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	Engineering and Design INSTRUMENTATION OF EMBANKMENT DAMS AND LEVEES	
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30 June 1995

**US Army Corps
of Engineers**

ENGINEERING AND DESIGN

Instrumentation of Embankment Dams and Levees

ENGINEER MANUAL

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DEPARTMENT OF THE ARMY EM 1110-2-1908
U.S. Army Corps of Engineers
CECW-EG **Washington, DC 20314-1000**

Manual
No. 1110-2-1908 30 June 1995

Engineering and Design
INSTRUMENTATION OF EMBANKMENT DAMS AND LEVEES

1. Purpose. This manual provides guidance to Corps of Engineers personnel who are responsible for monitoring and analyzing embankment dams and levees.

2. Applicability. This manual applies to HQUSACE elements, major subordinate commands (MSC), districts, laboratories, and field operating activities (FOA) involved with planning, design, construction, installation, monitoring, analysis, and maintenance of instrumentations systems in Corps of Engineers embankment dams and levees.

FOR THE COMMANDER:

JAMES D. CRAIG
Colonel, Corps of Engineers
Chief of Staff

This manual supersedes EM 1110-2-1908 Part 1 dated 31 Aug 1971 and Part 2 dated 19 Nov 1976.

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Chapter 1
Introduction

1-1. Purpose

This manual provides guidance to Corps of Engineers (CE) personnel who are responsible for monitoring and analyzing embankment dams and levees.

1-2. Applicability

This manual applies to HQUSACE elements, major subordinate commands (MSC), districts, laboratories, and field operating activities (FOA) involved with planning, design, construction, installation, monitoring, analysis, and maintenance of instrumentations systems in Corps of Engineers embankment dams and levees.

1-3. References

a. A variety of sources was used to compile the information presented herein, including publications of professional societies, and guidance from consultants and from that developed by the Corps of Engineers and other federal agencies. References specifically applicable to chapter topics are included in that respective chapter text. A listing of all references is included as Appendix A.

b. Permission to use copyrighted material was obtained. The following sources are acknowledged.

(1) Figures 2-2, 2-3, 4-1 through 4-12, 4-16 through 4-26, 6-1, B-5, and B-6, Tables 4-1 through 4-4 and 9-1, a portion of the text in Chapter 4, and the lists in Sections 6-7*c* and 6-12 were obtained from the following source:

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> Dunnicliff, John. 1990. Twenty-Five Steps to Successful Performance Monitoring of Dams. Volume 9, Number 4. *Hydro Review*. Copyright, HCI Publications, 1990. Reprinted by permission of HCI Publications.

1-4. Focus

This revision focuses on issues that are of current concern in the Corps' mission of dam safety which includes monitoring embankment dams and levees. Design and construction of new projects have been decreasing. The majority of Corps dams have been instrumented, and the basic instrumentation concepts for monitoring seepage, pressure, and movement have been emphasized over the years in several CE regulations, directives, and programs. Geotechnical personnel are generally familiar with the behavior of instrument systems for which they are responsible. The current challenge for personnel responsible for embankment dam and levee safety is increased, and

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continuous attention must be paid to operation and maintenance of existing embankment structures and instrument systems. Therefore, a significant amount of engineering judgment must be applied to major rehabilitation, assessment of system performance, replacement, maintenance, and other situations that have become unique to each embankment structure and instrument system. This manual provides information and guidance that is needed for modifying existing systems as well as for new system installation for new construction.

1-5. Approach

Every instrument system is unique and a significant amount of engineering judgment must be applied to each. It is not possible to provide blanket instructions and/or specific procedures that are universally applicable to every situation that may be encountered. Therefore, this manual emphasizes the use of judgment rather than providing a recipe to follow. Whether analyzing data to determine the competency of a sensor, planning a new system for a rehabilitation project, or selecting a sensor for retrofitting a system with automation, responsible personnel must take the initiative to observe the conditions that require attention, to recognize the need for some action to be taken, to apply available information and properly assess what action is appropriate, and, finally, to follow through with implementing the efforts that are necessary.

1-6. Scope

The manual addresses all aspects of instrumentation including the traditional methods of monitoring, the important geotechnical concepts that must be understood, and the growing concerns of rehabilitation, replacement, and maintenance. New initiatives such as automation are also addressed. The manual also addresses features that influence the performance of embankment dams and levees. Therefore, information presented can be applied to abutments, foundations, and the reservoir rim. Instrumentation of concrete and steel structures is not addressed. Refer to EM 1110-2-4300 and TR REMR-CS-5 for guidance for these features. Instrumentation for research and investigative purposes also is not specifically included.

1-7. Format of the Manual

The manual begins with a description of geotechnical aspects of embankment dams and levees, and briefly discusses important concepts of applying instrumentation. This is followed by addressing various methods of monitoring, the potential for automation, and the installation that is appropriate. The last portion of the manual addresses operation and maintenance issues including data management and analysis, maintenance, and continual reassessment over the life of the project. For quick reference, a summary of each successive chapter follows:

a. Chapter 2 - Behavior of Embankments and Abutments. The chapter begins by discussing the geotechnical aspects of soil behavior, including soil structure, the presence and buildup of pressures and stresses, and the effects of them on the embankment materials. It also identifies specific mechanisms that are inherent to embankment dam performance and that are key to accessing behavior. This chapter contains fundamental information which is essential to understanding the parameters that are monitored and the environment in which instruments perform.

b. Chapter 3 - Instrumentation Concepts, Objectives, and System Design Considerations. This chapter builds on geotechnical knowledge, identifies parameters in embankment structures that may require monitoring, and offers an approach to planning and designing systems to achieve that purpose. It includes important characteristics of instrument systems that must be considered and recommendations for designing them such that all critical aspects of the process are addressed. The suggested qualifications of the personnel that are responsible for implementing various related instrumentation tasks are also presented.

c. Chapter 4 - Summary of Measurement Methods. The most commonly used devices and technologies for embankment monitoring are discussed. The performance characteristics are described as well as the preferred uses and applications. This information is needed for the selection of appropriate sensors for various applications.

d. Chapter 5 - Automation Considerations. Current guidance for automating new or existing systems is given in this chapter. Automation presents an increasingly viable alternative to traditional manual instrument systems. Certain characteristics of automation, however, are unique and require special attention. Information in this chapter should be kept in mind as other instrumentation aspects (e.g., data analysis, installation, sensor selection, and maintenance) in other chapters are discussed.

e. Chapter 6 - Installation. This chapter discusses several issues that are critical to obtaining reliable and functional instrument systems including contractor qualifications, quality control, instrument protection, acceptance tests, drilling methods, placement of sensors, seals, and filters, and documentation.

f. Chapter 7 - Data Management, Analysis, and Reporting. This chapter stresses the importance of acquiring valid and complete field information, and the thorough interpretation and meaningful presentation of the data. Other related topics include data validity, selection of scales for plotting, and use of data to prompt the maintenance of instruments. It also contains valuable suggestions for various ways of analyzing raw as well as processed data and managing computerized databases.

g. Chapter 8 - Instrument Maintenance. Testing and calibration of components are critical to instrument performance and data validity. Chapter 8 suggests specific basic attention that is required for portable, retrievable, and embedded components of the instrument system. Historical documentation, maintenance programs, as well as instruments that require more than the basic maintenance of portable, retrievable, and embedded components are also discussed.

h. Chapter 9 - Continual Reassessment for Long-Term Monitoring. The performance of embankment dams and levees must continue for the life of the project. Therefore, comprehensive programs must be established to assure continued attention in the overall context of the behavior of the embankment structures. Changes in performance with time, remedial modifications to the structure in the course of useful life, and the inevitable damage or loss of operating instruments requires significant judgment regarding abandonment, rehabilitation, replacement, or upgrade of instruments. This chapter addresses these issues.

1-8. Use of the Manual

There are three primary uses of this manual: planning and design of instrument systems, continuous use of instrument systems, and making decisions regarding the modification or replacement of instrument systems. Planners and designers are reminded of theoretical and practical concepts and are assisted with acquiring a reliable and appropriate system. Personnel responsible for the use of the systems are provided guidance regarding data retrieval, analysis, and maintenance. Dams and levees, and associated instrument systems, require increased attention with age and use. Practical approaches to modification and replacement are provided.

1-9. Implementation of an Instrumentation Program

An instrumentation program is a comprehensive approach that assures that all aspects of instrumentation from planning and design through maintenance and rehabilitation are commensurate with the overall purpose. An instrumentation program is an important contributing effort to the much larger concept of dam safety. As such, the characteristics of the instrumentation program must be consistent with the other entities of dam safety such as dam safety training, emergency response, periodic inspections, remedial studies, and structure modifications. In the overall context of understanding and responding to the behavior of the dams and levees, particularly with aging structures and increasing maintenance, it is most important to apply the quality and quantity of attention that is required. Qualified personnel, quality equipment, and timely information and assessment must be encouraged and supported. Without this level of attention and commitment, the importance of all entities of dam safety will deteriorate, wasted effort and expense will result, and areas that depend on input from the instrumentation program will also suffer.

Chapter 2
Behavior of Embankments and Abutments

2-1. Introduction

A basic familiarity with geotechnical concepts is necessary to understand the application of instrumentation devices and analyses of instrumentation data. Key geotechnical aspects of embankment dam and levee behavior are described in this chapter. These geotechnical aspects are related primarily to pore water pressure and deformation. For a detailed treatment of these geotechnical topics, the reader is referred to other engineer manuals and geotechnical textbooks (e.g., Terzaghi and Peck 1967, and Holtz and Kovacs 1981). For detailed information on design and construction considerations refer to EM 1110-2-2300 and EM 1110-2-1913.

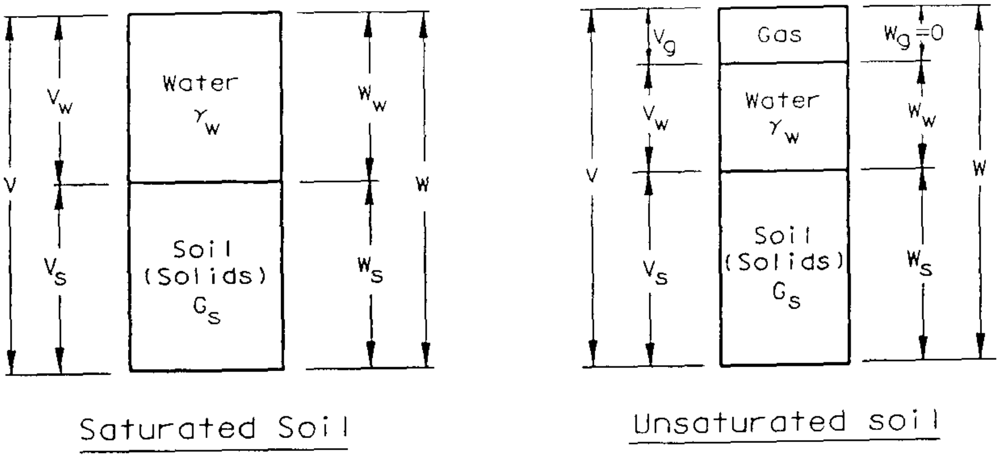
2-2. Basics of Soil Structure

a. Soil structure. Soil as it exists in the ground or as compacted in embankment fills consists of solid particles between which are spaces called ***voids, pores***, or ***pore spaces***. The pore spaces may be filled with either gas, usually air, or water. When all the voids are filled with water, the soil is ***saturated***. If any gas is present in the pore spaces, the soil is called ***unsaturated***. The term ***partially saturated*** or vadose zone is used by some when referring to unsaturated soils. Diagrams of both saturated and unsaturated soil structure are shown in Figure 2-1.

b. Types of soils. Soils are categorized into two broad groups: ***cohesionless soil*** and ***cohesive soil***. Cohesionless soils are those soils that consist of particles of rocks or minerals having individual grains usually visible to the eye. These materials, sands and gravels, are granular and nonplastic, meaning that they do not stick together when unconfined, and have little or no strength when air dried. Usually these soils have not been altered by chemical decomposition. Inorganic silt is fine grained with little or no plasticity and is considered a cohesionless material. Cohesive soils such as clays consist of fine-textured materials with microscopic and submicroscopic particles resulting from chemical decomposition of rocks. These materials have some strength when unconfined and air dried. Water affects the interaction between the mineral grains and gives plasticity or cohesion between the particles.

