the response time to achieve 90 percent equilibration increases with decreasing hydraulic conductivity and with increasing volume of the sensing zone (i.e., open-system piezometers are less responsive than closed-system diaphragm piezometers with pneumatic or vibrating wire systems). Hydraulic systems introduce additional delay in response time, associated with the length of tubing from the sensor to the readout location. Methods for estimating the response time are presented in Terzaghi and Peck (1967).

Open standpipe piezometers have often been lost due to debris dropped into the standpipe that either clogs the tip or precludes lowering of the water level measuring device. A grouted-in steel pipe with a removable cap can be installed at the top of the piezometer to protect temporary or permanent installations from accidental loss due to debris.

When an open-standpipe piezometer is installed in an area where the embankment height periodically increases, the riser pipe will need to be raised as fill is placed. To minimize the potential for surface water ponding and infiltration along the riser pipe/soil interface, the ground surface around the riser pipe should be elevated such that surface water drains away from the pipe.

Water levels in standpipe piezometers can be measured by a variety of methods, but the most common approach is an electrical water level meter. These devices typically consist of a two-conductor cable with a cylindrical stainless steel weight at the lower end. The weight is divided electrically into two parts and separated by a plastic bushing, and a conductor is connected to each part. The upper end is connected to a battery and a buzzer, light or ammeter. When the weighted probe is lowered into the piezometer, an electric circuit is completed when the probe encounters the water surface. The water depth is measured using permanent depth markings on the cable. Cable lengths over 1000 feet are available, but a probe with a 300-foot-long cable is usually sufficient for most coal refuse facilities. Special versions of these probes include features to measure temperature and conductivity. Other options for water level depth measurement include a weighted tape measure (for shallow-depth piezometers only), pressure transducer (Appendix 13A.2.4.3), ultrasonic transducer, and float and recorder system. Transducer and float/recorder systems are typically used with remote monitoring systems.

13.2.2.4 Closed-System Piezometers

Closed-system (pressure-transducer) piezometers have application when:

- Fine-grained material is being monitored such that response times for open-system piezometers would be too large.
- Remote readout is desired in order to minimize potential interference with and damage from earthwork equipment.
- Remote readout is desired so that measured piezometric levels can be integrated with data from other remotely monitored instruments.
- The material being monitored is not completely saturated.

Figure 13.8 provides guidance regarding the approximate response times for closed-system piezometers as a function of the hydraulic conductivity of the soil surrounding the sensing zone of the piezometer. As shown in the figure, the response time to achieve 90 percent equilibration increases with decreasing hydraulic conductivity. Hydraulic systems introduce additional delay in response time, associated with the length of tubing from the sensor to the readout location. Methods for estimating the response time are presented in Terzaghi and Peck (1967).

While pore pressures in unsaturated materials are not normally monitored at coal refuse disposal facilities, measurements in fine-grained materials (e.g., fine coal refuse or fine-grained foundation soils) and remote monitoring are situations when closed-system piezometers should be considered. As with instruments used for deformation and movement measurements, pneumatic, vibrating wire and electrical resistance transducers are available for measuring pore-water pressures. These transducers are typically installed in a borehole and backfilled with granular soil around the sensing zone, a bentonite seal above the sensing zone, and a cement-bentonite backfill to the ground surface. Recently, installation of closed-system piezometers within fully grouted boreholes has gained attention, as subsequently discussed. This installation method eliminates the cumbersome installation of a sand pack and bentonite seal, facilitates the installation of several piezometers in a nested configuration, and has a lower cost and faster installation than the traditional approach.

Pneumatic piezometers have advantages where high thunderstorm activity is anticipated. However, if pneumatic piezometers are used, normally-closed transducers are preferred to normally-open transducers because less diaphragm displacement is required for measuring the pore-water pressure in the sensing zone (Dunnicliff, 1993). The transducers are typically housed in corrosion-resistant plastic or stainless steel. A normally-closed pneumatic piezometer installation is illustrated in Figure 13.10.

Vibrating-wire piezometers have a metallic diaphragm separating the pore water from the measuring system (Dunnicliff, 1993). These devices are typically housed in stainless steel. Most vibrating-wire piezometers have a dried and hermetically-sealed cavity around the sensor to minimize the potential for corrosion, a thermistor to adjust for temperature effects, and some have an in-place check feature to account for zero drift and to permit in-service calibration. A vibrating-wire piezometer installation is illustrated in Figure 13.11.

Electrical-resistance piezometers are housed in stainless steel to resist the effects of lateral stresses on the device and to minimize corrosion. These devices are manufactured using semiconductor, unbonded and bonded electrical-resistance gages. An electrical-resistance piezometer installation is illustrated in Figure 13.12. These piezometers are constructed with an intake filter that separates the formation pore fluid from the diaphragm and sensor. The filter must be strong enough to not be damaged during installation and to resist embedment stresses without undue deformation. For coal refuse facilities, piezometers should be constructed using a coarse, low-air-entry filter that readily allows the passage of both gas and water. Typical low-air-entry filters have a pore diameter of 20 to

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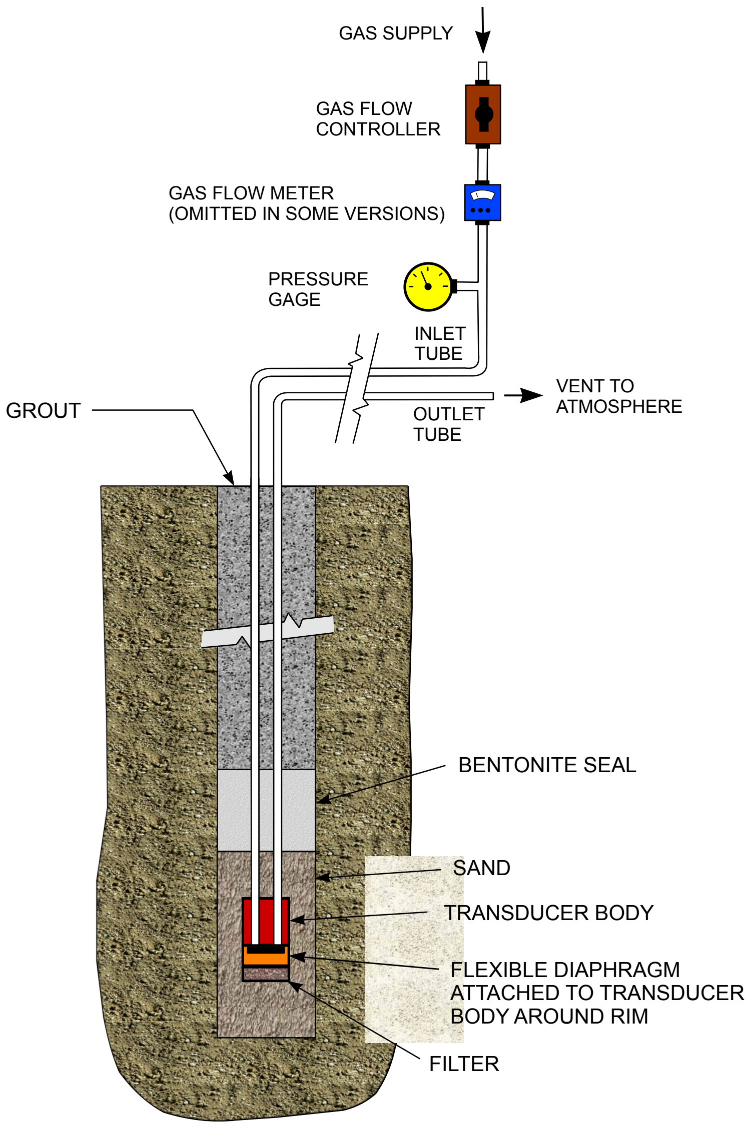

(DUNNICLIFF, 1993)

FIGURE 13.10 NORMALLY-CLOSED PNEUMATIC PIEZOMETER

80 microns (0.0008 to 0.0031 in) and air entry values ranging from 3 to 30 kPa (0.4 to 4.0 psi). Intake filters should be saturated prior to installation.

Contreras et al. (2007) have demonstrated the viability of directly surrounding diaphragm piezometers with cement-bentonite grout. Through computer simulation, laboratory testing, and field demonstration, they illustrated that a properly designed cement-bentonite grout mix will allow transmission of a low volume of pore water over a short distance (between the borehole wall and piezometer), yet maintain an overall low hydraulic conductivity in the vertical direction, thus isolating the instrument. The cement-bentonite grout should have a hydraulic conductivity of not more than 1,000 times the formation hydraulic conductivity to be effective, and trial mixes of typical water-cement-bentonite mixtures resulted in hydraulic conductivities between 10^{-5} and 10^{-7} centimeters per second. Note that the piezometers shown in Figures 13.10, 13.11 and 13.12 could also be installed using full grouting as described by Contreras et al. (2007).

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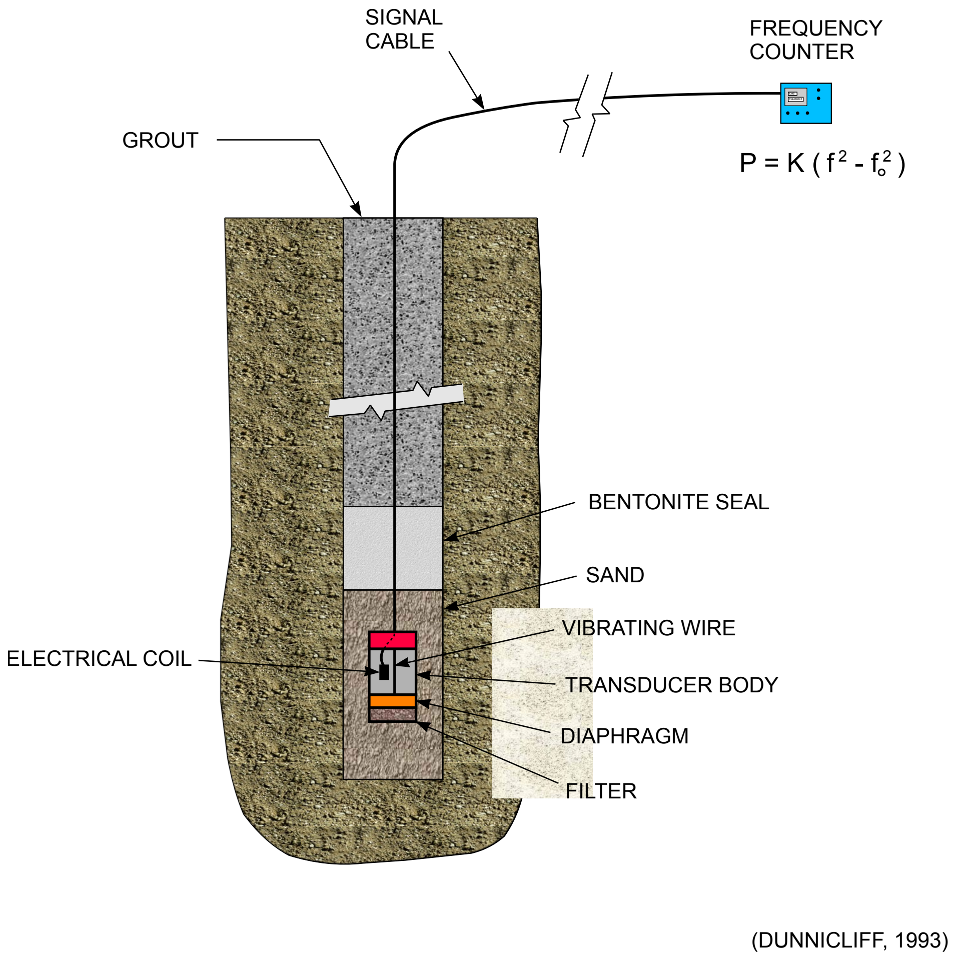

FIGURE 13.11 VIBRATING-WIRE PIEZOMETER

13.2.3 Surface Water Flows and Hydrologic Parameters

Monitoring of surface flows at a coal refuse facility site has the following purposes:

- To develop an understanding of seepage flows, either through, beneath or around an embankment and to evaluate the significant changes as the embankment configuration changes with time.
- To detect an unusual change in seepage quantity that may be an indicator of a developing seepage/stability problem.
- To determine discharges associated with runoff from storms for hydrology/hydraulic analyses and for environmental purposes.
- To determine discharges from mines with workings in proximity to an impoundment.