c. Stress and pressure. In geotechnical engineering, the terms ***stress*** and ***pressure*** are defined as force per unit area, with typical units of pounds per square inch (lb/in.^{2}) or pascals (Pa). Usually, pressure is a general term for force per unit area and stress is the force per unit area that exists *within* a mass. In the practice of geotechnical engineering, these terms are sometimes used interchangeably. The total force applied to or acting within a given area is known as the ***total stress***. That component of the total stress that is transmitted by grain-to-grain contact within the soil mass is called the ***effective stress***. The component of the total stress transmitted through the pore water is called the ***pore water pressure***, or the ***neutral stress***. The total stress consists of the sum of the effective stress and the pore water pressure. This relationship is known as Terzaghi's principle of effective stress. In unsaturated soils, a component of the total stress is transmitted to the pore gas portion of the voids and is called the ***pore gas pressure***. If pore gas pressure exists it will always be greater than the pore water pressure (Dunnicliff 1988). All the components of the total stress are applied over the same area as the total stress.

d. Consolidation. When a load is applied or increased on saturated soil layers, the increased force (total stress) is initially carried by the pore water pressure. The process of transferring the total stress to effective stress and decreasing the pore water pressure by squeezing out the water is known as ***consolidation***. Figure 2-2 illustrates what happens to the pore water pressure, effective stress, and volume of the soil as a total stress is applied. The change in volume shown in Figure 2-2b, that occurs as the total stress is transferred from the pore water pressure to the effective stress, generates vertical ***deformation*** that results in ***settlement***. The amount by which the pore water pressure exceeds the equilibrium pore pressure is known as the ***excess pore water pressure***. The decrease of the excess pore water pressure is called ***dissipation*** and is a function of the ***permeability*** of the material. Settlement results from the dissipation of excess pore water pressure and reorientation of the soil particles due to the additional load. Permeability is a measure of the rate at which water can move through the soil and determines how rapidly settlement occurs. When a soil has never been subjected to an effective stress greater than the existing overburden pressure, the soil is ***normally consolidated***. A soil that has been subjected to an effective stress greater than the existing overburden pressure is an ***overconsolidated soil***. Soils that have been subjected to glacier loadings are generally overconsolidated soils.



W = total weight of mass
W_s = weight of solids material
W_w = weight of liquid
W_g = weight of gas, usually assumed to negligible
V = total volume of mass
V_s = volume of solids material
V_w = volume of liquid
V_g = volume of gas
V_v = volume of voids = $V_w + V_g$ = volume not occupied by solids
G_s = specific gravity of solids
γ_w = unit weight of liquid

Figure 2-1. Saturated and unsaturated soil structure

Movement of the soil to resist sliding can also generate excess pore water pressure. The effective stress is related to the ability of the soil to resist sliding and its ***shear strength***. Thus, gains in shear strength during the consolidation process can be monitored by measuring pore water pressure. An example of this is the monitoring of pore water pressure as levees are constructed on soft foundations.

2-3. Groundwater Level and Pore Water Pressure

a. Hydrostatic piezometric conditions. The ***groundwater level*** or table is defined as the elevation that the free water surface assumes in permeable soils or rock because of equilibrium with atmospheric pressure in a hole extending a short distance below the capillary zone, as shown in Figure 2-3(a). The water-bearing stratum

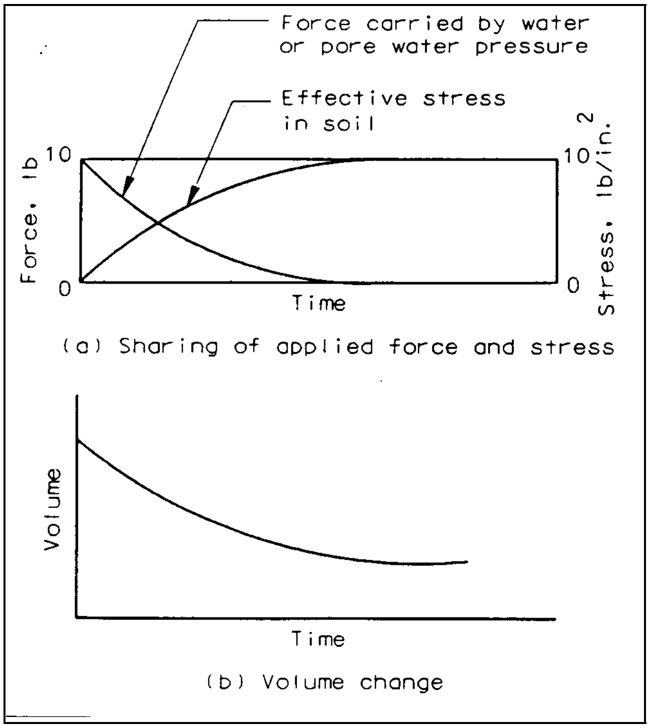


Figure 2-2. Response of effective stress, pore water, and soil volume to an applied total stress (Dunnicliff 1988)

containing the groundwater is called an ***aquifer***. The ***capillary zone*** is defined as the interval between the free water surface and the limiting height above which water cannot be drawn by capillarity. Normal behavior of groundwater conditions occurs when the pore water pressure increases hydrostatically with depth below the groundwater level. In this condition the pore water pressure, also called the ***hydrostatic pressure***, can be calculated by multiplying the unit weight of water by the vertical distance from the point of interest (screen location, sensor location, etc.) to the groundwater surface.

b. Pore water pressure. Figure 2-3 illustrates the groundwater condition soon after a layer of material is placed over existing soil layers and before consolidation is complete. Thus, excess pore water pressure exists in the clay and the groundwater is no longer in equilibrium. The five perforated pipes in Figure 2-3 are installed such that the soil is in intimate contact with the outsides of the pipes. The second pipe (pipe b) is perforated throughout its length while the other pipes are perforated only near the bottom. Due to the high permeability of the sand, the excess pore water pressure in the sand is dissipated immediately. Thus, pipe (a) indicates the groundwater level. Pipe (b) indicates the groundwater level because the permeability of the sand is such that the excess pore water

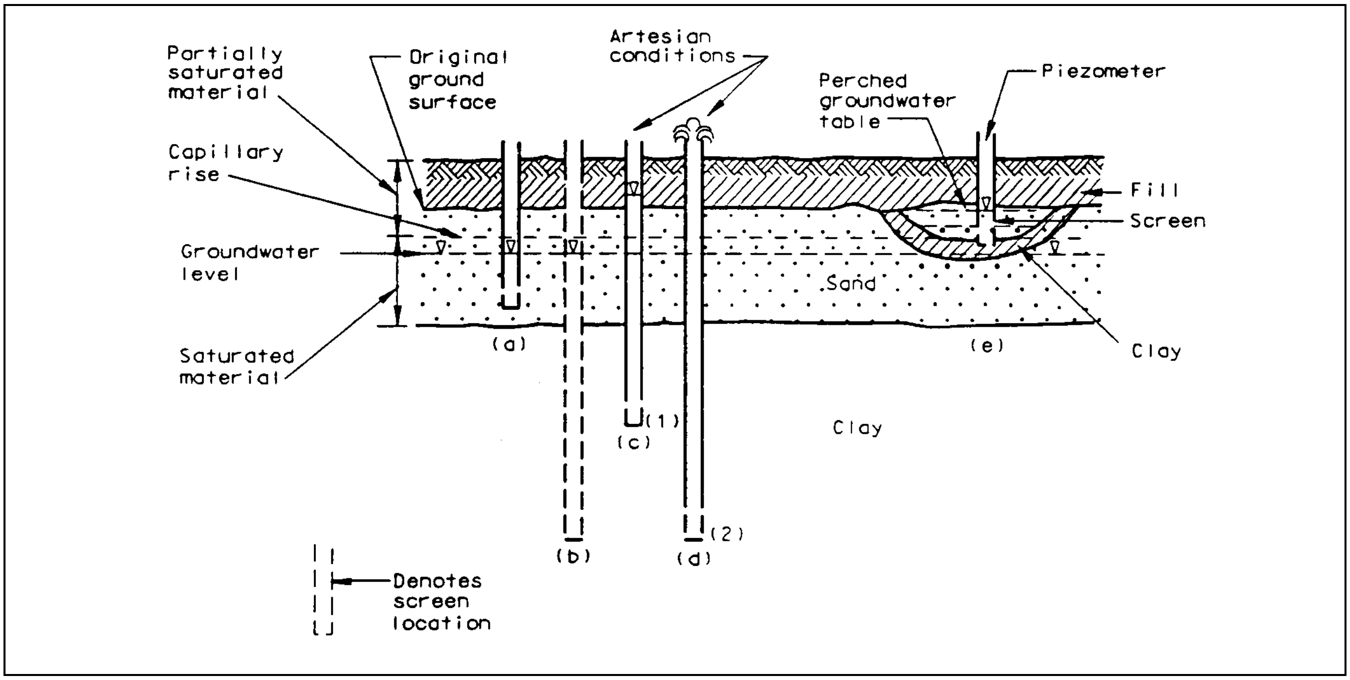


Figure 2-3. Groundwater level and pore water pressure when there is flow of groundwater (Dunnicliff 1988)

pressure from the clay will be dissipated into the sand. Pipes (c) and (d) indicate the pore water pressures in the clay at two locations. More dissipation of the excess pore water pressure has occurred in pipe (c) than in pipe (d) because the drainage path for excess pore water pressure is shorter and the rate of dissipation is greater in pipe (c) than in pipe (d). Pipe (b) in Figure 2-3 is an ***observation well***, because there are no subsurface seals that prevent a vertical connection between multiple strata. A ***piezometer*** is a measuring device that is sealed within the ground so that it responds only to groundwater pressure around itself and not to groundwater pressure at other elevations. Pipes (a), (c), and (d) are called piezometers because they indicate pore water pressure at one location (they are sealed above and below the perforated locations) and not to the groundwater pressure at other elevations. The ***piezometric elevation*** or ***piezometric level*** is the elevation to which water will rise in a piezometer.

c. Positive pore water pressures. Pore water pressure that is above atmospheric pressure is called ***positive pore water pressure***. Pore water pressure can be increased by applying a compressive force to the soil or when a shearing force is applied to a soil that decreases its volume while preventing dissipation of pore water pressure. Excess pore water pressure resulting from any type of stress change can also be called ***induced pore water pressure***.

d. Negative pore water pressures. ***Negative pore water pressure*** occurs when the pore water pressure is less than atmospheric pressure. This condition can occur when a compressive load is removed or when a densely packed soil is sheared and increases in volume.

e. Non-hydrostatic groundwater conditions. Pore water pressure does not always increase hydrostatically with depth below the groundwater level. These groundwater conditions include:

(1) Perched water table. ***Perched water tables*** are caused when a permeable material overlies a relatively impermeable strata above the main groundwater level and retains some groundwater. A piezometer placed in a perched water table will indicate an elevated surface as illustrated in Figure 2-3, pipe (e).

(2) Artesian pressure. ***Artesian pressures*** are found in strata that are confined between impervious strata and are connected to a water source at a higher elevation. A well drilled to an artesian aquifer having a pore water pressure above the ground surface will flow without pumping and is called a free-flowing artesian well. Artesian conditions are shown in Figure 2-3, pipes (c) and (d).

f. Variation in piezometric levels and pressures. Piezometric levels and pressures are rarely constant over an extended period of time. Natural forces such as precipitation, evaporation, atmospheric pressure, and seepage may cause wide variations in the groundwater level.