Monitoring of flows from coal refuse embankments through visual observation should be routine for all coal refuse disposal facilities, and quantitative monitoring of seepage through instrumentation or direct measurement should be performed during construction and operation of impoundments. Monitoring of surface runoff occurs much less frequently and usually is performed only when there are concerns related to flow diversion.

13.2.3.1 Measurement of Impoundment Water Level

Frequent monitoring of the water level at a coal refuse facility impoundment is important because:

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- The pool elevation can change rapidly with time due to runoff from rainfall, spring flow from the watershed, inflow from the processing plant, increases in the level of settled solids, outflows through the decant and spillway systems, and seepage through the embankment.
- The level of water in the impoundment directly affects the rate of seepage flow and the groundwater conditions (pore pressures, piezometric levels, moisture contents) within the embankment.
- Existing reservoir conditions should be regularly checked for comparison with the storage capacity and freeboard requirements in the approved design plan.

Several types of gages for measuring water level are available. The simplest instrumentation is a staff gage consisting of a calibrated rod driven or concreted into solid ground or attached to a structure such as a decant tower. A staff gage allows the reservoir water elevation to be quickly and accurately determined and recorded during regular impoundment inspections. The location of the calibrated rod must be chosen so as not to be affected by changes in facility configuration and deposition of fine refuse and to be easily accessible. Often, this can be best accomplished by installation of several short gage rods with overlapping elevation markings in a stepwise arrangement along the upstream reservoir slope or along the hillside above the reservoir.

Continuously recording gages use floats within a stilling well for measuring the water level. The sensitivity of these instruments to siltation and changes in the level of settled solids make their use unattractive at most facilities.

For any type of gage, an accurate datum must be established so that the monitored pool elevation can be related to the elevations of other facility components. Care should be taken to minimize the potential effects of settlement, tilting, sliding and/or sloughing on the gages.

13.2.3.2 Measurement of Seepage Flows and Other Surface Water Flows

13.2.3.2.1 Importance of Seepage Flows

Seepage flows normally occur in one or a combination of the following forms:

- Flows from internal drainage systems that collect water seeping through the embankment for controlled discharge at the downstream toe.
- Underdrain systems installed (normally at non-impounding facilities) for collecting and transporting groundwater flow from springs through a drain system to the downstream toe without infiltration into the embankment material.
- Very low volume seepages that may emerge on the downstream embankment face.
- Flows from concentrated spring areas along abutments or in the valley bottom downstream from the embankment including those connected to abandoned mines.
- General upwelling of water into a valley bottom over a wide area with no single concentrated location.
- Seepage into or out of mine workings in the vicinity of the impoundment area.

Seepage flow rates are an important indicator of the performance of a facility's seepage collection and control system, which is a critical element in the safety of an impounding embankment. An unusual reduction in seepage flow may indicate clogging of an internal drain, while an unusual increase may be a sign of internal erosion. Unusual changes in seepage quantities must be detected and further investigated, as they could lead to stability problems or even failure of the embankment. For this reason, seepage flow rates should be routinely monitored, especially at high and significant hazard potential impoundments.

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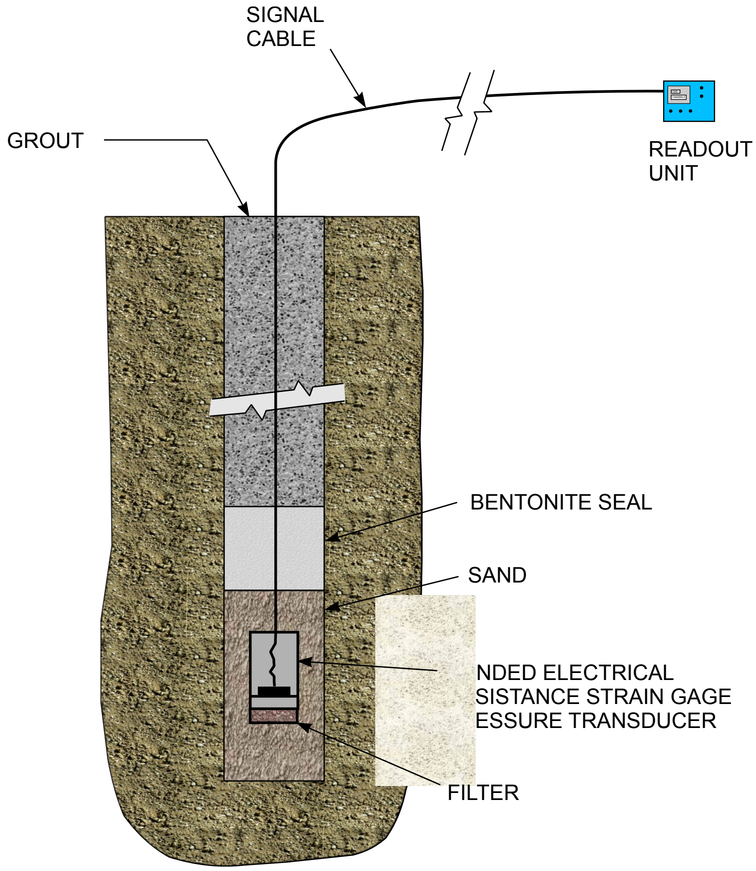

(DUNNICLIFF, 1993)

FIGURE 13.12 BONDED ELECTRICAL-RESISTANCE PIEZOMETER

Where seepage flows are through a pipe system, the flow volume normally can be monitored by:

- Collecting water in a calibrated bucket for a measured period of time.
- Calibrating the rate of flow versus the water depth in the discharge pipe.

Small seeps are normally monitored either by visual observation or by construction of small containments with discharge through a pipe. The discharge from the pipe can be collected in a bucket or the depth of flow can be correlated to the rate of flow. Large discharges downstream from springs or underdrains are usually monitored by a weir installed across the flow path. Widespread downstream seepage should be monitored during periods of dry weather when runoff from rainfall is not occurring. Flows can be measured at downstream culverts or by installing a weir at a point where all of the seeping water passes.

If collected seepage water must be treated prior to discharge, the treatment system may include a flow measuring device (e.g., flow meter, flume, continuous recorder) to control the rate of chemical additions or the retention time. These flow measuring devices can also be used for seepage rate monitoring.

The following characteristics of seeping water are useful for evaluation:

- Quantity of flow
- Temperature at the discharge point

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- Quantity of suspended solids
- Water chemistry

Suspended solids in seepage can be an important indicator of piping, which could result in significant increases in seepage and even eventual impoundment failure. Determination of the presence of suspended solids is usually made subjectively by visual observation (e.g., the water is collected in a container and checked for fines), but if a developing problem is suspected, installation of sediment traps and/or quantitative testing may be necessary.

Evaluation of water chemistry can be an important indicator of the source of seeping water. For example, when seepage increases erratically with time, the source of the seepage may be associated with local groundwater conditions rather than the refuse facility impoundment. Comparison of the chemistry of the impounded water or groundwater samples to that of the seeping water can provide correlations for identification of the source of the seepage. However, determination of water chemistry represents a significant increase in the complexity of the monitoring program and generally is not performed unless other data indicate that it is needed. Wells completed in site geologic strata for monitoring the impact of the disposal facility on the natural groundwater can be useful for establishing local groundwater quality and evaluating seepage paths.

When required, pH, specific conductance, and dissolved oxygen can be measured with relatively simple field water quality testing equipment or continuous recording equipment. If other chemical analyses are required, water samples must generally be collected and subjected to laboratory analytical testing. Key indicators in areas where refuse disposal facilities are normally located include sulfate, total and ferrous iron, manganese, acidity/alkalinity, dissolved solids and suspended solids. The use of amendments with coal refuse disposal may suggest other key indicators (e.g., chloride for combustion waste).

13.2.3.2.2 Measurement of Seepage Flow Rates

The primary purpose for measuring seepage rates is to verify that the magnitude of seepage is reasonable in relation to the potential sources such as the upstream impoundment and local groundwater conditions that can vary with seasonal rainfall. The most important observed condition, and one that requires immediate attention, is when long-term relatively constant flows increase rapidly without a corresponding change in upstream conditions.

A number of methods for measuring flow from pipes have been developed and are described in the Water Measurement Manual (USBR, 2001) or other textbooks on hydraulics such as Chow (1959) and Brater et al. (1996). These methods include, for example:

- Direct volume measurement using a calibrated bucket, pan or tank
- Calibrated weirs
- Flow nozzles and orifices
- Venturimeters
- Current meters
- Commercial water meters
- Flumes

For small flows, the simplest procedures for measuring the rate of flow are: (1) by filling a calibrated bucket during a measured time (volume per time) and (2) calculating the flow based on the geometry of the discharging water surface, provided the pipe discharges freely. Figure 13.13 illustrates the following methods for measuring the flow rate at open-ended horizontal and vertical pipes:

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- The California method (Figure 13.13a) for pipes not flowing full, where the measured trajectory and depth to water at the end of the pipe is used to calculate flow rate.
- The Purdue method (Figure 13.13b) is preferred for pipes flowing full or more than 50 percent full. For this method, the x and y coordinates of the discharge are measured, and empirical graphs provided by the USBR (2001) are used to determine the corresponding flow.
- The third method (Figure 13.13c) is used for estimating discharge from a vertical pipe. The rate of flow is determined from the curves presented on the figure based on the height of the jet and the inside diameter of the pipe.

Calibrated weirs are a simple and reliable means for monitoring flow. If a weir is being used to monitor seepage flow or discharge from a mine, the flow should not be comingled with surface runoff. A V-notch weir is frequently used for monitoring low flows because the decreasing width of the weir with decreasing flow maximizes the height of flow and enables an accurate determination. Situations where use of a V-notched weir is appropriate are presented in USBR (2001). If monitoring is required for only a short period of time, a V-notch weir can be as simple as a piece of exterior plywood (with the V-notch) installed into the ground to a sufficient depth and width that there is no seepage flow beneath or around the weir. The disadvantage of this type of weir is that its life is very limited because of deterioration of the wood when exposed to water and weather conditions. Another alternative for this type of weir is construction of a concrete head wall with a plastic or steel plate forming the weir. For facilities where the water quality may have corrosive characteristics, the V-notch plate can be made of fiberglass or stainless steel to extend the useful life.

Figure 13.14 shows typical construction details for a concrete weir with an attached plate, and Table 13.8 summarizes necessary conditions for accurate measurement for sharp-crested weirs (USBR, 2001). Two important construction details for V-notched weirs are: (1) sealing of the entire upstream side of the weir so that no water flows under or around the weir and (2) placing sufficient riprap or other channel protection downstream to prevent erosion in the area where the weir discharges.

To avoid flow restriction, a free-fall condition where the nappe does not cling to the downstream side of a weir should occur. However, under field conditions, it is sometimes difficult to locate a weir so that a free-fall condition will occur at all discharges. Figure 13.15 provides formulas and a series of curves for estimating flow through a V-notch weir under free-fall conditions (design conditions), as well as an approximate method for estimating flow with downstream submergence of up to 90 percent of the depth of flow through the weir. If the weir will be frequently submerged and accurate measurements are necessary, modifications to the weir structure may be necessary. When tables or graphs are used to determine the flow rate over weirs, care must be taken that the water measurement location and weir type match the conditions for which the tables or graphs were developed.