2-4. Time Lag in Groundwater Observations

a. Hydrostatic time lag. Most piezometers require some movement of pore water to or from the device to activate the measuring mechanism. When pore water pressures change, the time required for water to flow to or from the piezometer to create equalization is called the ***hydrostatic time lag***. The hydrostatic time lag is dependent primarily on the permeability of the soil, type and dimensions of the piezometer, and the change in pore water pressures. The volume of flow required for pressure equalization at a diaphragm piezometer is extremely small, and the hydrostatic time lag is very short. For an open standpipe piezometer, the time lag may be reduced by providing a large intake area and reducing the diameter of the riser pipe, thereby reducing flow required for pressure equalization. The pressure of gas bubbles (natural or result of corrosion) can also cause a time lag. Hydrostatic time lag is not significant when piezometers are installed in highly pervious soils such as coarse sands. Those piezometers that have a long time lag are described as having a ***slow response time***. The time required to establish equalization of pore water pressures after installing or flushing a piezometer is called the ***stress adjustment time lag***, sometimes referred to as the ***installation time lag***.

b. Determination of time lag. An estimate of the hydrostatic time lag aids in selecting the proper type of piezometer for given subsurface conditions at a given site. The order of magnitude of the time required for 90% response of several types of piezometers installed in homogeneous soils can be determined from Figure 2-4. As stated in Dunnicliff (1988), the 90% response is considered reasonable for most practical purposes since the 100% response time is infinite. The response time of open standpipe piezometers can be estimated from equations derived by Penman (1960). As an example,

$$t = 3.3 \times 10^{-6} \frac{d^2 \ln [L/D + \sqrt{1 + (L/D)^2}\,]}{kL} \qquad (2\text{-}1)$$

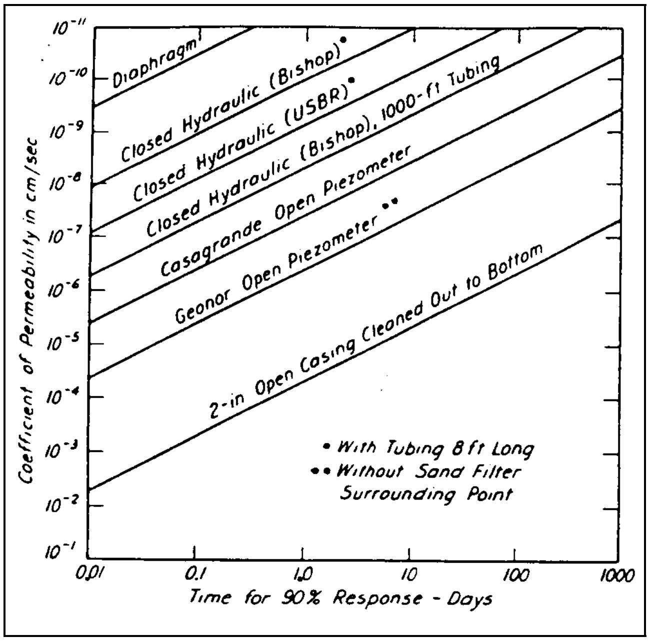


Figure 2-4. Approximate response time for various types of piezometers (after Terzaghi and Peck 1967)

where

t = time required for 90% response, days

d = inside diameter of standpipe, centimeters (cm)

L = length of intake filter (or sand zone around the filter), centimeters (cm)

D = diameter of intake filter (or sand zone), centimeters (cm)

k = permeability of soil, centimeters per second (cm/sec)

Similar equations and other procedures have been developed by Hvorslev (1951) and others. It is often more desirable to measure time lag in the field by comparing pool fluctuation with desired piezometer readings as illustrated in Figure 2-5.

2-5. Mechanisms That Control Behavior

The engineering behavior of soils is controlled by either hydraulic, stress-deformation, or strength mechanisms. When a soil is subjected to excess pore water pressures, the water flows through the pore spaces creating friction and a resistance to flow. The permeability of the soil is a function of this friction and resistance to flow. When water is flowing through soil, the water exerts a force on the soil particles in the direction of flow. Also if the soil is saturated, water acts on the soil with a buoyant force whether or not the water is moving. Stress-deformation characteristics of cohesionless soils are caused by rearrangement of the relative positions of grains as shear deformation occurs. For cohesive soils, the stress-deformation characteristics are governed by the time required for water to flow through the pore spaces in the soil and for subsequent volume changes to occur. Shear strength is governed by the nature, size, and shape of the soil grains, packing density, and effective stresses within the soil. Shear failure occurs when the applied stresses increase beyond those that can be sustained by the soil.

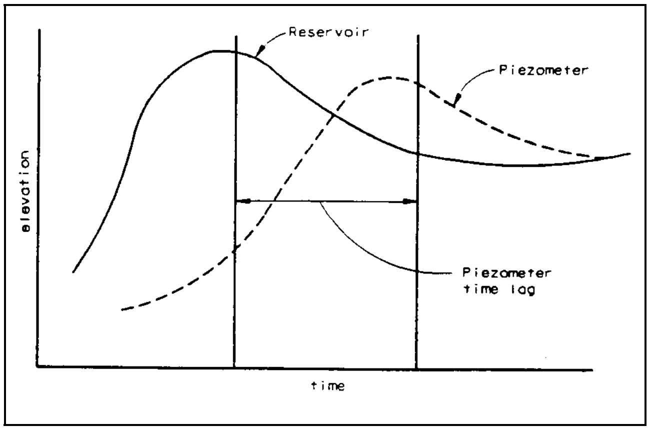


Figure 2-5. Time lag measurement from time-history plot of reservoir level and piezometer

a. Embankments and foundations. Earth and rock-fill embankments may experience failure by the following mechanisms: overtopping, instability, and internal seepage. Overtopping results when the reservoir or river level exceeds the embankment height. This condition can occur due to incorrect estimations of water volume or as the result of some other mechanism (i.e., slope instability) causing a displacement of a large mass of water.

(1) Embankment and foundation instability. When the available shearing resistance along a potential surface of sliding of an embankment slope is greater than the shear stress or driving force on that surface a stable slope results. Any increase in pore water pressure along the potential surface of sliding decreases the shearing resistance and the factor of safety against sliding. If the foundation is stronger than the embankment soil, the slope will generally move within the embankment. If the

embankment is overlying a soft foundation, the properties of the foundation material will determine if stability is a problem. The embankment loading could cause a movement through the foundation or a movement along a weak foundation layer. In addition, the embankment could cause settlement and lateral bulging of the foundation. If the foundation consists of loose uniform cohesionless material, an earthquake can cause liquefaction and sliding within the foundation.

(2) Piping. Seepage can cause piping (internal erosion) when the velocity of the flowing water is sufficient to move or carry soil particles. If the soil has some cohesion, a small tunnel or pipe could form at the downstream exit of the seepage path. As the soil is eroded, the pipe lengthens inside the embankment. Once piping begins, there is less resistance to flow, the flow in the pipe increases, and piping accelerates. Silt and fine sands are most prone to piping. In a well-designed embankment, piping is prevented by using filters or drains to ensure that material from upstream cannot migrate downstream.

(3) Transverse cracking. The load of the embankment can cause foundation settlement and some settlement and lateral movement in the compacted fill. Uniform settlement of the embankment or foundation is usually not a problem. However, when the abutments are steep, settlement may cause cracking transverse to the axis of the dam.

b. Soil around structures and abutments. When soil is placed around structural elements or against abutments, behavior mechanisms of concern include seepage, stability, and sliding of the structural element. The interface between the soil and either the abutments or a structural element is a potential location for abnormal seepage. Special care and compaction effort are needed in this area to ensure that the potential for piping is minimized. In addition, whenever material is placed against abutments or other existing surface, the potential exists for weak shear surface planes to develop, which could become a shear surface. Good compaction along the interface should prevent this type of mechanism. Sliding of a structural element is a function of the force caused by the ***active earth pressure*** pushing on the element minus the shearing resistance along the base of the element and the force caused by the ***passive earth pressure***.

Chapter 3
Instrumentation Concepts, Objectives, and System Design Considerations

3-1. Introduction

This chapter expands on geotechnical concepts discussed in the previous chapter, identifies parameters in embankment structures and foundations that may need to be monitored, and provides an approach to the development of an appropriate instrumentation system. ER 1110-2-110 provides policy guidance on instrumentation for safety evaluations of civil works projects. Instrumentation necessary to assist in the evaluation of the safety of embankments is considered an integral part of the geotechnical design.

3-2. Unique Characteristics of Geotechnical Engineering

Geotechnical engineering of embankment projects requires the exploration and analysis of a wide variety of earth and rock materials. These materials must be considered for adequacy as foundations and for use in structures. Since earth and rock are created by natural processes, unlike other engineering materials such as steel and concrete, they seldom exhibit uniform properties. There is risk in every project that unexpected conditions will be encountered. The inability of exploration programs to detect in advance all potential significant properties and conditions in natural deposits requires designers to make assumptions and generalizations that may be at variance with actual field conditions. However, even though geotechnical design and construction of embankments are subject to uncertainties, visual observations supported by quantitative measurements obtained from appropriate instrumentation can provide engineers with information for checking and verifying design assumptions. Visual observations combined with instrumentation data provide the basis for assessing embankment and foundation performance and safety during actual operations.

3-3. Characteristics of Geotechnical Instrumentation

Field instrumentation is more vital to the practice of geotechnical engineering than to most other branches of engineering, in which designers have greater control over the materials utilized for construction. Therefore, geotechnical engineers must have more than casual knowledge of instrumentation. However, geotechnical engineers must recognize that, although instrumentation is a valuable tool that can be utilized for monitoring performance and safety, it is not a stand-alone solution to monitoring embankment performance. The determination of the need for instrumentation must be kept in perspective. In the words of Dr. Ralph Peck (as cited by Dunnicliff 1988) “Every instrument on a project should be selected and placed to assist with answering a specific question; if there is no question, there should be no instrumentation.” Instrumentation cannot guarantee good design, trouble-free construction, or long-term maintenance-free operation. The wrong type of instruments placed in inappropriate locations can provide information that may be confusing, or divert attention away from other signs of potential distress. It is not appropriate to mandate instrumentation at every dam or levee with the expectation that some unknown defect will be revealed during monitoring and provide a warning of an impending failure. Instruments cannot indicate signs of pending deterioration or failure unless they happen to be placed at the right location. Geotechnical instrumentation is not intended to be a sole basis for embankment evaluation; it is intended to provide data for evaluation within a comprehensive embankment safety inspection and surveillance program.

3-4. Instrumentation Objectives

The principal objectives of a geotechnical instrumentation plan may be generally grouped into four categories: first, analytical assessment; second, prediction of future performance; third, legal evaluation; and fourth, development and verification of future designs. Instrumentation achieves these objectives by providing quantitative data to assess groundwater pressure, deformation, total stress, temperature, seismic events, leakage, and water levels. Total movements as well as relative movements between zones of an embankment and its foundation may also need to be monitored. A wide variety of instruments may be utilized in a comprehensive monitoring program to ensure that all critical conditions for a given project are covered sufficiently. The most commonly used geotechnical instrumentation is described in Chapter 4.

a. Analytical assessment. Analysis of data obtained from geotechnical instrumentation may be utilized to verify design parameters, verify design assumptions and construction techniques, analyze adverse events, and verify apparent satisfactory performance as discussed below.

(1) Verification of design parameters. Instrumentation can be utilized to verify design parameters with

observations of actual performance, thereby enabling engineers to determine the suitability of the design. Instrumentation also aids engineers in modifying designs by incorporating the effects of actual field conditions. The design of earth and rockfill embankments generally entails a rigorous and sometimes complex study of forces, which must be based on conservative geotechnical assumptions concerning material characteristics and structural behavior. These generalized assumptions can leave some unknown conditions, variations, and uncertainties in the design. Observations from instrumentation systems, and an assessment of structural performance of an embankment, can help resolve these unknowns, allowing necessary refinements and improvements to be made in the design.

(2) Verification of design assumptions and construction techniques. Experience has shown that most new or modified designs and construction techniques are not readily accepted until proven satisfactory on the basis of actual performance. Data obtained from instrumentation can aid in evaluating the suitability of new or modified techniques.

(3) Analysis of adverse events. When a failure, a partial failure, a severe distress condition, a visually noted non-severe change in shape, appearance, or seepage has occurred at a dam or levee project, data from instrumentation can be extremely valuable in the determination of the specific cause or causes of the event. Also, instrumentation is often installed prior to, or during, remedial work at a site to determine the effectiveness of the improvements and the effect of the treatment on existing conditions.

(4) Verification of apparent satisfactory performance. It is just as necessary to confirm satisfactory performance of a project as it is to identify areas of concern. Positive indications of satisfactory performance are very reassuring to evaluating engineers and operators of a dam or levee project. Instrumentation data can prove to be valuable should some future variation in historic data occur, signaling a potential problem. Also, records of satisfactory performance are valuable for use in future design efforts.

b. Prediction of future performance. Instrumentation data should be used in such a manner that informed, valid predictions of future behavior of an embankment can be made. Such predictions may vary from indicating continued satisfactory performance under normal operating conditions to an indication of potential future distress which may become threatening to life or safety, and necessitate remedial action. Often earth and rockfill embankments constructed for flood-control purposes remain dry, or maintain only very low level conservation or recreation pools, except during infrequent flood events. As a result, these embankments may have existed for years without ever experiencing maximum design conditions. However, instrumentation data obtained during intermediate flood events can be projected to predict performance during potential maximum flood stage or reservoir levels.

c. Legal evaluation. Valid instrumentation data can be valuable for potential litigation relative to construction claims. It can also be valuable for evaluation of later claims relative to changed groundwater conditions downstream of a dam or landward of a levee project. In many cases, damage claims arising from adverse events can be of such great monetary value that the cost of providing instrumentation can be justified on this basis alone. Instrumentation data can be utilized as an aid in determining causes or extent of adverse events so that various legal claims can be evaluated.

d. Development and verification of future designs. Analysis of the performance of existing dams and levees, and instrumentation data generated during operation, can be used to advance the state-of-the-art of design and construction. Instrumentation data from existing projects can promote safer and more economical design and construction of future earth and rockfill embankments.

3-5. Basic Instrumentation Concepts

A determination of the number, type, and location of instruments required at a dam or levee can only be addressed effectively by combining experience, common sense, and intuition. Embankments represent unique situations and require individual solutions to their instrumentation requirements. The instrumentation system design, therefore, needs to be conceived with care and consideration for the site-specific geotechnical conditions present in the embankment, foundation, abutments, and reservoir rim. Substantial geotechnical reasons, such as unique design or difficult foundation conditions, severe downstream hazard, visually observed problems or concerns, remoteness of location, normally unmanned operation, or other concerns justify providing instrumentation. It also must be recognized that instruments are actually discontinuities, or nonrepresentative objects, introduced into soil/rock structure systems. Their presence, or the flows or displacements required to generate an observation, may alter the parameters which are being measured. Engineers installing field instrumentation must understand the fundamental physics and mechanics involved, and how the various available instruments will perform under the conditions to which they will be subjected.

3-6. Instrumentation System Planning

Planning an embankment instrumentation system requires the consideration of many factors, and a team effort of the designers (or those responsible for evaluating existing projects) and personnel having expertise in the application of geotechnical instrumentation. Developing an instrumentation system should begin with a definition of an objective and proceed through a comprehensive series of logical steps that include all aspects of the system. A series of recommended steps is provided below. This systematic planning is based on the approach recommended by Dunnicliff (1988 and 1990). The steps are listed in Table 3-1.

a. Prediction of mechanisms that control behavior. During the design of a new project or analysis of an existing project, geotechnical engineers should identify site weaknesses and areas of sensitivity. Based on these items, hypotheses regarding hydraulic, stress deformation, or strength mechanisms that are likely to affect project behavior for various conditions should be developed. The instrumentation program should then be planned around the hypotheses. For example, a soft foundation material may lead to a concern for stability and settlement; therefore, instrumentation is required to monitor pore water pressures and consolidation. Or, if abutment materials cause concern for excessive seepage, instrumentation may be selected to monitor flow quantities and solids content in the seepage.

b. Definition of purpose of instrumentation. The primary purpose of instrumentation is to provide data useful for determining whether or not an embankment or foundation is behaving in accordance with engineering predictions. When an embankment has special foundation conditions or uncommon design features, instrumentation can help in determining if design concepts for these conditions or features are being realized during construction and operation. A comprehensive monitoring program must be developed for the special conditions and features at that site. If an embankment has no special foundation conditions or uncommon design features, the need for instrumentation is less certain. Many conventional embankments of moderate height on good foundations have only minimal instrumentation.

c. Definition of geotechnical questions. Every instrument on, in, or near an embankment should be selected and placed to assist in answering a specific concern. Before addressing measurement methods, a listing should be made of geotechnical questions that are likely to arise during the design, construction, or operation phases. For the various phases, questions should cover initial site conditions, performance during construction, performance during first filling, performance during drawdown, and long-term performance. Dunnicliff (1990) listed examples of possible geotechnical questions

Table 3-1
Steps for Developing an Instrumentation System (Dunnicliff 1990)

Step	Element of Plan
a	Prediction of mechanisms that control behavior
b	Definition of purpose of instrumentation
c	Definition of geotechnical questions
d	Selection of parameters to monitor
e	Prediction of magnitudes of change
f	Selection of instrument locations
g	Selection of instruments
h	Determination of need for automation
i	Planning for recording of factors which influence measurements
j	Establishment of procedures for ensuring data validity
k	Determination of costs
l	Planning installation
m	Planning long-term protection
n	Planning regular calibration and maintenance
o	Planning data collection and management
p	Coordination of resources
q	Determination of life cycle costs

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associated with the appropriate features and parameters (see Table 3-2).

d. Selection of parameters to monitor. Typical parameters that can be monitored include groundwater pressure, deformation, total stress, temperature, seismic events, leakage, and water levels. Engineers need to consider which parameters are most significant for a particular project.

e. Prediction of magnitudes of changes. Predictions of magnitudes of anticipated change are necessary so that required instrument ranges and sensitivities, or accuracies, can be selected. An estimate of the maximum possible value, or maximum value of interest, leads to a selection of instrument range. An estimate of the minimum value of interest leads to a selection of instrument sensitivity and accuracy. Where measurements are for construction or safety purposes, predeterminations can be made of numerical values that indicate the need for immediate analysis or remedial action (hazard warning levels). Wherever possible a positive means should be developed for remediating any problem that may be disclosed during construction by results of instrumentation data. If the observations demonstrate that remedial action is necessary, the action should be based on appropriate, previously anticipated plans. Construction personnel should have contingency plans to follow in the event that hazard warning levels are reached at the site. For example, embankment construction on a site with a soft foundation would require a predetermination of hazard warning levels. The planned remedial action might include a waiting period to allow for dissipation of pore water pressure and associated gain in strength of the foundation prior to proceeding with construction. Design and construction personnel should maintain an open channel of communication so that remedial action plans can be discussed at any time.

f. Selection of instrument locations. Locations for instruments should be determined based on predicted behavior of the site. The locations should be compatible with the geotechnical concerns and the method of analysis that will be used when interpreting the data. A practical approach to selecting instrument locations includes: (1) identify zones of particular concern such as structurally weak areas that are most heavily loaded, and locate appropriate instrumentation, (2) select zones that can be represented by typical cross sections where predicted behavior is considered representative of behavior as a whole (Typically, one cross section will be at or near the maximum height of the dam, and one or two other sections will be at appropriate locations.), (3) identify zones where there is discontinuity in the foundation or abutments, (4) install some additional instruments at other potentially critical secondary locations to serve as indices of comparable behavior, and (5) locate rows of survey monuments at intervals in the longitudinal direction at appropriate elevations. If behavior at one or more of the secondary locations appears to be significantly different from the primary sections, engineers should also provide additional instruments at these secondary locations. When

Table 3-2
Examples of Possible Geotechnical Questions (Dunnicliff 1990)

Questions to Answer	Features to Assess	Parameters to Monitor
What are initial site conditions?	Foundation Abutments Drainage basin	Pore water pressure Hydrology Meteorology
How does the embankment perform during construction?	Foundation Embankment Abutments	Pore water pressure Horizontal/vertical movement
How does the embankment perform during first filling?	All features and adjacent terrain	Pore water pressure Horizontal/vertical movement Seepage Dissolved solids
How does the embankment perform during drawdown?	Upstream face Adjacent natural slopes	Pore water pressure Slope stability
How does the embankment perform during long-term operation?	All features	All parameters

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selecting all locations, the survivability of instruments should be considered. Damage during construction to the instrument, riser, or cable should be prevented by good design and temporary and permanent protection of surface exposure. Protection against vandalism should also be part of the design.

g. Selection of instruments. Reliability is the most desirable feature in the selection of monitoring instruments. This is to ensure that dependable data of adequate accuracy can be obtained throughout the period when the information is needed. Often there is a tendency to seek unnecessarily high accuracy and when accuracy and reliability are in conflict, high accuracy should be sacrificed for high reliability. High accuracy often requires excessive delicacy and fragility. Usually the most reliable instrumentation devices are the simplest devices. Where a choice exists, the simpler device is likely to have more success. The performance record of commercially available instruments should be considered. There is an inherent risk in using any electronic instrument that does not have a satisfactory track record. However, in some cases, simple instruments are not satisfactory, and more complex devices must be provided. For instance, an open standpipe piezometer may be the simplest instrument for observing a piezometric level, but the point at which the pore water pressure needs to be measured may be located where direct vertical access is impossible. In this case a less simple instrument will be required to make measurements at a remote location. In general, transducers can be placed in the following order of decreasing simplicity and reliability: optical, mechanical, hydraulic, pneumatic, electrical. When considering costs, the lowest initial cost of an instrument should never dictate the selection of an instrument. Instead, a comparison of the overall cost of procurement, calibration, installation, life cycle maintenance, reading, and data processing of the available instruments (plus a consideration of replacement cost if there is some risk the instrument should go bad) should be made. The least expensive instrument is not likely to result in the least overall cost because it may be less reliable. The cost of instruments themselves is usually a minor part of the total cost. Engineers must also keep in mind that instruments themselves can cause problems. The installation of instruments, even under the best of circumstances, can introduce discontinuities into embankments and foundations. Horizontal or vertical protecting risers or cables leading from instrumentation can have areas of poor compaction and preferential paths for seepage. Avoid horizontal conduits in the primary direction of seepage flow. Potential weaknesses introduced by an installation should be balanced against the potential benefits from the observations. Engineers need to develop an adequate level of understanding of the instruments that they select, and they will often benefit from discussing their application with a representative of the manufacturer or with an instrumentation consultant before selecting instruments. During discussions, users should convey as much information as possible about the planned application and seek out any limitations of the proposed instruments.

h. Determination of need for automation. Automated data acquisition systems (ADAS) have become a valuable means of collecting geotechnical instrumentation data. Developments in the field of electronics have made it possible to install and operate remote ADAS that provide accurate, reliable, and effective real time data collection. With increased emphasis on dam safety and the continued decrease in manpower, the advantages of providing automatic systems are numerous. Consideration should be given to providing ADAS at new projects and to retrofitting at existing projects. However, it must be understood that while ADAS can provide valuable data in a timely manner, they are only to be considered as an integral part of an overall dam safety program. An ADAS does not replace visual observations and the sound evaluation of instrumentation data provided. Further discussions on ADAS are presented in Chapter 5.

i. Planning for recording of factors which influence measurements. Measurements alone do not produce satisfactory assessments. A successful geotechnical monitoring program relates instrumentation measurements to causes. Therefore, plans should be developed to maintain records of all factors that might cause changes in the measured parameters. For example, it is necessary to record construction details and progress, geology and subsurface conditions, and results of visual observations of expected and unusual behavior. Data such as reservoir and tailwater levels, rainfall amounts, ambient and water temperatures, barometric pressure, and seismic events should also be included. Chapter 7 discusses data management, analysis, and reporting of instrumentation readings.

j. Establishment of procedures for ensuring data validity. Personnel responsible for monitoring instrumentation must be able to determine if the instruments are functioning correctly. This can sometimes be determined through visual observations or with backup systems. A backup system can be useful to confirm, or deny, the behavior indicated by some component of the primary system, even when the backup accuracy is significantly less accurate than the primary system. For example, optical surveys can be used to confirm apparent slope movements detected by inclinometers. Or, electronic or pneumatic pressure transducers used for long-term monitoring of pore water pressure can be supplemented by twin-tube hydraulic piezometers as backup. Data can also be evaluated for validity by examining consistency. For example, where consolidation is being monitored, dissipation of pore water pressure should be consistent with measured settlement, and increases in pore water pressure should be consistent with added loading. Repeatability can also indicate data validity. It is often worthwhile to take many readings over a short period of time to determine whether a lack of normal repeatability indicates suspect data. Wherever possible, the most dependable method of ensuring collection of dependable data is to provide the simplest instrumentation system available that will provide the desired data.

k. Determination of costs. Funding for instrumentation of a project should be planned during the design stage of a new project or the planning stage of an existing project evaluation. Early planning will identify the amount of funds needed, what funding is available, and if additional funding sources are needed. When the need for instrumentation is properly and correctly established, and when the program is properly planned, there should be sufficient justification for funding. Instrumentation does not have to reduce costs to be justified. Instrumentation is valuable in proving that the design is correct, or in some cases, instrumentation might show that the design is inadequate, increasing construction costs. However, the value of ensured safety and the avoidance of failure, saving the cost of damages and/or cost of repairs, makes instrumentation programs cost-effective. Cost estimates should take into consideration the cost of instruments, installation, calibration, automation, long-term protection, maintenance, and data collection and management.