A rectangular weir should be used when relatively large flows are anticipated and should be designed by an engineer with experience related to weirs. The larger potential flows make construction details for a rectangular weir very important if excessive erosion and undercutting that could destroy the weir during high flow periods are to be avoided. The rate of flow over a rectangular weir is a function of the weir length and width and the shape of the crest and sides. Calibration of a rectangular weir should be performed in the field. An approximation of flow rate is given by the following formula (USBR, 2001):

$$Q = C_e L_e H^{3/2} \tag{13-2}$$

where:

Q = discharge (length^3/time)

C_e = 3.22 + 0.4 (H/P) for L/B equal to 1 (weir constant)

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L_e = equivalent length of weir, approximately equal to weir length L (length)

H = measured head on the weir (length)

P = crest height of weir (length)

B = average width of approach to weir (length)

Refinements in estimating the effective coefficient of discharge (C_e) for other values of L/B are presented in USBR (2001). Other types of weirs have been used and are appropriate if designed and installed in accordance with the intended use. These types of weirs are discussed in the standard references on hydraulics, such as USBR (2001), Chow (1959), and Brater et al. (1996).

13.2.3.3 Measurement of Rainfall and Snowfall

Local precipitation data are needed at impoundment sites where differentiation of reservoir seepage from other sources is important. This need may occur at impoundment sites where underground mines are located below or near an impoundment and where it may be critical to monitor the rate and volume of water that can infiltrate the mine workings and affect mine breakthrough potential. Rainfall data may also be useful in evaluating how groundwater flow contributes to abutment seepage. Often, data from nearby meteorological stations operated by the U.S. Weather Bureau can be used for estimating precipitation at a site. However in mountainous regions or where the density of existing stations is low, rainfall and snowfall at a refuse disposal facility can vary significantly from measurements at meteorological stations. At these sites, simple precipitation measuring gages can be installed for daily measurement and recording of precipitation. If more information is required or if site personnel are not available to record daily measurements, a more sophisticated monitoring system with continuous recording may be appropriate. Standard equipment and procedures for monitoring climatic conditions are discussed by Linsley et al. (1982).

13.2.3.4 Observation of Temperature and General Weather Conditions

Whether a precipitation station is established or not, monitoring of temperature and general weather conditions (e.g., cloudy, sunny) should be performed at a refuse disposal site. This information is often useful when reviewing periodic inspection reports, assessing requirements for maintenance or evaluating unexpected conditions that have occurred.

13.2.4 Miscellaneous Instrumentation and Monitoring

The most commonly used monitoring instruments are those for measuring static displacements, pore-water pressures and water flow, as discussed in the previous sections. Other, less often used but frequently necessary, instrumentation is discussed briefly in the following subsections.

13.2.4.1 Measurement of Soil Pressure

Soil pressures on structures such as conduits installed under and through embankments are important. Two types of instruments for measuring total stress in soil are available: embedment cells and contact earth pressure cells (Dunnicliff, 1993). Embedment earth pressure cells are used to measure total stress in a soil mass, but these instruments are beset with problems that render most measurements useless. Most of the problems are attributable to errors associated with conformance between the cell and the surrounding soil mass. Dunnicliff (1993) describes these problems in detail. If the total soil pressure at points in a refuse embankment is needed for verification of design assumptions, field measurements of the in-place density should be considered in lieu of measuring total pressures with embedment pressure cells. For situations where data on the performance of a conduit is desired, monitoring of the internal deformation of the conduit will likely produce more useful results. Section 12.2 provides guidance for monitoring the performance of deeply buried conduits with respect to the effects of earth pressure. Conduit deflection measurements can be obtained with laser or optical equipment using the laser ring method.

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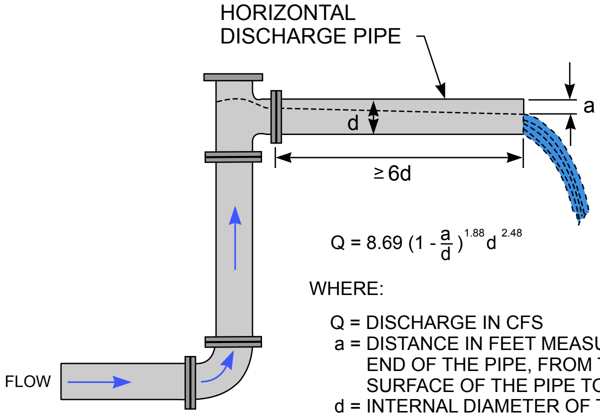
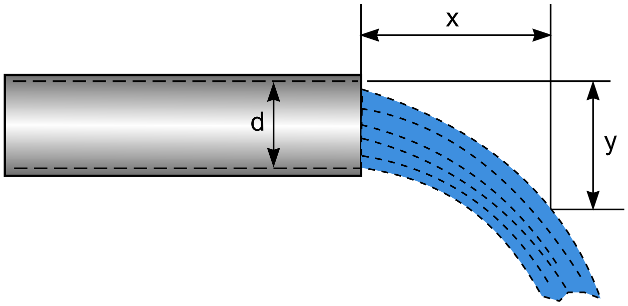


$$Q = 8.69\left(1 - \frac{a}{d}\right)^{1.88} d^{2.48}$$

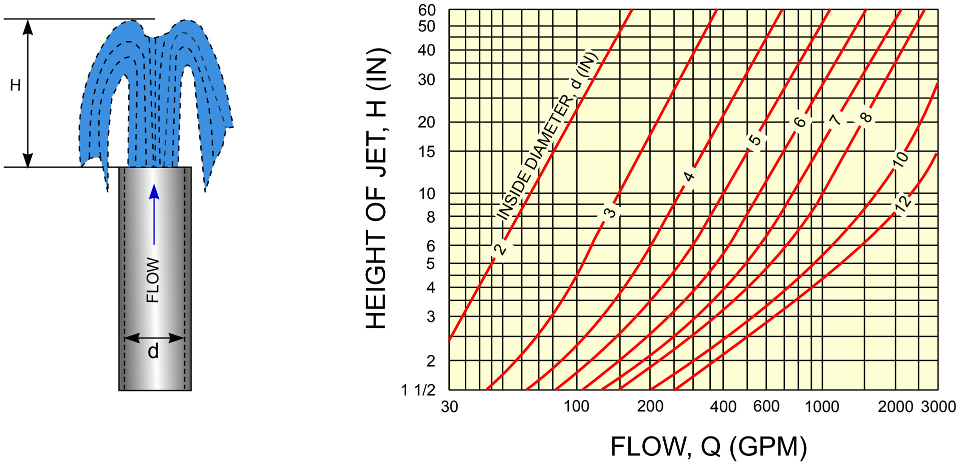
WHERE:

Q = DISCHARGE IN CFS
a = DISTANCE IN FEET MEASURED IN THE PLANE OF THE END OF THE PIPE, FROM THE TOP OF THE INSIDE SURFACE OF THE PIPE TO THE WATER SURFACE
d = INTERNAL DIAMETER OF THE PIPE IN FEET

13.13a TYPICAL ARRANGEMENT FOR MEASURING FLOW BY THE CALIFORNIA PIPE METHOD



13.13b PURDUE METHOD OF MEASURING FLOW FROM A HORIZONTAL PIPE



13.13c DISCHARGE CURVES FOR MEASUREMENT OF FLOW FROM VERTICAL STANDARD PIPES

FIGURE 13.13 MEASUREMENT OF FLOW FROM PIPES

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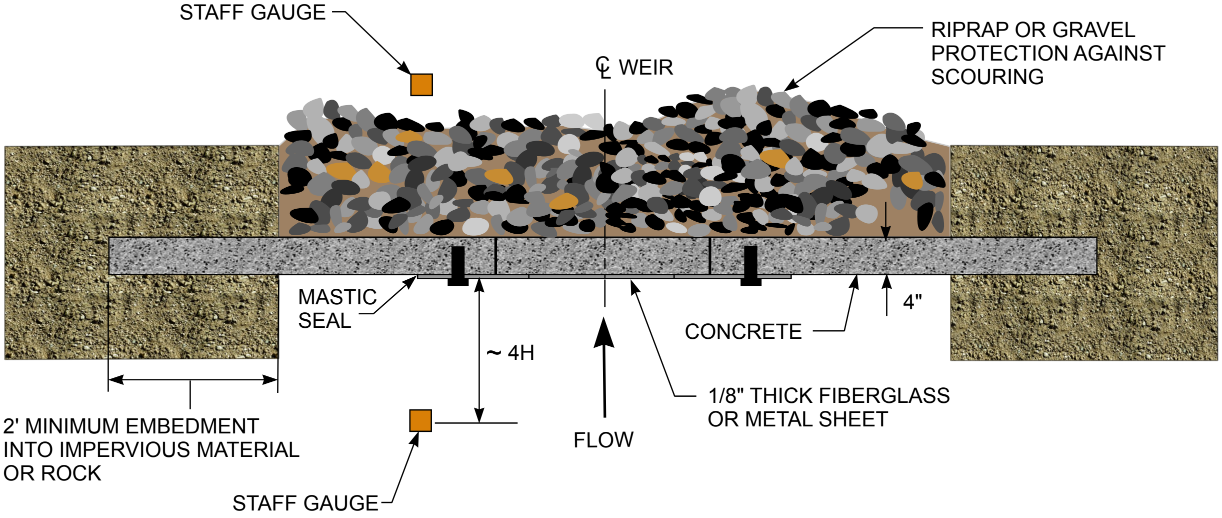
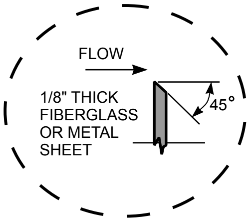
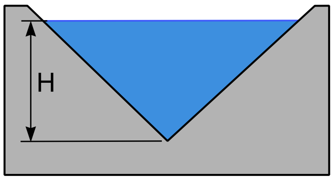