l. Planning installation. Proper installation is critical to achieving reliable performance and obtaining desired information. Installation procedures should be planned well in advance of scheduled installation dates, following guidelines presented in Chapter 6. Written step-by-step procedures should be prepared, making use of the manufacturer’s instruction manual and the designer’s knowledge of specific site geological conditions. The written procedures should include a detailed listing of required materials and tools, and installation record sheets should be prepared for documenting factors that may influence measured data. Whenever possible, instrumentation should be installed by experienced Government personnel, rather than by contract personnel. For projects under construction, installation plans should be coordinated with the construction contractor and arrangements made for access, safety of personnel, and both temporary and permanent protection of instruments and monuments from damage. An installation schedule should be prepared that is consistent with the construction schedule.

m. Planning long-term protection. Consideration should be made for protection of instrumentation over the long-term. Survivability should be included in determining the original location of all instruments with respect to traffic patterns, operation of project maintenance equipment, and access to project visitation. Where necessary, installations should be buried out of sight in watertight containers, or adequate protection should be provided at the surface. Buried cable locations and other subsurface locations should be clearly documented on as-built drawings to prohibit future damage. In some isolated areas, it may be necessary to provide bulletproof housing. Appropriate parts and components should be available for replacement of instruments that may become inoperative for one reason or another over a long period of time.

n. Planning regular calibration and maintenance. The design of an instrumentation system must take into consideration the fact that regular calibration and maintenance of hardware will be required over the life of the project. During the design of the system, procedures and schedules should be developed for regular maintenance of readout units and any components which are accessible. Calibration and maintenance are discussed in Chapter 8.

o. Planning data collection and management. Procedures for collecting, processing, presenting, interpreting, and reporting instrumentation data should be developed prior to installation of the system. The effort required for these tasks should not be underestimated. Too often data collection files become filled with large quantities of partially processed and undigested data because sufficient time and funds were not appropriated for activities required after the instruments were installed. With the development of computerized data collection, processing, and presentation procedures, overall manual effort has been greatly reduced. However, the limitations of computerization must be recognized. No computerized system can replace engineering judgment, and engineers must make a special effort to ensure that measured effects are correlated with probable causes. The tasks of interpretation, judgment, and implementation must be performed by competent personnel rather than computers. Data management and analysis are discussed in Chapter 7.

p. Coordination of resources. Tasks to be considered during the monitoring program include planning regular calibration and maintenance of instruments, instrument replacement procurement, installation, and calibration, data collection, and data management. When tasks are assigned, the person with the greatest vested interest in the data should be given direct responsibility for producing the data accurately. Instrumentation personnel need to have a background in the fundamentals of geotechnical engineering, and be reliable, patient, and motivated. In addition, they need to demonstrate attention to detail. Qualifications for personnel are presented in paragraph 3-8.

q. Determination of life cycle costs. Once planning for the system is completed, the cost estimate for the tasks suggested in paragraph 3-6*k* should be updated. Care must be taken to ensure that sufficient funds are provided to cover all aspects of the program, including instrument maintenance and the data collection and processing costs for the life of the project.

3-7. Procurement

The specialized nature of instrumentation facilities and the care required in the procurement, installation, and calibration of equipment demand that these features of work be retained under close operational control of qualified Corps of Engineers personnel. Direct procurement by the Government of instruments, cable, tubing, and indicating or recording equipment, and similar items not normally encountered in construction work, is recommended.

3-8. Personnel Qualifications and Responsibilities

A variety of tasks must be accomplished for an instrumentation program to be successful. The tasks include instrumentation installation, calibration, automation, long-term protection, maintenance, and data collection and management. Generally, these responsibilities can be delegated among individuals with diverse skills and backgrounds, or the same individual can be responsible for various tasks. Responsibilities should be very clear, communication being the single most important link among the various personnel (Table 3-3). The overall scope of the work should be supervised by a senior-level geotechnical or instrumentation engineer.

a. Project inspection personnel. Inspection of the project features should be accomplished on a routine basis during both construction and project operation. The actual schedules should vary depending on the criticality of the particular feature. A project engineer, project superintendent, or maintenance foreman are the most likely candidates, but anyone at the project with proper training can accomplish the inspections. As an example, the inspector should look for evidence of seepage or distress in the embankment or abutments, particularly springs, seeps, or boils developing along the downstream toe of the embankment, or zones of settlement, caving, bulging, or other distress in the embankment. Remarks should be noted on a preprinted form, and if deemed necessary, the appropriate District personnel should be notified immediately.

b. Instrumentation and/or automation equipment installation personnel. Installation should be coordinated by the senior-level geotechnical engineer, since proper installation of instruments and automation equipment requires specific knowledge and requirements.

c. Data collection personnel. It is highly recommended that permanent project employees be assigned data collection responsibilities. These employees should be properly instructed by the senior-level geotechnical or instrumentation engineer, and receive training on the importance of the tasks. Project personnel responsible for collecting data are too often temporary or summer hires who have limited knowledge of the geotechnical questions of concern. If permanent personnel are assigned to accomplish this task, they too often do not understand or enjoy the work, thereby affecting data quality. Repeatedly training part-time employees is difficult and time-consuming. There are three options when considering personnel to read manual instruments. The task of reading the manual instruments can often be combined with the maintenance of automation equipment if the data collection is partially automated. A second option is to hire a permanent employee whose job description includes the reading of manual instrumentation on a District project or area-wide basis. Ideally, a single individual at the District or project level should make the manual readings, since this allows for consistency of data, and also allows the individual to become familiar with the historical behavior of the instruments. A third option is to contract the work out, but this is not generally recommended because of the possible turnover in the contractor's reading personnel.

d. Instrumentation and automation equipment maintenance personnel. The maintenance of instrumentation and automation equipment is becoming increasingly more complex due to the partial automation of many Corps projects. A discussion on the personnel requirements relating to maintenance is included in paragraph 8-2.

Table 3-3
Personnel Responsibilities

Title	Responsibility
Senior-level geotechnical or instrumentation engineer	Coordinates and supervises the entire instrumentation program, including design of instrumentation and automation equipment, selection, procurement, and installation. Provides training to instrumentation personnel and assists in personnel decisions. Should assist in data interpretation and analysis and provide technical assistance or guidance to other geotechnical engineers responsible for final data analysis.
Project inspection personnel	Inspect the project during both construction and operation. Make notes of changes (seepage, boils, caving, etc.) and notify District personnel if necessary.
Instrumentation and/or automation equipment installation personnel	Responsible for initial instrumentation and installation; assure initial readings are correct and make necessary initial calibrations.
Data collection personnel	Collect data from manually read instrumentation. May also enter data into the computer.
Instrumentation and automation equipment maintenance personnel	Maintain instrumentation and automation throughout life of the project. Recalibrate and replace instruments as necessary.
Data entry personnel	Enter collected data into the computer. May also be responsible for collecting data from the field.
Data management, reporting, and plotting personnel	Process data from all District projects. Work with senior-level geotechnical or instrumentation engineer. Work with various software programs, data transfer from remote sites, programming, creating reports, and submitting data plots.
Instrumentation program manager	See senior-level geotechnical or instrumentation engineer.
Review and analysis personnel	Review and analyze final data to assure the project is performing in accordance with design. Also notify maintenance personnel of inaccurate readings or malfunctions.

e. Data entry personnel. The task of data entry is often combined with other tasks. Data entry can be at the project site by data collection personnel, or in the District office by data management personnel. Data entry can be handled by non-geotechnical personnel, such as information management personnel. However, since initial error checking should be accomplished at the data entry level, it is highly recommended that a person familiar with the instruments enters all data.

f. Data management, reporting, and plotting personnel. This position is generally filled at the District level by an engineering technician with strong computer skills, who processes the data from all District projects. This person must work closely with the senior-level geotechnical or instrumentation engineer who is responsible for coordination of the entire instrumentation program. Tasks include interrelating with numerous software programs, data transfer from remote sites, programming, creating reports, and submitting data plots. It is also necessary that the individual be trained in data collection and field maintenance so that he or she better understands the instruments and automation equipment in use.

g. Instrumentation program manager. The overall management of an instrumentation program should be supervised by a single instrumentation or geotechnical engineer, whose responsibilities should include instrumentation and automation equipment design, selection, procurement, and installation. He or she should coordinate all of the tasks listed above, provide training to the instrumentation personnel, and assist in personnel decisions. As a minimum, this person should assist in data interpretation and analysis, and provide technical assistance or guidance to other geotechnical engineers responsible for final data analysis.

h. Review and analysis personnel. Senior-level geotechnical or instrumentation engineers must be involved in the final review and analysis of all instrumentation data. It is possible that this task can be accomplished by the instrumentation program manager, but other engineers must be involved so that multiple reviews are being accomplished. The program manager and the technical reviewers should establish data review schedules and formulate reports on a consistent and frequent basis.

Chapter 4
Summary of Measurement Methods

4-1. Introduction

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

4-2. Instrumentation Measurement Methods

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

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

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

c. Electrical resistance strain gage devices.

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

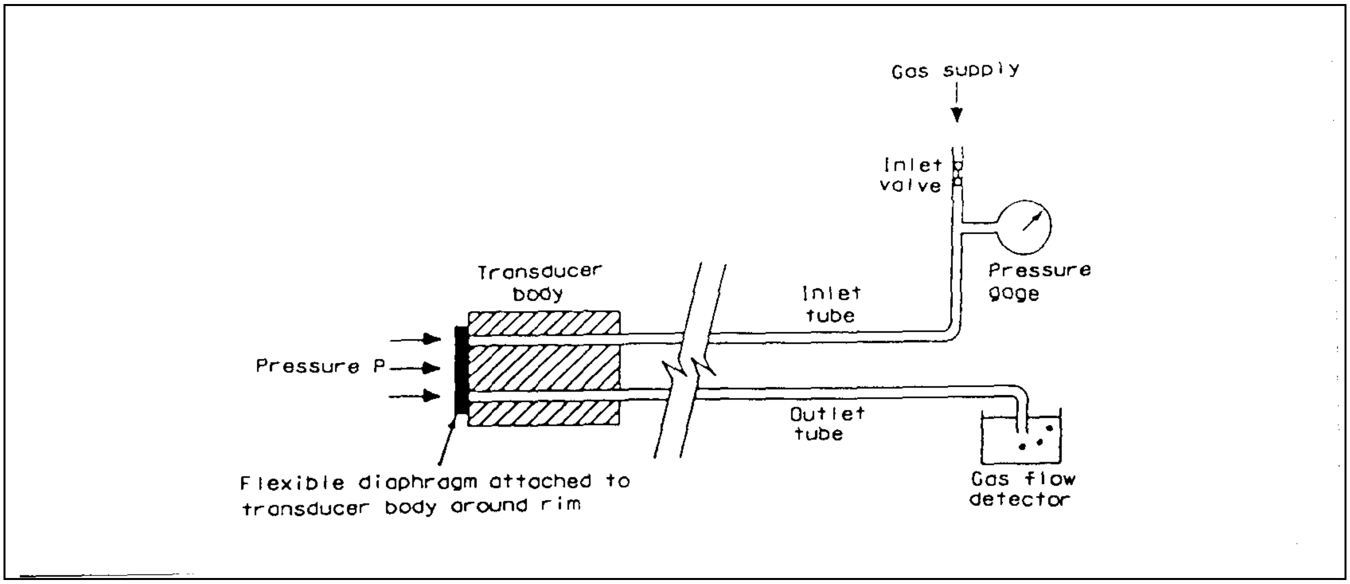

Figure 4-1. Schematic of pneumatic device (Dunnicliff 1988)

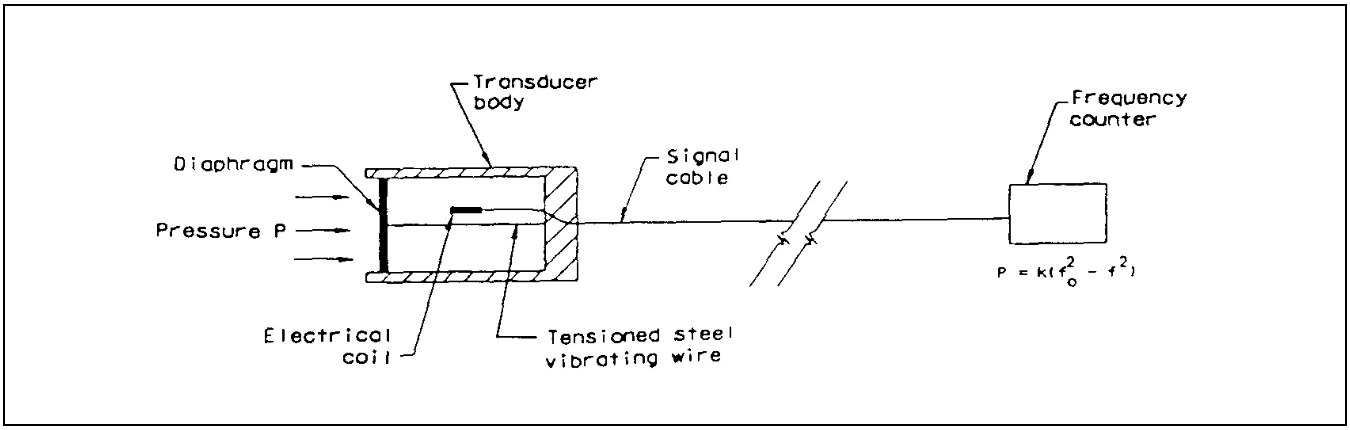

Figure 4-2. Schematic of vibrating wire pressure sensor (Dunnicliff 1988)

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

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

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

d. Electrical transducers for measuring linear displacement.