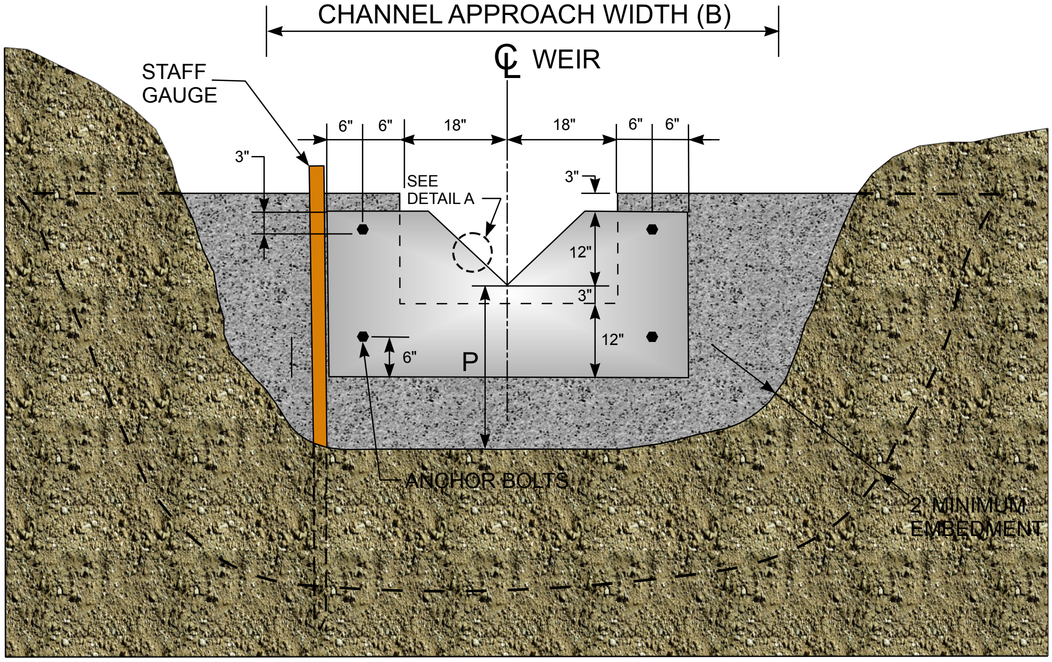
13.14a PLAN



DETAIL A



DETAIL B - FLOW AT WEIR NOTCH



13.14b ELEVATION

FIGURE 13.14 TYPICAL V-NOTCH WEIR

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TABLE 13.8 GUIDANCE FOR ACCURATE WEIR FLOW MEASUREMENT

1. The upstream face of the weir plates and bulkhead should be plumb, smooth, and normal to the axis of the channel. Weir plate fasteners should be located and installed in a manner that minimizes effects on the flow and water surface.
2. The entire crest should be level for rectangular shapes, and the bisector of V-notch angles should be plumb.
3. The edges of the weir opening should be located in one plane, and the corners should have the specified angles.
4. The top thickness of the edges of the crest and side plates should be between 0.03 and 0.08 in.
5. All weir plates should have the same thickness for the entire boundary of the overflow crest. If the plates are thicker than specified in Item 4 above, the plate edges should be reduced to the required thickness by chamfering the downstream edge of the crest and sides to an angle of at least 45 degrees; an angle of 60 degrees is highly recommended for a V-notch to help prevent water from clinging to the downstream face of the weir.
6. The overflow sheet or nappe should touch only the upstream faces of the crest and side plates. Low flow conditions (< 0.2 ft of head) may result in the nappe clinging to the downstream weir face. If such conditions are sustained and accurate measurements are required, a reduced-size weir may be needed.
7. The measurement of head on the weir is the difference in elevation between the invert of the weir and the water surface at a point located upstream from the weir a distance of at least four times the maximum head on the crest.
8. Approach flow conditions should be fully developed, mild in slope, and free of curves, projections and waves. The approach flow velocity should generally be less than 0.5 ft/sec.

(ADAPTED FROM USBR, 2001)

Contact earth pressure cells can be used to measure total soil stress against a buried structure such as a wall or conduit. These instruments do not experience the problems associated with embedment cells, and it may be possible to measure total stress at the face of a structure with reasonable accuracy if issues of cell stiffness and temperature are considered during the instrumentation planning process. Dunnicliff (1993) recommends that diaphragm cells used for this application have two active faces (i.e., pressure is measured both on the cell face against the structure and on the face against the soil fill) and that hydraulic-type cells be avoided because they cannot be mounted flush with the structure face. Even if these guidelines are followed, however, considerable attention must be given to the number of cells needed, laboratory calibrations, temperature effects, cell stiffness, irregularities on the structure face, and a number of installation details. Therefore, if project requirements demonstrate a need for earth pressure measurements, earth pressure cells should be used with caution and with modest expectations for the outcome.

13.2.4.2 Measurement of Blast Vibrations

Portable seismographs are generally used for isolated cases where vibrations associated with blasting could affect structures of interest. The seismograph sensors are either accelerometers or velocity transducers that produce a record of the motion with time, usually in the form of particle velocity, although particle displacement and particle acceleration measurement are also possible. Velocities are measured triaxially (i.e., with respect to vertical, longitudinal and transverse axes) at the location where the instrument is anchored. If multiple instruments are installed at a site, they should be aligned in the same direction (e.g., with the longitudinal axes parallel to the long axis of the impoundment). Field instruments can be set to trigger at a specified velocity and can record and store hundreds of events that can then be downloaded to a personal computer or transmitted to a remote location. The frequency content of blast vibrations is typically much higher than would affect a coal refuse or earth dam. In most cases, blast monitoring is undertaken at surface structures (i.e., near local buildings) to verify that the blast ground motions do not exceed permissible standards. Section 6.6.7 addresses blasting impacts.

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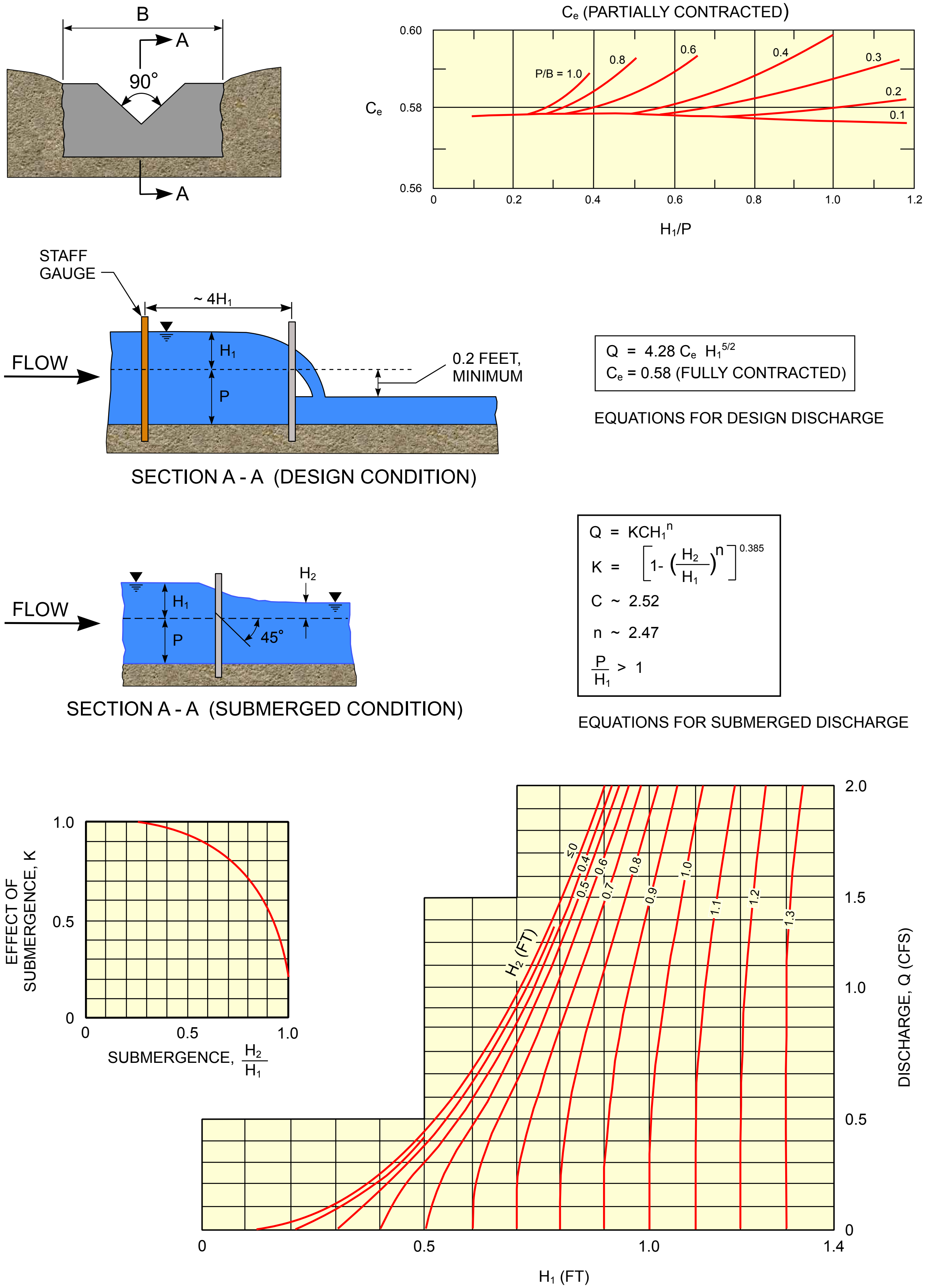

$$Q = 4.28\, C_e\, H_1^{5/2}$$

$C_e = 0.58$ (FULLY CONTRACTED)

EQUATIONS FOR DESIGN DISCHARGE

$$Q = KCH_1^n$$

$$K = \left[1 - \left(\frac{H_2}{H_1}\right)^n\right]^{0.385}$$

$C \sim 2.52$

$n \sim 2.47$

$\frac{P}{H_1} > 1$

EQUATIONS FOR SUBMERGED DISCHARGE

FIGURE 13.15 FLOW DEPTH–DISCHARGE RELATIONSHIP FOR 90-DEGREE, V-NOTCH WEIR

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13.2.4.3 Measurement of Temperature

Evaluation of the extent of (or potential for) burning in a refuse embankment or in coal seams requires monitoring of temperatures at and below the ground surface. Internal temperature can be monitored by permanently-installed thermocouples on probes driven into an embankment. Also, temperatures in an embankment or in abutment coal seams can be measured by lowering conventional thermometers or telethermometers (remote sensing thermometers) down boreholes or piezometer standpipes.

Evaluation of surface temperatures over large areas can also be performed using remote sensing technology, including thermal imaging. Aircraft-mounted thermal imaging can cover very large areas and can detect minor variations in the ground surface temperature, which can assist in site characterization and on focusing subsurface exploration efforts.

13.3 INSTRUMENTATION MAINTENANCE

While a functional and reliable instrumentation system can be achieved with proper instrument design and installation, the system must be maintained so that it will continue to be functional and reliable in service. This section provides a discussion of general maintenance and recalibration practices.

13.3.1 Importance of Maintenance and Recalibration

Careful attention to factory calibration, pre-installation acceptance tests, installation, and post-installation acceptance tests should result in an instrumentation system that performs in accordance with expectations. To keep instruments operating satisfactorily during their service life, regular maintenance and recalibration are required. Lack of regular maintenance and recalibration can result in erroneous data that can lead to incorrect conclusions regarding facility performance. Lack of maintenance can also jeopardize the functioning of an instrumentation system leading to the loss of instruments. Malfunctioning or damaged instruments will normally need to be replaced or repaired.

Maintenance and recalibration activities should be conducted in accordance with a plan for regular instrument calibration and maintenance, as described in Step 8 in Table 13.1. Maintenance procedures should be based on the manufacturers' instruction manuals and on-site conditions, as indicated in the design plans. These procedures should include preventative maintenance program schedules, troubleshooting, cleaning, drying, lubricating, battery servicing, and repair and replacement instructions for each type of instrument. Maintenance and recalibration should be the responsibility of personnel responsible for instrument monitoring, and it is essential that these individuals be knowledgeable about the types, expected and actual performance, and the maintenance and recalibration requirements of the instrumentation and data acquisition systems for the facility.

Personnel responsible for instrumentation maintenance and recalibration should be reliable, dedicated, and motivated individuals who pay attention to detail. They should have a background in the fundamentals of geotechnical engineering and should understand mechanical and electrical equipment. They should understand the purpose of instrumentation and how the instruments function. Maintenance and recalibration of instrumentation should be supervised by the data collection personnel, who are most likely to notice potential problems and to observe malfunctions, deterioration, or damage.

A service history record of maintenance, recalibration, repair, and replacement of the components of the instrumentation system should be maintained, and this record should be reviewed by the personnel responsible for evaluating facility performance. The service history should include dates, observations, problems that occurred, measures taken, and the personnel who were involved. A service history documents the general behavior of the instrumentation system and can serve as a guide to future maintenance activities. The service history also facilitates the transfer of responsibility associated with turnover in personnel.

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Spare parts and interchangeable components should be available for replacing failed or questionable instrument components without interrupting system operation. An inventory of spare parts and instruments should be available and should be updated as necessary. Spare readout units should be available in the event of malfunction of the primary readout units.

13.3.2 Recalibration and Maintenance during Service Life

When instruments are in service, they require regular recalibration and maintenance if their normal operational characteristics are to be maintained. Generally, recalibration should be performed on a defined schedule, as documented in the Operation and Maintenance Plan. Routine recalibration of instrumentation system components is best performed by personnel responsible for data collection with the knowledge of personnel responsible for data analysis.