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

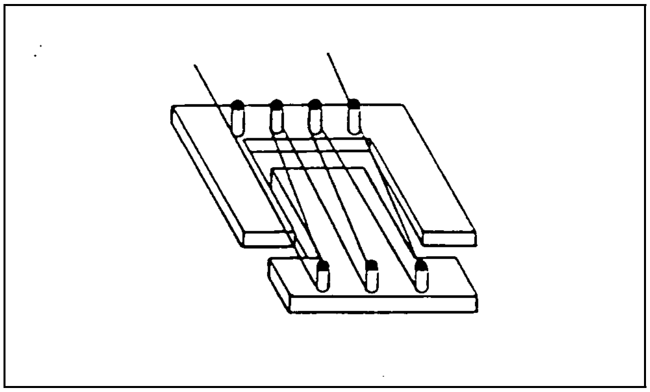

Figure 4-3. Schematic of unbonded wire resistance strain gage (Dunnicliff 1988)

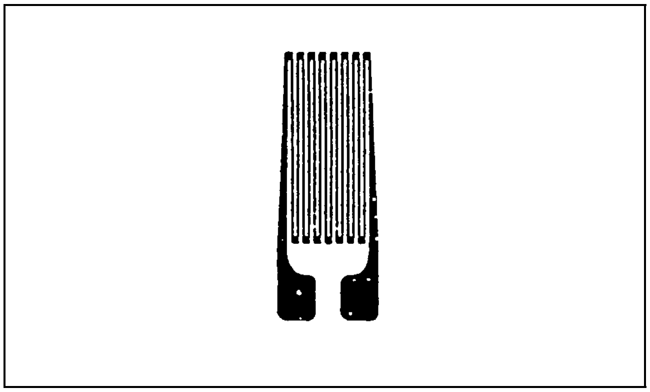

Figure 4-4. Uniaxial bonded foil resistance strain gage (Dunnicliff 1988)

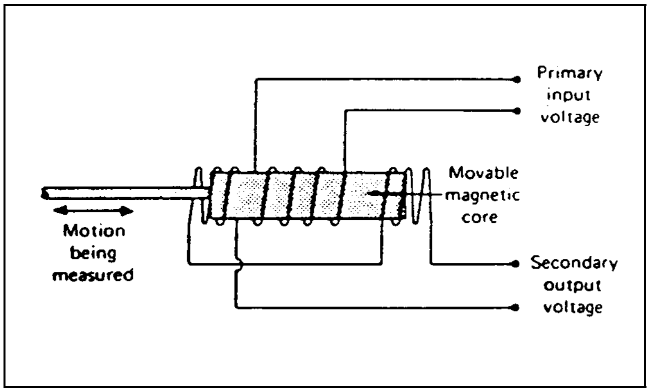

Figure 4-5. Schematic of linear variable differential transformer (LVDT) (Dunnicliff 1988)

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

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

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

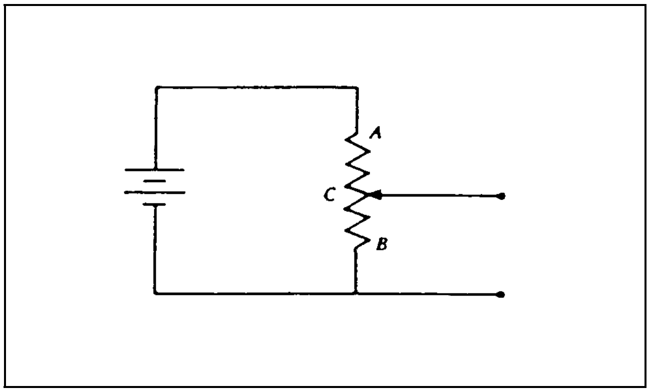

Figure 4-6. Schematic of linear potentiometer (Dunnicliff 1988)

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

e. Other electrical systems.

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

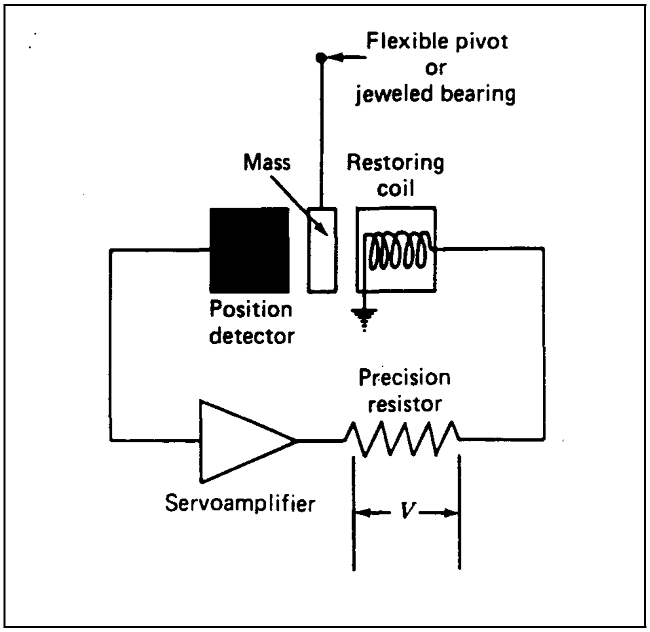

Figure 4-7. Schematic of force balance accelerometer (Dunnicliff 1988)

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

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

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

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

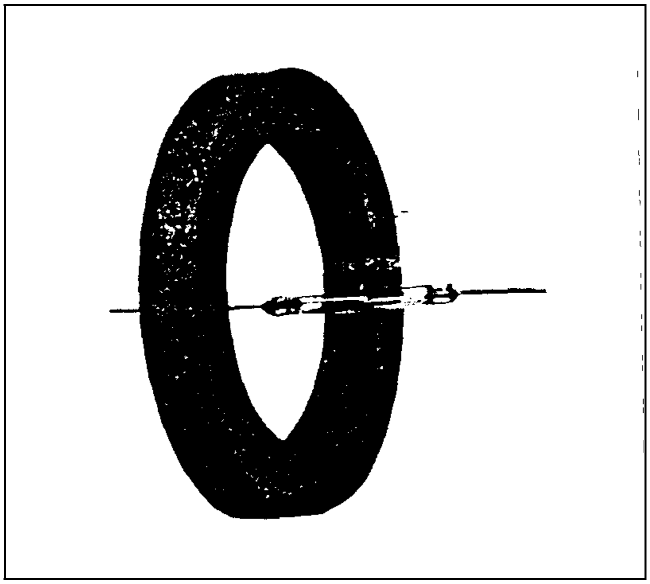

Figure 4-8. Magnet/reed switch (Dunnicliff 1988)

4-3. Measurement of Piezometric Pressure

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

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

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

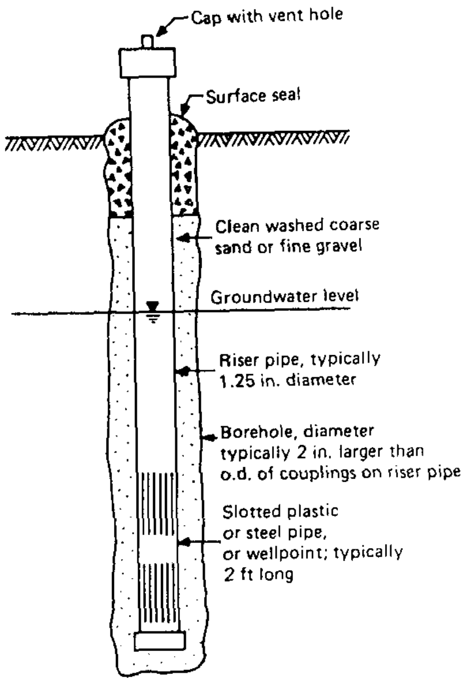

Figure 4-9. Schematic of observation well (Dunnicliff 1988)

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

d. Twin-tube hydraulic piezometers.

(1) The twin-tube hydraulic piezometer is shown schematically in Figure 4-11. The piezometric elevation is determined by adding the pressure gage reading to the elevation of the pressure gages. If both plastic tubes are completely filled with liquid, both pressure gages should indicate the same pressure. However, if gas has entered the system (through the filter, tubing, or fittings) the gas will cause an inaccurate pressure reading on one or both gages. The gas must be removed by flushing. Dual gages therefore indicate the need for flushing and re-calibration.

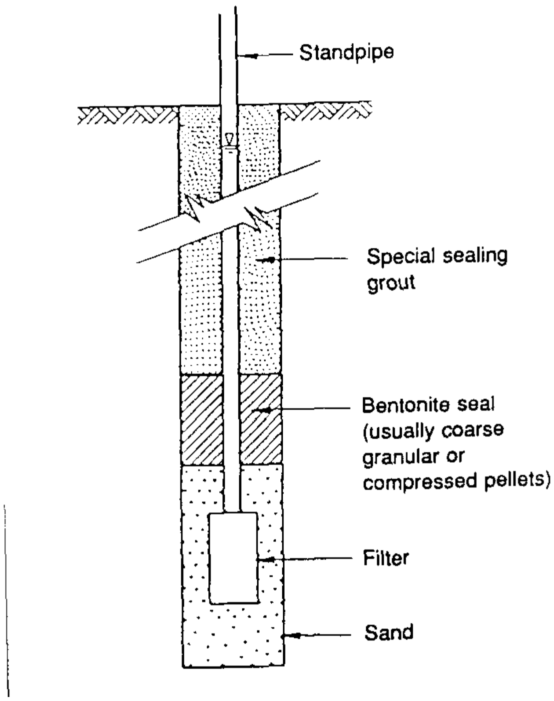

Figure 4-10. Schematic of open standpipe piezometer installed in a borehole (Dunnicliff 1988)

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

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

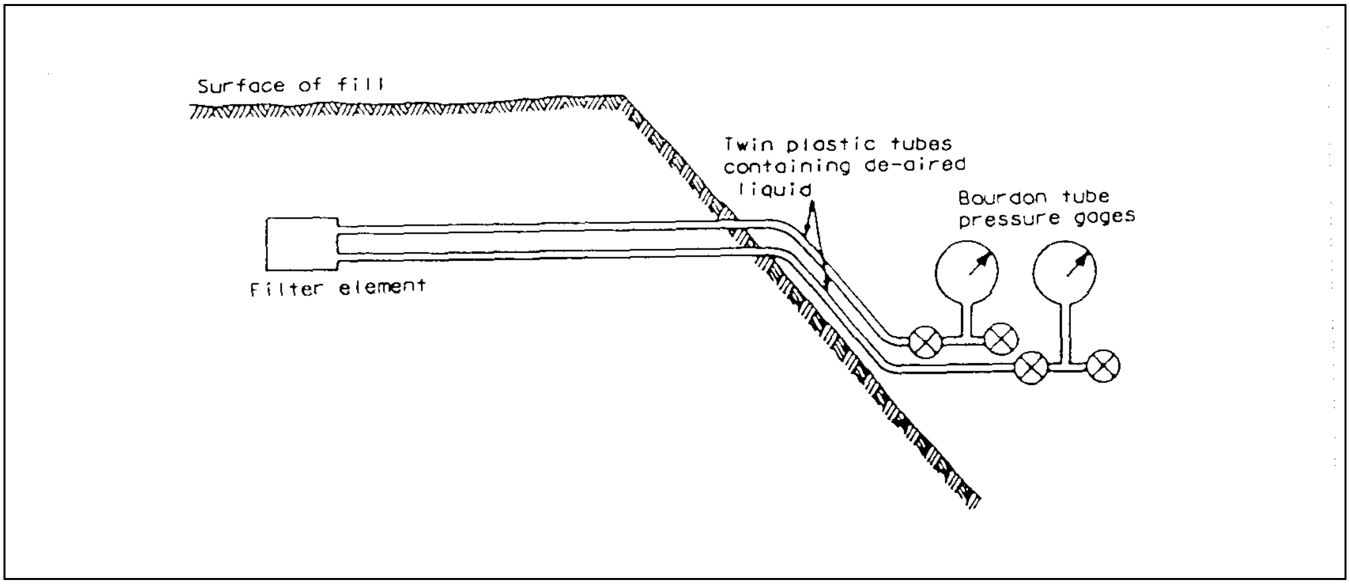

Figure 4-11. Schematic of twin-tube hydraulic piezometer installed in fill (Dunnicliff 1988)