Instrumentation data should be carefully examined for indications that recalibration is needed. If abrupt changes or unexplained long-term trends in data are observed without apparent reason, the affected instrument should be checked to determine whether or not the data reflect actual conditions or are the result of instrument malfunction. If a need for recalibration is indicated, procedures should follow the instrument manufacturer's recommendations. General guidelines for the recalibration and maintenance of geotechnical and structural instrumentation systems and associated data acquisition equipment are provided in USACE (1995c).

In addition to regular recalibration, weirs, flumes, or other water measurement devices require regular maintenance so that: (1) water does not bypass the device, (2) leakage around or under the device is sealed, and (3) sediment deposition has not altered the approach conditions for the device.

13.4 AUTOMATED DATA ACQUISITION

Automated data acquisition systems have been demonstrated to be reliable and cost effective for monitoring the performance of constructed works and their surrounding environment, especially at sites where access is difficult or where regular survey and/or monitoring control are not practical or economical. With time, automated data acquisition systems will continue to improve with the likelihood that their use at coal refuse facilities becomes more common. Where deployed at coal refuse disposal facilities, automated data acquisition systems have been generally used for monitoring impoundment pool and piezometer levels.

Most automated data acquisition systems are programmed to retrieve data from multiple instruments on a prescribed schedule, process the readings to present the results in terms of engineering dimensions, and store or transmit the data. System components and design are discussed in Appendix 13A.4.

Figure 13.16 illustrates the application of an automated data acquisition system at a coal refuse disposal impoundment for monitoring piezometer levels and transmitting the data to a mine office more than a mile away. Features such as data collection from multiple piezometers, radio transmission, data storage and distribution of data by e-mail have been incorporated into monitoring programs. Quaranta et al. (2008) discuss an automated data acquisition program used for collecting the following data at a coal refuse disposal facility: water level, pH, specific conductance, and temperature at piezometers; water discharge; and the impoundment pool level. Weather station data (ambient air temperature, barometric pressure, rainfall, and wind speed) were also collected. This reference presents the system design, equipment, and operation issues encountered.

13.5 INSTRUMENTATION COSTS

Instrumentation systems are typically employed at refuse embankments and dams for monitoring water levels, pore-water pressures, deformations, and other important parameters depending upon

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site conditions. For below-grade instrumentation used on conventional geotechnical engineering projects, the initial purchase price of an instrument and the cost of installation represents 15 to 30 percent of the total instrument life-cycle costs, which also include periodic readings, maintenance, data analysis and interpretation, data management, and eventual decommissioning (McKenna, 2006). Based on experience from numerous instrumentation projects, McKenna (2006) concluded that the typical life-cycle cost for an instrument employed for conventional geotechnical engineering projects is about 15 times the initial purchase price. For coal refuse disposal facilities that can operate over very long periods, the initial price of an instrument may represent an even smaller percentage of the life-cycle costs. McKenna (2006) offers the following lessons learned:

Lesson 1 – The best way to save money is to install instruments that are suited to the site-specific and performance conditions critical to the safe operation of the structure. This lesson reinforces several steps in the planning process that were discussed in Section 13.1.

Lesson 2 – The actual cost of the instrument is very small compared to the life-cycle costs, so instruments should be purchased with reliability in mind.

Lesson 3 – Every instrument should be installed with care, should be maintained, and should be read by a trained and diligent technician in accordance with project quality control procedures.

Some additional thoughts on instrumentation are provided in the following:

- The greatest cost of instrumentation is obtaining the readings, and the greatest risk is the additional expense associated with poor quality or inaccurate readings.
- Instrumentation suppliers should be viewed as a partner in the complete process, especially for designers who have limited experience with instrumentation.

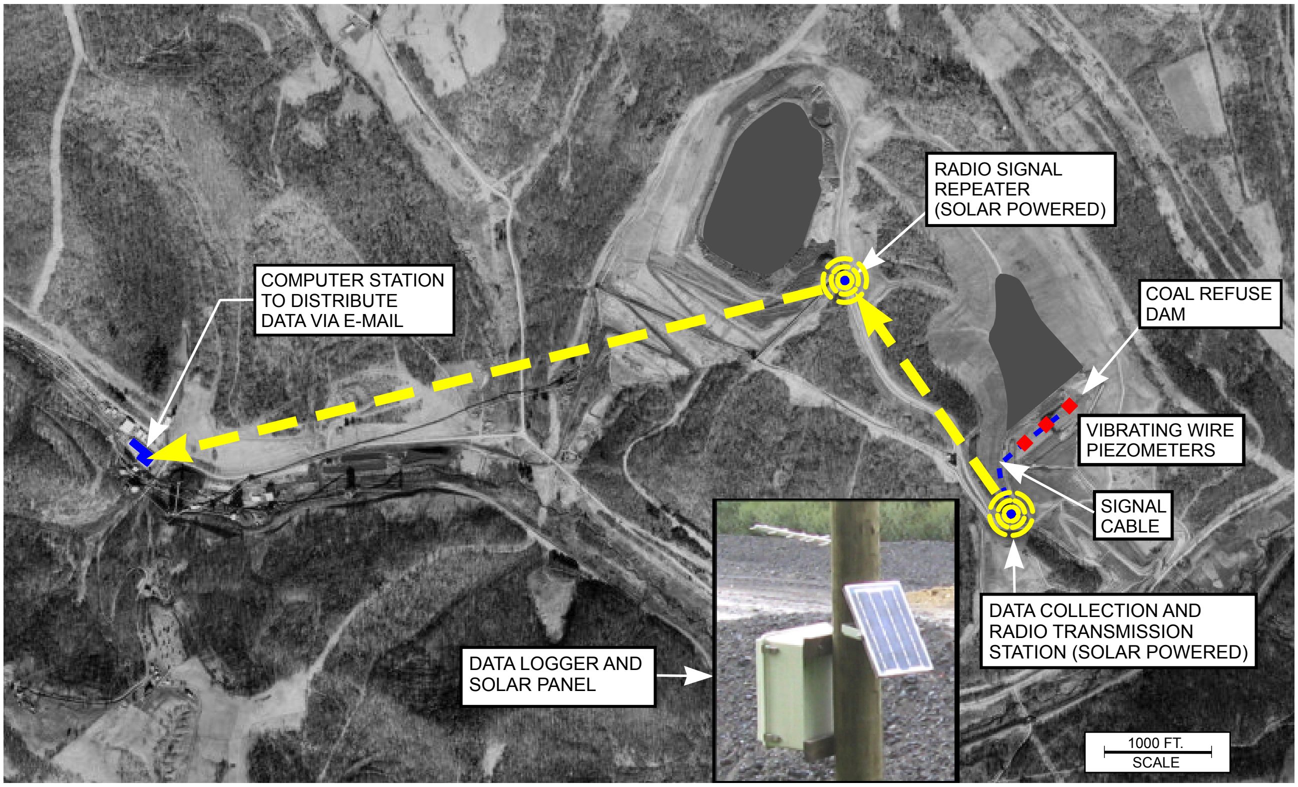

FIGURE 13.16 AUTOMATED DATA ACQUISITION SYSTEM AT COAL REFUSE DISPOSAL FACILITY

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- Measures should be taken to see that data reading procedures are in place for each type of instrument, personnel are trained with respect to the procedures and equipment, readout equipment is properly maintained and regularly calibrated, and all raw data is recorded, plotted and evaluated according to project requirements.
- The same technician and equipment should be used to obtain all instrumentation readings to the extent possible. Automated data acquisition systems can improve the consistency and reliability of the data while providing more continuous monitoring.
- Instruments should be carefully protected because replacement can be difficult and costly.
- In areas where it would be particularly difficult to replace a failed instrument, redundant instruments should be considered.
- As time progresses, some opportunities for instrumentation system improvement may become apparent. Changes should be implemented, as needed, to improve the data gathering process and the quality of the data obtained.

This chapter has provided a discussion of the important aspects of implementing an instrumentation program at a coal refuse disposal facility including planning, instrument selection, installation, and data retrieval and processing. The benefits of well planned and properly installed and maintained instrumentation include:

- Enhancing the ability to compare the actual performance with the performance anticipated by the designer
- Enhancing the ability to recognize problem conditions before they become serious
- Aiding in the design and construction of expansion plans or remedial measures when they are needed

In summary, the cost of geotechnical instrumentation should be considered in context with the benefits that can be achieved, especially given the long in-service life of most coal refuse facilities.

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Appendix 13A

MEASUREMENTS, TRANSDUCERS AND DATA-ACQUISITION SYSTEMS

This appendix provides information regarding measurements and measurement uncertainty, transducers and data acquisition systems supplementing the general discussion of these topics in Chapter 13.

13A.1 MEASUREMENT AND MEASUREMENT UNCERTAINTY

Quantitative measurements obtained by field instrumentation provide a means for confirming a safe and efficient design and verifying safe and economical construction. Because all measurements involve error and uncertainty, the measures by which error and uncertainty are defined should be considered as part of the field instrumentation design. The standard measures used to define error and uncertainty in instrument measurements include:

- Conformance is the ability of an instrument to measure performance without affecting the measurement. Similar to in-situ structures, instruments that are stiffer than the surrounding media tend to attract load while instruments that are softer than the surrounding media tend to shed or arch load away. Therefore, instrument behavior should match the behavior of the medium in which it is installed as closely as possible.
- Accuracy is the closeness of a measurement to the true value and is determined during calibration by comparison to the true value.
- Precision is the closeness of several measurements to the mean value and is synonymous with reproducibility. The difference between accuracy and precision is illustrated in Figure 13A.1.
- Resolution is the smallest division on the instrument readout scale.
- Sensitivity is the amount of output response an instrument produces in response to an input quantity (e.g., 1000 millivolts per inch)
- Linearity refers to the proportionality between the indicated value and the actual value. Thus an instrument with a linearity of ½ percent full scale means that the maximum error resulting from a linear calibration will be ½ percent of the full-scale reading.
- Hysteresis is a property of systems that do not instantly respond to the forces applied to them, but react slowly, or do not return completely to their original state.
- Noise refers to random measurement variations caused by external factors that result in lack of precision or accuracy.
- Error is the deviation between the measured value and the true value. Types of errors include gross error, systematic error, sampling error and random error.

Measurement uncertainties must be considered as part of instrument selection and also in the evaluation of measurement data.

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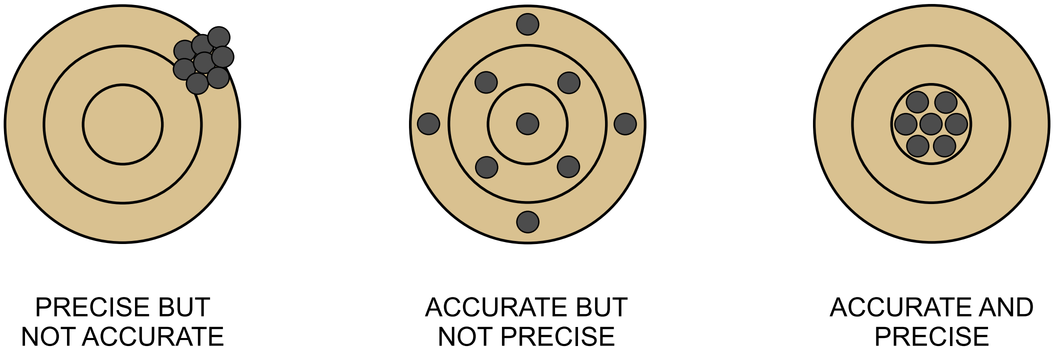

(DUNNICLIFF, 1993)

FIGURE 13A.1 GRAPHIC ILLUSTRATION OF ACCURACY AND PRECISION

13A.2 INSTRUMENT TRANSDUCERS

While performance monitoring at coal refuse facilities is typically conducted using position surveys of surface monuments and other devices such as staff gauges, inclinometers, standpipe piezometers, weirs, and rainfall gauges, geotechnical and structural instrumentation employing transducers is becoming more prevalent because these devices facilitate remote monitoring, transmission and processing of performance data. For such applications, instruments frequently consist of a transducer, data acquisition system and a communication link between them. A transducer is a device that converts a physical response or change into a corresponding output signal. Transducer types can be classified as:

- Mechanical
- Hydraulic
- Pneumatic
- Electrical

Measurement of geotechnical and structural behavior is typically accomplished using instruments employing more than one transducer type. The selection of an instrument appropriate for a particular application depends on the type of measurement required, the project setting and related environmental factors, and the duration for which measurements are required. Data acquisition systems for these instruments range from simple portable readout units to complex, automated systems.

13A.2.1 Mechanical Instruments

The most commonly used mechanical instruments are dial gages and micrometers. A dial gage converts the linear movement of a spring-loaded plunger to movement of a pointer against a dial scale. Accuracies are usually ± 0.001 inches or ± 0.0001 inches with a range of movement of typically 1 to 2 inches, although instruments with ranges up to 12 inches are available. Most dial gages are inexpensive, but they are somewhat fragile and can be affected by environmental factors such as dust and dirt. For long-term application, sealed and waterproof versions are available.

A micrometer functions by the rotation of a finely threaded measuring rod that moves into or out of a sealed housing. Movement of the rod is measured by a scale on the housing that indicates the number of revolutions. Fractional revolutions are determined using gradations marked around the rod and a vernier on the housing. Accuracy for micrometers reading in

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inches is ± 0.001 inches. The rod length can be changed to permit a measurement range up to 6 inches, and digital outputs are available to overcome difficulties with reading vernier scales.

Dial gauges, micrometers and other simple gauges (e.g., crack monitors) have been used at dams and impoundments on mine sites where adverse conditions are suspected. Some applications have included monitoring crack apertures and relative displacements in or adjacent to rigid structures, such as concrete spillways or intakes and pipes.

13A.2.2 Hydraulic Instruments

Although not normally used for monitoring the performance at coal refuse facilities, the most commonly used hydraulic instruments are Bourdon-tube pressure gages and manometers. A Bourdon tube is a flattened tube that is coiled into a C-shape. When the tube is pressurized, the tube expands causing it to uncoil. The uncoiling motion is linked to a pointer that rotates over a circular scale. Bourdon tubes typically have an accuracy of ± 0.5 percent full scale for 4- and 6-inch-diameter dial gages, but gages with higher accuracy (e.g., ± 0.1 percent full scale) may be required for meeting project requirements, especially for long-term applications. Bourdon-tube gages are used with hydraulic piezometers, hydraulic load cells, borehole pressure cells, and some readout units for pneumatic transducers (Dunnicliff, 1993).

A manometer is a liquid-filled U-tube. The pressure on one side of the U-tube is balanced by an equal pressure on the opposite side. Manometers are used for long-term monitoring of very small positive or negative pressures and are easily calibrated and have a greater longevity than Bourdon tubes. Manometers are used with twin-tube hydraulic piezometers and liquid-level settlement gages (Dunnicliff, 1993). In these devices, the pressure difference between the liquid surfaces at the opposite ends of the manometer has a known relationship to the elevation difference via an assumed or measured density of the liquid. Potential problems with a manometer are discontinuity in the liquid due to formation of gas bubbles, changes in the density of the liquid due to temperature effects, and surface tension effects. Dunnicliff (1993) describes each of these problems and provides recommendations to prevent their occurrence.

Use of these instruments requires physical access to the readout location. If remote data recording is necessary, an electrical pressure gage should be used (Dunnicliff, 1993).

13A.2.3 Pneumatic Instruments

Pneumatic instruments function by supplying a known pressure via tubing that reacts against a sealed diaphragm in the pneumatic transducer. When the pressure in the inlet line just balances the pressure against the transducer diaphragm, the diaphragm displaces slightly. This condition is determined by a return of gas flow from the outlet line (for a gas-flowing instrument), or the pressure in the outlet line is measured using a Bourdon tube or electrical pressure gage (for a non-gas-flowing instrument). For simple applications, manually-operated readout units for pneumatic instruments are available. Where a large number of pneumatic instruments must be monitored, readout units can be connected to large gas tanks, and data acquisition and control systems can be used to energize the systems and to scan and record the measurements.

Important characteristics of most commercially available pneumatic transducers include sensitivity to diaphragm displacement, sensitivity to gas flow rate, and the length of tubing. For reliable performance: (1) transducer components should not be prone to corrosion, (2) a dry gas such as carbon dioxide or nitrogen should be used, and (3) the tubing and fittings should be air tight and impermeable to moisture infiltration. Pneumatic transducers and data acquisition systems are used in pneumatic piezometers, earth pressure cells, load cells, and liquid settlement gages (Dunnicliff, 1993).

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Pneumatic piezometers are routinely used at coal refuse disposal facilities, primarily to monitor pore pressure within low-hydraulic-conductivity deposits that may exhibit elevated pore pressure when loaded. Specifically, these types of piezometers have been used to monitor pore pressures within fine coal refuse subject to upstream construction loading. When instruments for such an application are selected, their reliability and recommended service period should be evaluated.

13A.2.4 Electrical Instruments

13A.2.4.1 Electrical Resistance Gages

Electrical resistance gages are used for many geotechnical and structural monitoring applications. These gages are precisely manufactured conductors that change resistance in proportion to the change in length of the gage. Most strain gages have a nominal resistance of 120 or 350 ohms. The gage factor, which is a measure of the strain sensitivity of the gage, is typically about 2 for bonded foil and wire gages and between about 50 and 200 for semiconductor gages.

The bonded foil strain gage is the most widely used type, and it has significant advantages over all other types of strain gages. Bonded foil gages consist of a metal foil pattern mounted on an insulating backing or carrier, constructed by bonding a sheet of thin-rolled metal foil 2- to 5-μm thick on a backing sheet that is 10- to 30-μm thick. The measuring grid pattern including the terminal tabs is produced by photo-etching. Bonded foil gages are used because of the quality of their manufacturing and because the temperature characteristics of the gage can be matched to the material being measured. Higher resistance gages are preferred for transducer applications because such devices permit a higher voltage input that results in a higher voltage output and minimizes the effects of extraneous resistance changes. A variant of the foil gage is the weldable resistance strain gage, which typically consists of a foil gage attached to a thin stainless steel mounting flange. Strain gages can be used for long-term monitoring applications provided that methods used for gage installation, sealing, and protection are appropriate for the application.

The output from electrical resistance gages is generally measured using a Wheatstone bridge circuit, which is described by Dunnicliff (1993). The circuit consists of four resistors arranged in a diamond orientation, as shown in Figure 13A.2. An input DC voltage (excitation voltage) is applied between the top and bottom of the diamond, and the output voltage is measured across the middle. When the output voltage is zero, the bridge is "balanced." One or more of the legs of the bridge may be a resistive transducer such as a strain gage. If the circuit has one strain gage, it is referred to as a quarter-bridge circuit. Similarly, if the circuit has two or four strain gages, the circuits are referred to as half-bridge and full-bridge circuits, respectively. For quarter- and half-bridge circuits, the other legs of the bridge are electrical resistors with resistance equal to that of the strain gage(s). Although half-bridge and quarter-bridge circuits are often used, the full-bridge circuit is the optimal configuration for strain gage usage. It provides the highest sensitivity and the fewest error components, and because the full-bridge circuit produces the highest output, noise is a less significant factor in the measurements. For these reasons, the full-bridge circuit is recommended. A full-bridge configuration is typically used for load cells (Dunnicliff, 1993). In general, the primary application for resistance networks in geotechnical and structural instrumentation described in this Manual is for resistance strain gages used in piezometers to monitor dynamic pore water pressures (e.g., from rapid or cyclic loading) and also for measuring loads in structural elements such as rock bolts or permanent ground anchors for slope stabilization.

13A.2.4.2 Linear Variable Differential Transformer (LVDT) and Direct Current Differential Transformer (DCDT)

LVDTs and DCDTs consist of a moveable magnetic core passing through a primary and two secondary coils. An excitation voltage is applied to the primary coil that induces a voltage in the

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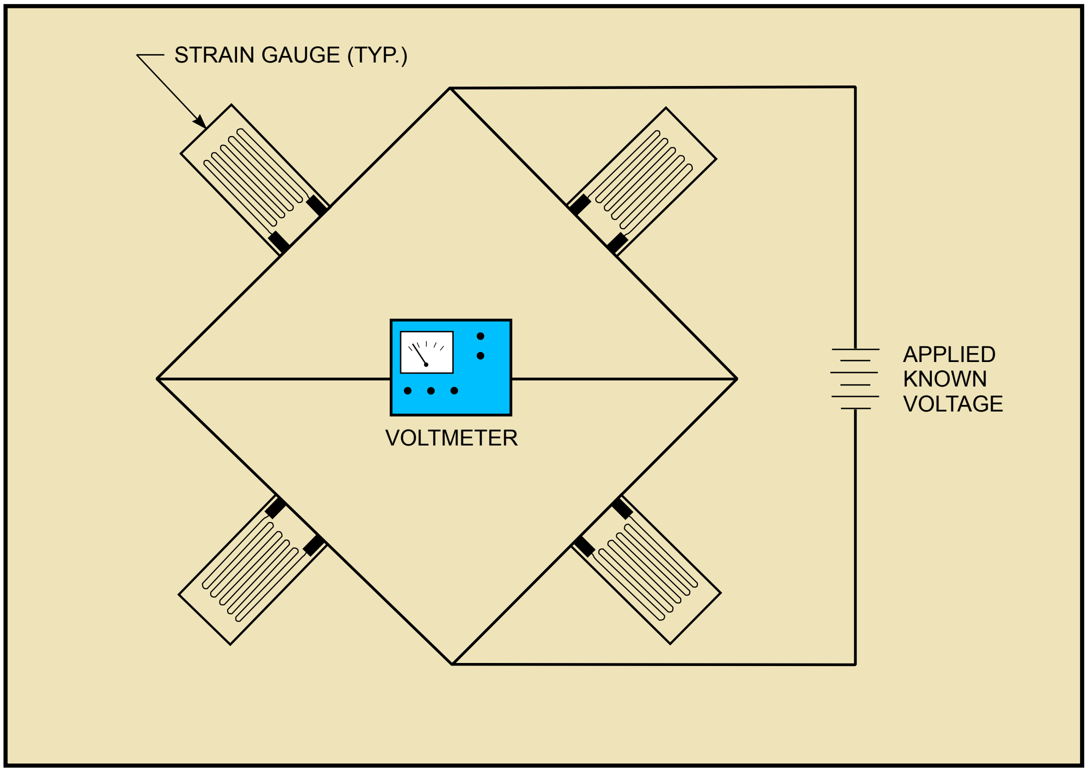

FIGURE 13A.2 WHEATSTONE FULL-BRIDGE NETWORK CONFIGURATION

secondary coils that is dependent upon the proximity of the magnetic core to each secondary coil. The secondary coils are connected in series opposition so that the net output from the device is the difference between the two voltages. When the core is located at the midpoint of the device, the net output voltage is zero. When the core moves from the midpoint, the net output voltage varies linearly. These devices have no hysteresis, and they are well suited for measuring very small displacements and dynamic movements. The primary difference between the two devices is that LVDTs are powered by an AC voltage while DCDTs are powered by a DC voltage. Also, DCDTs are provided with onboard oscillator, carrier amplifier, and demodulator circuitry while LVDTs require these components externally. DCDTs are preferred for geotechnical applications where specialized signal conditioning is not needed for amplifying output from the device. LVDTs and DCDTs are used in fixed borehole extensometers and other instruments to measure deformation (Dunnicliff, 1993).