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

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

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

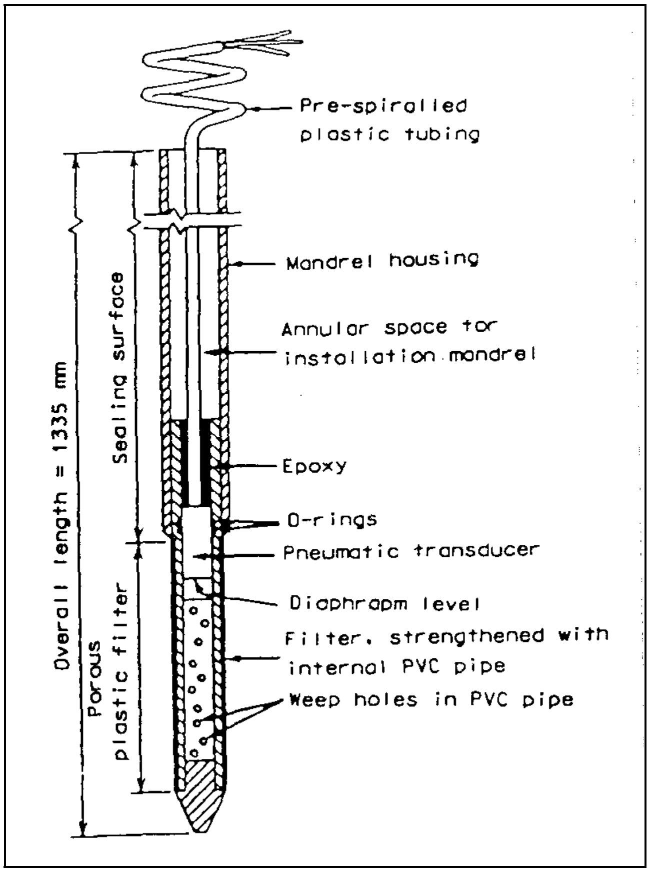

Figure 4-12. Pneumatic piezometer for installation by pushing in place below bottom of a borehole in very soft clay (Dunnicliff 1988)

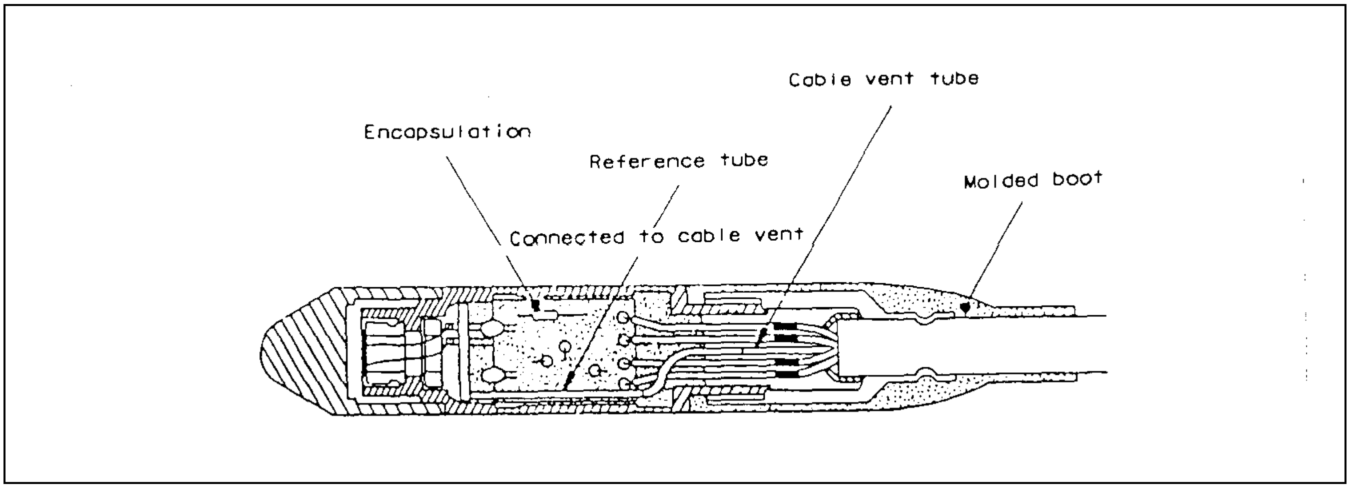

Figure 4-13. Fully encapsulated submersible pressure transducer (courtesy of Druck, Inc.)

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

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

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

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

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

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

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

Table 4-1
Instruments for Measuring Piezometric Pressure

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

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

[b] See Dunnicliff (1988)

Source: Dunnicliff (1988)

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

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

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

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

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

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

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

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

4-4. Measurement of Deformation

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

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

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

Table 4-2
Categories of Instruments for Measuring Deformation

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

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

Source: Dunnicliff (1988)

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

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

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

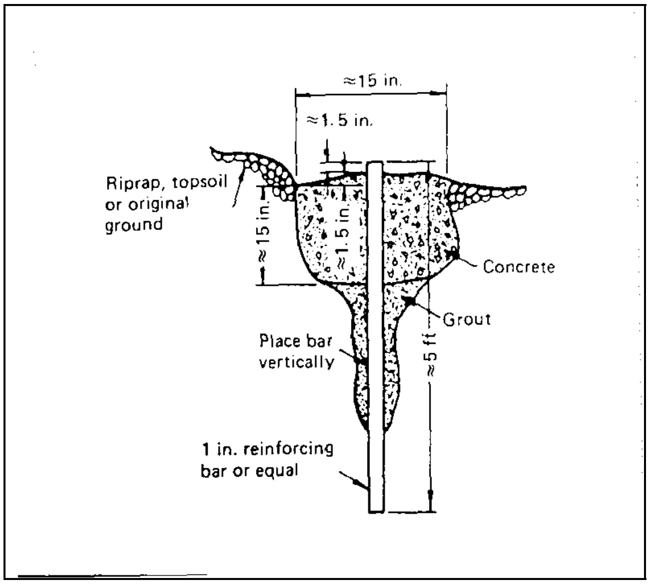

Figure 4-14. Measuring point for monitoring settlement on surface of embankment dams

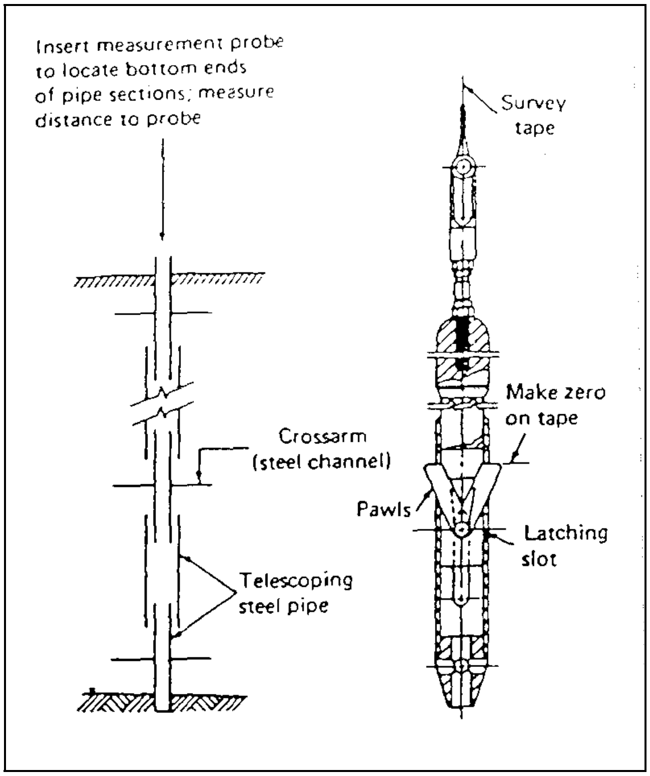

Figure 4-15. Crossarm gage: (a) Schematic of pipe arrangement and (b) measurement probe

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

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

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

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

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

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

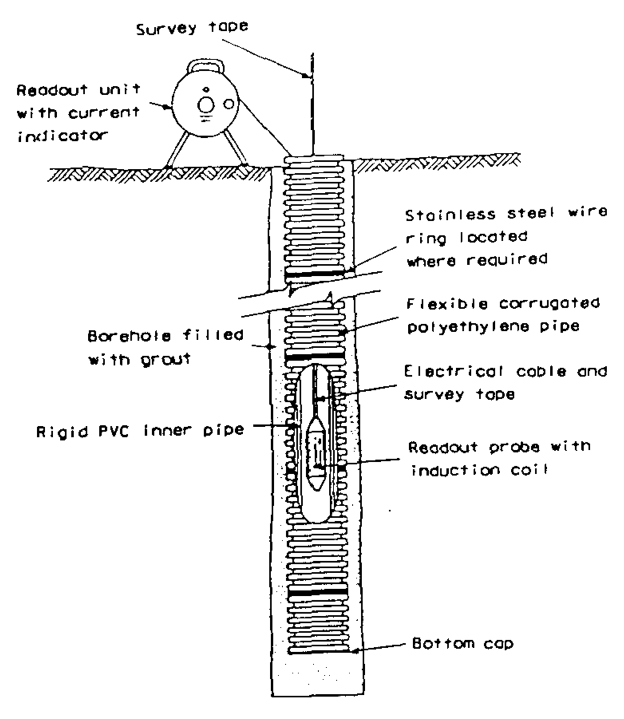

Figure 4-16. Schematic of Slope Indicator Company sondex probe extensometer installed in a borehole (Dunnicliff 1988)

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

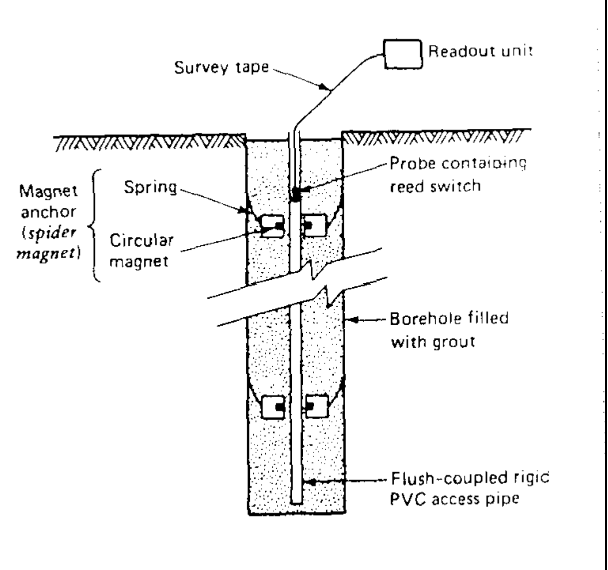

Figure 4-17. Schematic of probe extensometer with magnet/reed switch transducer, installed in a borehole (Dunnicliff 1988)

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

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

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

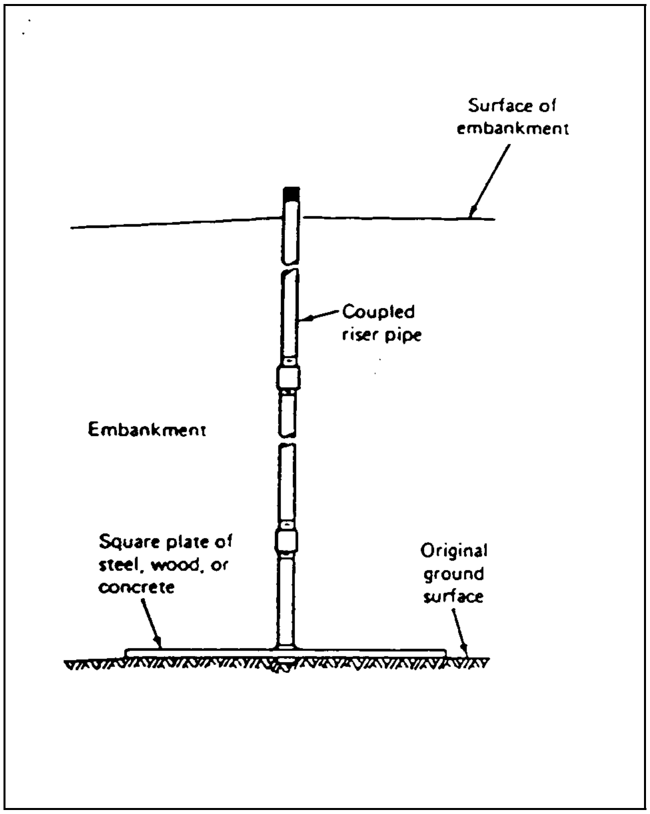

Figure 4-18. Typical settlement platform (Dunnicliff 1988)

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

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

e. Fixed borehole extensometers.