13A.2.4.3 Vibrating-Wire Transducer

The vibrating-wire transducer consists of a taut, ferromagnetic wire that is excited into transverse vibrations by a drive coil. These vibrations are detected using a pick-up coil. Both coils have permanent-magnet cores, and once the wire has been excited to its resonant frequency for a given tension, it is maintained at this frequency by connecting the two coils through an amplifier to form a self-oscillating system. Each resonant frequency is a measure of the tension in the wire and therefore the applied force. The advantage of the vibrating-wire transducer is that its direct frequency output can be handled by digital circuitry, eliminating the need for an analog-to-digital converter. Sources of error include wire corrosion, wire creep under permanent tension, and wire slippage at the anchoring locations, all of which usually result in a reduction in frequency.

The output from vibrating-wire devices is measured using the pluck and read method or the continuous excitation method. The pluck and read method involves applying one or more volt-

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age pulses to the drive coil to cause the wire to vibrate. The coil then receives the signal from the vibrating wire and transmits the measured voltage to a frequency counter, which measures the time required for a selected number of vibration cycles. The continuous excitation method uses a similar procedure to initiate wire vibration, but uses a second coil to detect the frequency. The signal is fed back to the driving coil, which then applies a continuous pulsing voltage. As the wire frequency changes, the driving frequency also changes, and the new frequency is measured as described for the pluck and read method.

Vibrating-wire transducers are used in pressure sensors for piezometers, earth pressure cells, liquid level settlement gages, load cells, and directly as surface and embedment strain gages (Dunnicliff, 1993). Vibrating wire piezometers are effective instruments for monitoring rapid pore pressure changes in fine coal refuse deposits during upstream construction and have also been used in standpipe piezometers to facilitate automated monitoring and data acquisition systems.

13A.2.4.4 Force-Balance Accelerometer

A force-balance accelerometer consists of a mass suspended in the magnetic field of a position detector. When the mass is subjected to a gravitational force along its measuring axis, the mass attempts to move and the motion induces a current change in the position detector. This change in current is relayed to a servo-amplifier connected to a restoring coil that imparts an electromagnetic force to the mass to resist movement. The current through the restoring coil is measured by the voltage across a precision resistor. The measured voltage is directly proportional to the input force. Force-balance accelerometers have exhibited good performance when used in portable tiltmeters and in inclinometers where the position of the transducer can be reversed to eliminate errors caused by zero shift.

13A.2.4.5 Magnetic Reed Switch

The magnetic reed switch is an on/off position detector used to indicate when conductive reeds are in a certain position with respect to a ring magnet. When a magnetic reed switch enters a sufficiently strong magnetic field, the reed contacts close and remain closed while they are in the magnetic field. Closure of the contacts normally results in activation of a buzzer and/or indicator light in a portable readout unit. Repeatability of the device depends on the radial position of the reed switch within the magnet. If the reed switch remains within the middle third of a 1¼-inch-diameter ring magnet, repeatability will be within ± 0.01 inches (Dunnicliff, 1993). The device is simple, reliable, precise, inexpensive and well suited to long-term applications. The magnetic reed switch is used in probe extensometers.

13A.2.4.6 Induction-Coil Transducers

Induction-coil transducers function by supplying an AC source to a primary coil and measuring the voltage induced in a secondary coil that is located within the magnetic field of the primary coil. For geotechnical applications, inductive-coil transducers have been used to measure strain in soils and displacement in probe, fixed embankment, and borehole extensometers (Dunnicliff, 1993). These devices have excellent long-term stability provided that the steel components are protected from corrosion.

13A.2.4.7 Other Types of Electrical Transducers

Other types of electrical transducers include the potentiometer, variable-reluctance transducer, magnetostrictive transducer, and the electrolytic level. These devices and their geotechnical and structural instrumentation applications are discussed in Dunnicliff (1993). Information is also available from commercial geotechnical and structural instrumentation suppliers.

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13A.3 SUPPLEMENTAL MOVEMENT-MEASUREMENT TECHNIQUES

Section 13.2.1.2 discusses the more commonly applied techniques for measurement of movements. This section discusses supplemental techniques including transverse deformation gages, liquid-level gages, time-domain reflectrometry and fiber-optic gages.

13A.3.1 Transverse Deformation Gages

Transverse deformation gages are installed in boreholes or pipes for measuring deformations transverse to their length (Dunnicliff, 1993). Typical applications include locating the depth of a slide plane and measuring deformations within and below embankments. Types of transverse deformation gages include shear plane indicators, plumb lines, inverted pendulums, in-place inclinometers and deflectometers. Of these devices, only in-place inclinometers have potential application at coal refuse disposal facilities.

In-place inclinometers are usually designed to operate in a vertical or near-vertical borehole and to provide nearly the same information as a standard probe inclinometer. The device consists of a series of gravity-sensors connected by articulated rods. The sensors can be either uniaxial for measuring displacements in one plane or biaxial for measuring displacements in two planes. The sensors are positioned at intervals along the borehole and can be oriented to capture displacements at critical locations. In-place inclinometers are typically installed in the same casings used for conventional inclinometers, thus permitting the devices to be removed for recalibration (possibly interrupting data continuity) or reused elsewhere. Compared to conventional inclinometers, in-place devices offer advantages such as more rapid reading, improved precision, automatic data acquisition, and alarm triggers. Their comparative disadvantages include greater complexity and expense and inability to remove the effect of any long-term drift of the gravity-sensing transducer by reversing the orientation of the sensor as can be done for conventional inclinometers.

13A.3.2 Liquid-Level Gages

Liquid-level gages are instruments that use a liquid-filled tube or pipe for determination of relative vertical deformation. Relative elevation is determined with a manometer or pressure transducer. Liquid-level gages are used primarily to measure the settlement of foundations or embankment fills. Because the devices are buried below the structure or embankment fill, there are no interferences of the type that occur with fixed embankment extensometers (Section 13.2.1.2.5.). Liquid-level gages can only measure relative movements between the measurement location and the reading station. If the exact settlement or heave at a specific point is required, the reading station elevation must be surveyed and referenced to a benchmark datum each time measurements are taken.

These devices are usually sensitive to changes in liquid density due to temperature effects, surface tension effects, and loss of continuity of the liquid in the tube. The greatest potential source of error is discontinuity of the liquid due to gas bubbles in the fluid. Single-point, multi-point and full-profile liquid-level gages are available. Single-point gage types include:

- Both ends at same elevation
- Readout unit higher than the measurement cell
- Readout unit lower than the measurement cell

The most common single-point gage types have the readout unit higher than the measurement cell with pressure readings accomplished using a transducer located either in the measurement cell or in the readout unit. Both of these gage types suffer from the limitation that only a single

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point is monitored, but the unit with the transducer in the readout is generally preferred because the transducer is accessible for calibration during the monitoring period, and the system has fewer limitations and requires less diligent oversight during installation and monitoring. Additional details related to gage types, advantages and limitations, and approximate precision of liquid-level gages are provided in Dunnicliff (1993).

Various multi-point gages have been developed, but users tend to prefer installing several single-point gages because loss of a single multi-point gage can result in the loss of the entire system (Dunnicliff, 1993). Full-profile gages consist of a near-horizontal plastic pipe and an instrument that can be pulled along the pipe. Readings are made incrementally along the length of the pipe so a full lateral profile is obtained. However, the devices have numerous limitations (e.g., temperature errors, lack of exact knowledge of the horizontal position in the pipe) that make a full-profile device such as a horizontal inclinometer (Section 13.2.1.2.7) a preferred choice.

13A.3.3 Time-Domain Reflectometry

Time-domain reflectometry (TDR) is radar along a coaxial cable. TDR involves measurement of the time it takes for an energy pulse to travel down a cable, encounter a known or unknown distortion in the cable, and reflect a signal back to a reading instrument. The time is converted to distance and the data are displayed as a waveform and/or distance reading. The ability to interpret TDR reflections anywhere along the cable allows activity to be monitored over large volumes or areas such that TDR monitoring can replace many single-point measurement instruments. The technique has been used for a variety of deformation measurements related to landslide and slope monitoring, ground subsidence due to mining, sinkholes, groundwater extraction, and scour of bridge foundations.

The use of TDR can complement inclinometer technology. TDR cable surveillance can detect very thin or localized shear zones. Use of TDR in combination with inclinometers or tiltmeters allows remote operation as well as sensing of both gradual tilt and localized deformation. O'Connor and Dowding (1999), Dowding (2002) and Dowding and O'Connor (2000) describe some of these applications.

Figure 13A.3 shows a TDR cable grouted into a borehole. The cement-bentonite grout backfill in the borehole must be designed to fracture easily, so that the cable is deformed as movement occurs within the surrounding medium. Appropriate grout strengths vary considerably, but grouts for boreholes in soil and rock are typically tremmied into place using grout pumps on drill rigs. In general, the unconfined compressive strength of the grout should be less than the strength of the material where the shear failure can occur. Blackburn and Dowding (2004) provide details regarding grout selection and design. Dowding (2002) reports that braided coaxial cable is sometimes strapped to the outside of inclinometer casing in larger holes to save money and drilling costs. Unfortunately this cost-saving method has not performed well, probably because of the low sensitivity of the braided cable and spreading out of the localized shear zone caused by the casing.

13A.3.4 Fiber-Optic Gages

Fiber-optic sensors make use of the ability of optical fibers to convey light from a source to a photosensitive detector (Dunnicliff, 1993). The sensors can be used to indicate the relative position between an object and the end of the fiber or the distance between two points along the fiber. The sensors can also monitor bending. Advantages of fiber-optic sensors include small size, reliability, insensitivity to temperature and humidity changes, immunity to electrical noise (e.g., lightning) low signal loss, and the ability to transmit light along curved paths.

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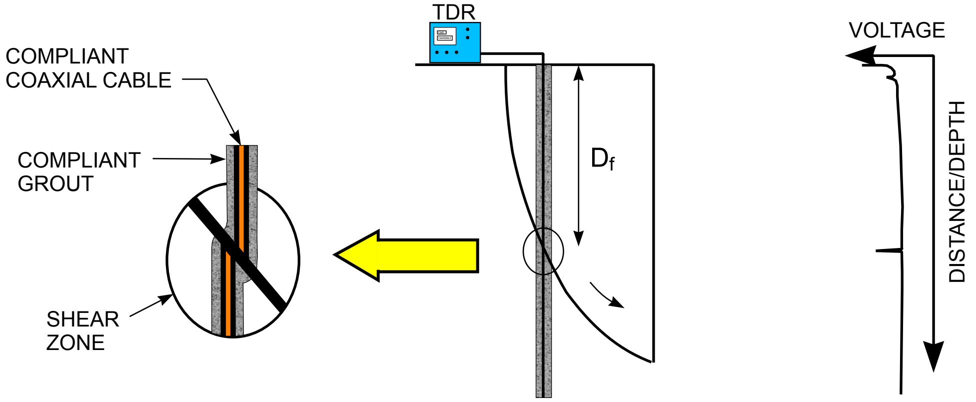

13.12a CABLE/GROUT DETAILS

13.13b CABLE IN SLOPE

13.12c REFLECTED SIGNAL

(DOWDING, 2002)

FIGURE 13A.3 TIME-DOMAIN REFLECTOMETRY OPERATION

A fiber-optic sensor consists of two facing mirrors that are made of a semi-reflective coating deposited on the tips of optical fibers. The gap between the mirrors (i.e., Fabry-Perot cavity length) varies from almost zero to a few tens of microns when the gage is unloaded. The separating distance is the gage length and represents the actual measuring base of the strain gage. The gage functions by reflection and cross interference of light emitted along the fiber-optic cable at the mirrors. The return optical signal is processed using a Fizeau interferometer and a linear charge-coupled device to determine changes in separation between the mirrors. If the gage is bonded to a substrate (e.g., a metal sensing element), strain variation in the axial direction will produce a variation of the cavity length, and strain is then equal to the ratio of the change in cavity length to the gage length. Both displacement and strain gage sensors are available (Choquet et al., 2000), but most reported applications for these devices have been for monitoring structural components.

13A.4 AUTOMATED DATA ACQUISITION

Although not yet commonly used to monitor performance at coal refuse disposal facilities, automated data acquisition systems have been demonstrated to be reliable and cost effective for monitoring the performance of constructed works and their surrounding environment, especially at sites where access is difficult or where regular survey and/or monitoring control are not practical or economical. With time, automated data acquisition systems will continue to improve with the likelihood that their use at coal refuse disposal facilities becomes more common.

Most automated data acquisition systems:

- Are programmed to retrieve data on a prescribed schedule without human intervention.
- Are designed to accommodate more than one transducer.
- Incorporate signal conditioning to amplify the output and present it in terms of engineering dimensions.
- Record data or transmit it elsewhere for recording.

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Figure 13A.4 presents a generalized block diagram for an automated data acquisition system. As described by Dunnicliff (1993), the power supply and signal conditioning convert the output of analog transducers into a signal that is measured and converted to numeric values by an analog-to-digital converter. In most systems the signals from the transducers are conditioned to produce a DC voltage or binary decimal signal. The electronics controlling the systems perform various functions such as: (1) controlling measurement frequency, (2) scaling and displaying the data, (3) converting output to engineering units, (4) averaging data, (5) checking for alarm limits, and (6) controlling external equipment such as alarms. The controlling electronics have some memory capacity, but generally data must be electronically stored for further analysis. Use of automated data acquisition systems is relatively simple for transducers that produce a full-scale DC output voltage of 1 volt or more because these devices require minimal interfacing and signal conditioning. LVDTs, DCDTs, potentiometers, force-balance accelerometers, and high-output electrical resistance strain gage networks are included in this category. Thermocouples, thermistors, and resistance temperature devices used for temperature measurements require minor interfacing for use with automated data collection systems.

Other transducers such as low-output electrical strain gages and vibrating-wire, magnetostrictive and induction-coil transducers require special signal conditioning. This signal conditioning is usually provided by a plug-in module to the automatic data acquisition system. For these types of transducers, a dedicated data logger provided by the transducer manufacturer is usually the best choice (Dunnicliff, 1993).

Non-electrical sensors such as pneumatic transducers; plumb lines and double-fluid, full-profile settlement gages; and twin-tube hydraulic piezometers can be monitored using an automatic data acquisition system and methods described in Dunnicliff (1993). Electrical transducers that function by being manually passed through a pipe (e.g., magnetic reed switches and induction-coil transducers used with probe extensometers) are not appropriate for use with automatic data acquisition systems.

A complete data acquisition system consists of data logger, data communications/retrieval system, and software components. The data logger should have proven reliability for geotechnical applications and be compatible with a wide range of sensors and data retrieval options. A single data logger can read a large number of sensors provided that they are confined to a relatively small area. Additional data loggers should be used if instruments are deployed over a wide area. This approach keeps signal cables short, reduces problems with signal noise, and minimizes the potential for damage from construction activities and electrical transients. The cost savings realized by reducing cable runs can sometimes pay for the additional data loggers.

Multiplexers increase the number of sensors that can be monitored by a data logger. Data loggers can control several multiplexers, each of which are capable of handling 32 two-wire sensors or 16 four-wire sensors of the same type. In practice however, a data logger usually controls only one or two multiplexers, and additional data loggers and multiplexers are employed if there are more instruments. Certain types of sensors require additional interfaces. For example, vibrating wire sensors require a vibrating-wire interface to be connected between the data logger and a multiplexer. Power to operate data loggers, multiplexers and instruments is generally from a battery that is charged by an AC power line or a solar panel. Where feasible, the system should be hard wired or potential power problems, such as maintaining battery charges during cold weather, should be investigated. All data loggers, multiplexers and related equipment should be housed in weatherproof enclosures.

Data retrieval options include wired and wireless links. Wired links for data retrieval include direct connection to a personal computer, telephone modems, short-haul modems, and multi-

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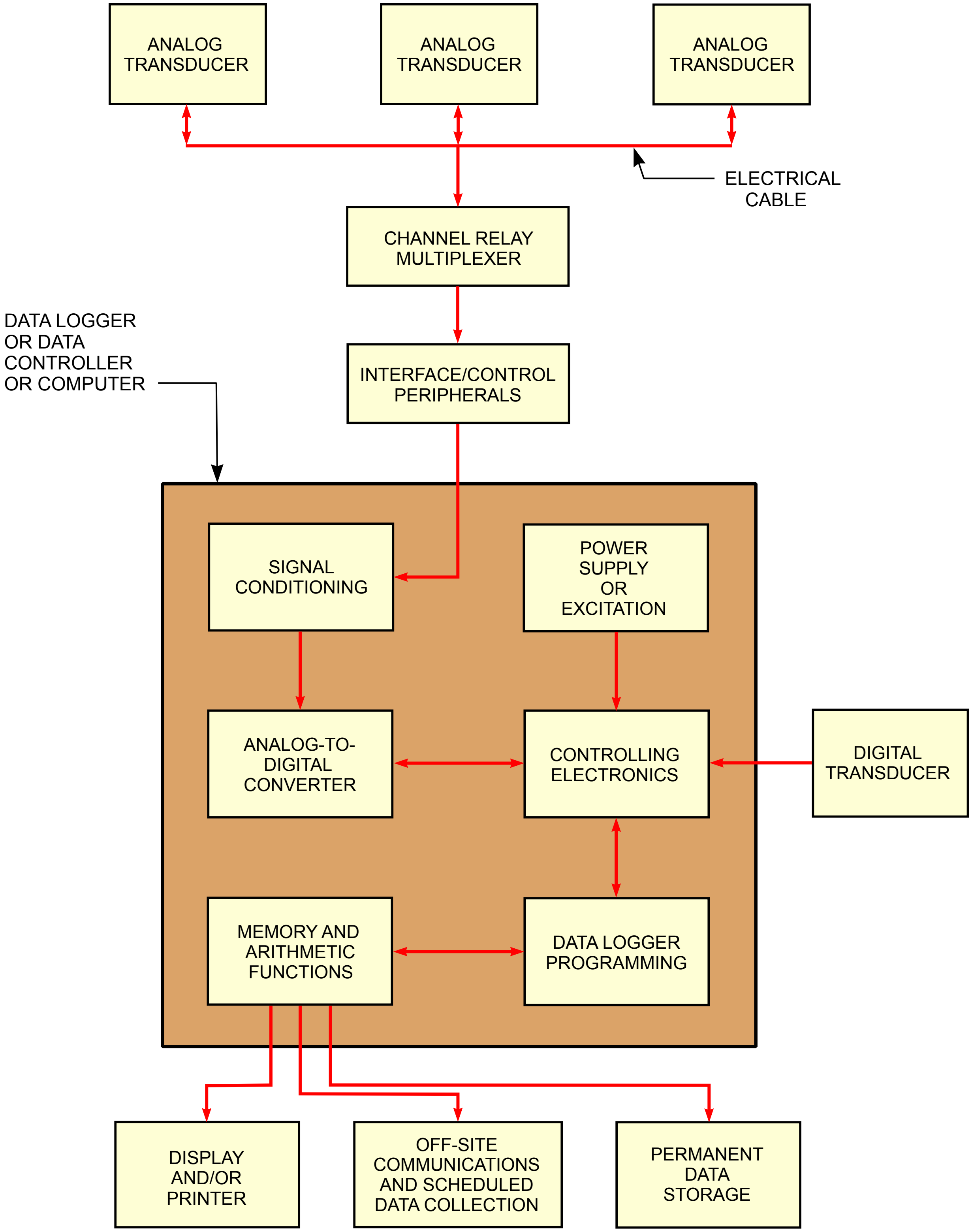

(ADAPTED FROM DUNNICLIFF, 1993)

FIGURE 13A.4 GENERALIZED BLOCK DIAGRAM FOR AUTOMATIC DATA ACQUISITION SYSTEM drop networks. Wired links are usually less expensive, easier to set up, and better for real-time data retrieval than wireless links. Wireless links for data retrieval include cell modems, spread-spectrum radio modems, licensed-frequency radio modems and satellite modems. Wireless links are useful when distances or obstacles make wired links impractical. Also, to the degree that wireless links eliminate surface runs of cable, they also reduce problems caused by electrical transients. However, before an investment is made in wireless links, a check should be made for the presence of high-voltage power lines or radio transmission towers that could make the site too noisy for a wireless link. Additional details regarding data retrieval options are described by van der Veen (2002).

Data logger control software provides a fast, reliable and cost-effective means to collect, process and distribute data from the data logger to a local or remote personal computer. The control software is typically customized for each application to facilitate automatic processing of readings, alarm checks, graphic displays, and report generation. The logger control software can operate on a web server so that access is available from the Internet, a company intranet, or a stand-alone personal computer. Users can access the web through web browsers and click on links to access data and graphic presentations. Access controls can be established for identification of individuals that have rights to set up projects, graphs, reports, and alarms. Data that are not logged automatically can be entered manually using a web browser. The software can scan incoming readings for alarm conditions and then store the readings in a project database.

Automatic data acquisition and transmission systems can make instrumentation programs more susceptible to lightning damage and ground fault problems, as the number and density of cables and electrical components increases on a site. Instrumentation manufacturers can provide guidance on protecting these systems, which may include (Shoup, 1992): (1) diversion systems consisting of multiple lightning arresters (lightning rods, grounded to depths below the sensors) positioned outside the area being instrumented, (2) protective ground systems consisting of non-insulated copper ground conductor paralleling cables from the proximity of the sensor to the terminal box (separated from the cables by approximately 6 inches and extending to a depth of 5 feet below the sensor), and (3) primary lightning protection devices such as gas discharge tubes to protect cable connections to data acquisition modules (provided an appropriate protective ground system is installed). Other measures may be appropriate for surface data acquisition systems and equipment, although replacement of these components is less of a concern.

13A.5 INSTRUMENT AND SYSTEM RELIABILITY

The most important criterion for performance monitoring is reliability (Dunnicliff, 1993). Reliability is a function of instrument and system features and project personnel. Instrumentation system features that are associated with reliable performance include:

- Simplicity
- Self verification
- Durability in the installed environment

Simplicity of transducers should be a primary objective when instruments for a particular application are planned and selected.

Self verification means that instruments can be verified (i.e., calibrated) in place. Examples given by Dunnicliff (1993) include:

- Checking a fixed borehole extensometer with electrical transducers by inserting a dial gage at the head.

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- Changing the head in a standpipe piezometer by raising or lowering the water level and verifying that the hydraulic response is consistent with the hydraulic conductivity of the surrounding ground.
- Using duplicate transducers of the same or different type to confirm local readings.
- Confirming that check sums from inclinometer readings are reasonably constant for all depth intervals.

Durability in the installed environment refers to the longevity of sensors, the connections between sensors and the data acquisition system, and the operation of the data acquisition system within the project setting. Factors such as pressure and temperature changes; duration of operation; chemical, biological and moisture environmental factors; and electrical grounding affect instrumentation system durability.

Sometimes it is not possible to achieve simplicity, self verification and durability in the installed environment, but these should be objectives in planning instrumentation systems, particularly for long-term applications. Equally and perhaps more important to the success of an instrumentation program are the people involved. The success of system planning, initial calibration and inspections, equipment installation, maintenance and recalibration, and data collection, processing and interpretation is directly related to the care and motivation of the people responsible for these activities.

The in-service functionality and reliability of an instrumentation system can be assessed by implementing an instrumentation maintenance program. The features of such a program include regular maintenance and recalibration, as described in Section 13.3.

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