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

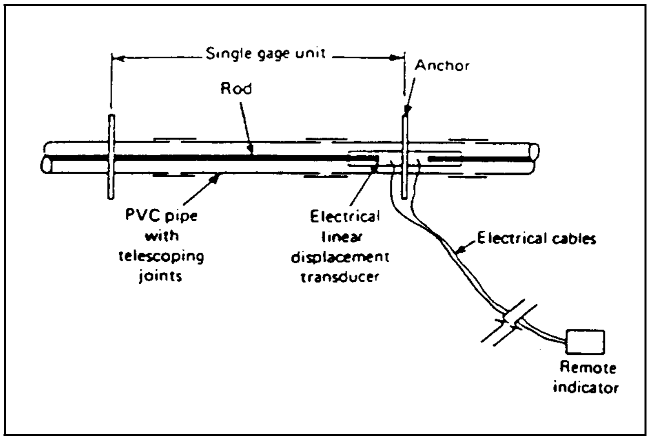

Figure 4-19. Schematic of fixed embankment extensometer with electrical linear displacement transducers (Dunnicliff 1988)

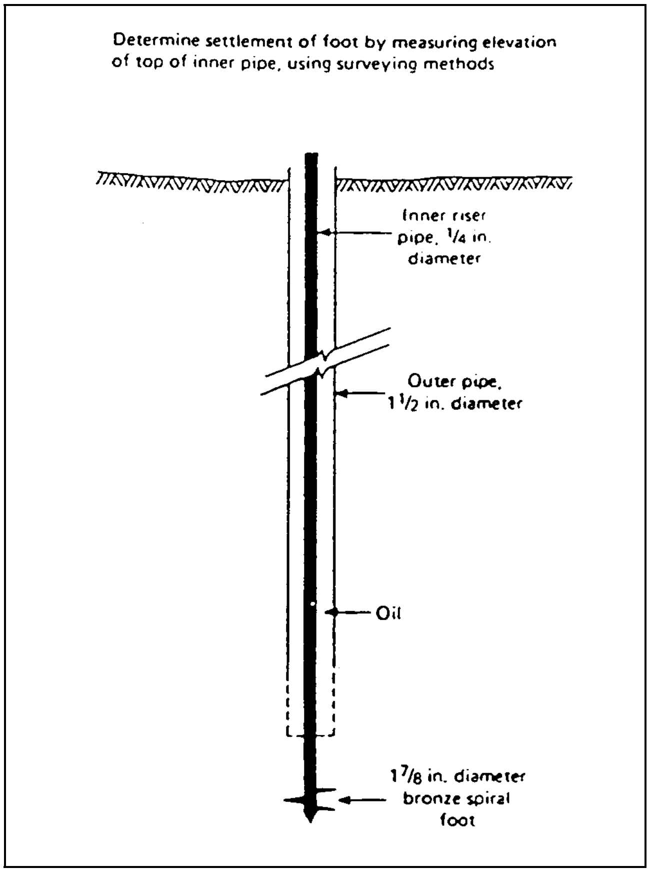

Figure 4-20. Schematic of spiral-foot subsurface settlement point (Dunnicliff 1988)

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

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

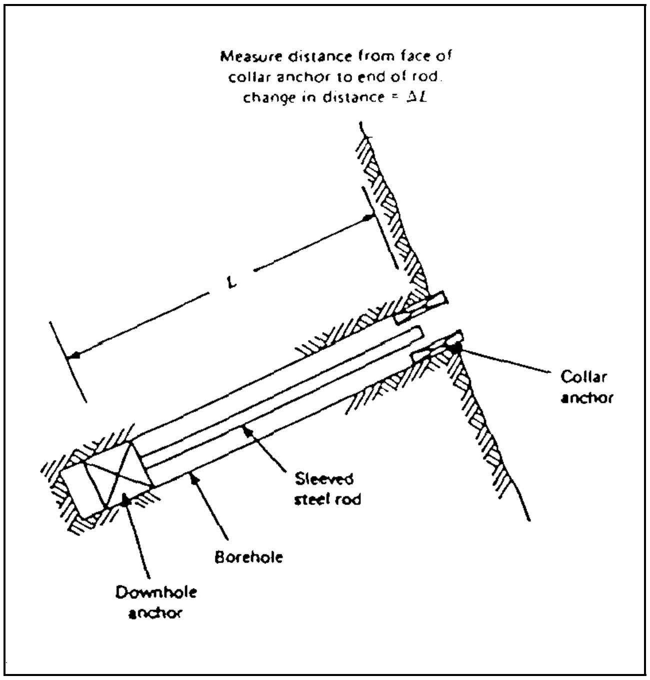

Figure 4-21. Operating principle of fixed borehole extensometer (Dunnicliff 1988)

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

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

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

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

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

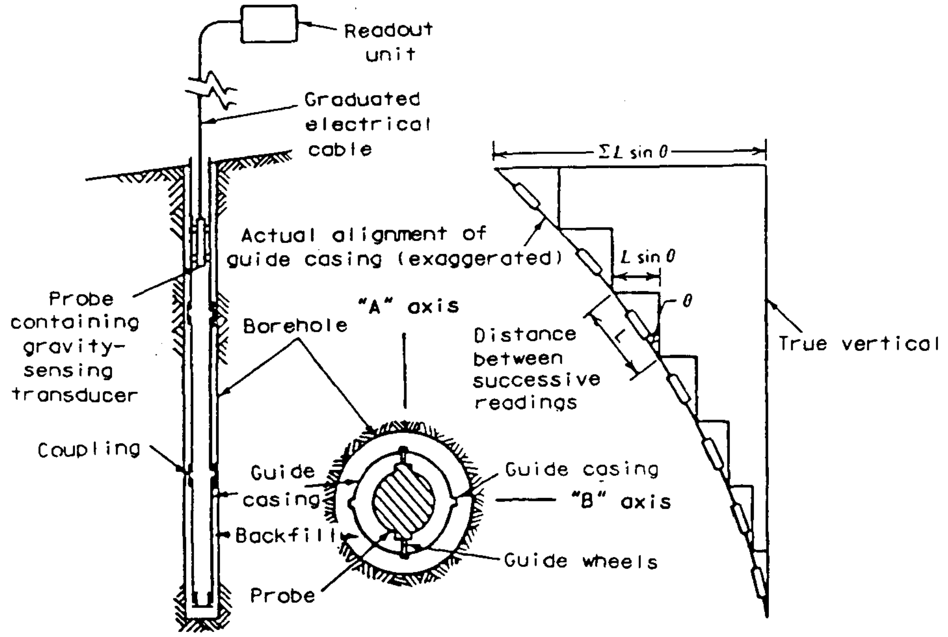

Figure 4-22. Principle of inclinometer operation (Dunnicliff 1988)

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

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

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

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

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

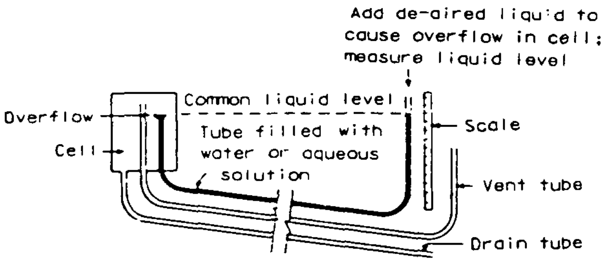

Figure 4-23. Schematic of overflow liquid level gage with both ends at same elevation (Dunnicliff 1988)

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

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

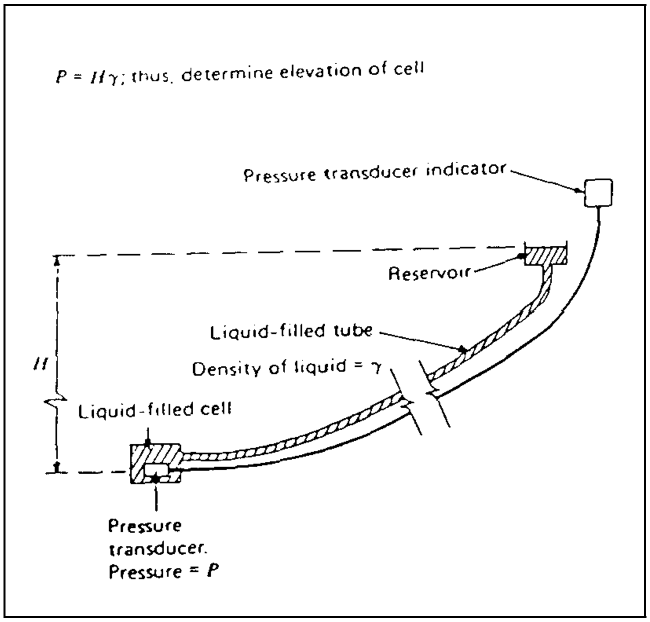

Figure 4-24. Schematic of liquid level gage with pressure transducer in cell, with readout unit higher than cell (Dunnicliff 1988)

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

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

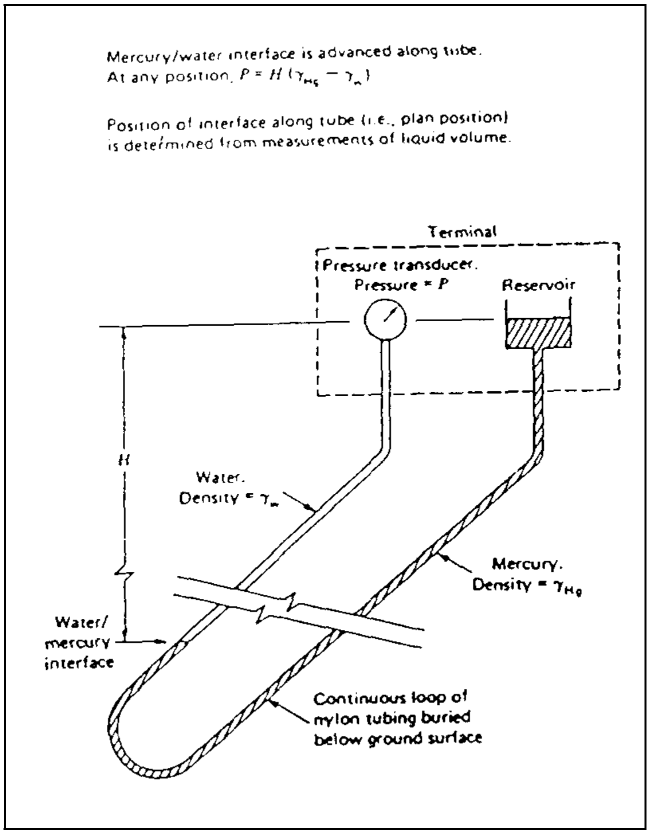

Figure 4-25. Schematic of double fluid settlement gage (Dunnicliff 1988)

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

4-5. Measurement of Total Stress

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

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

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

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

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

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

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

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

Source: Dunnicliff (1988)

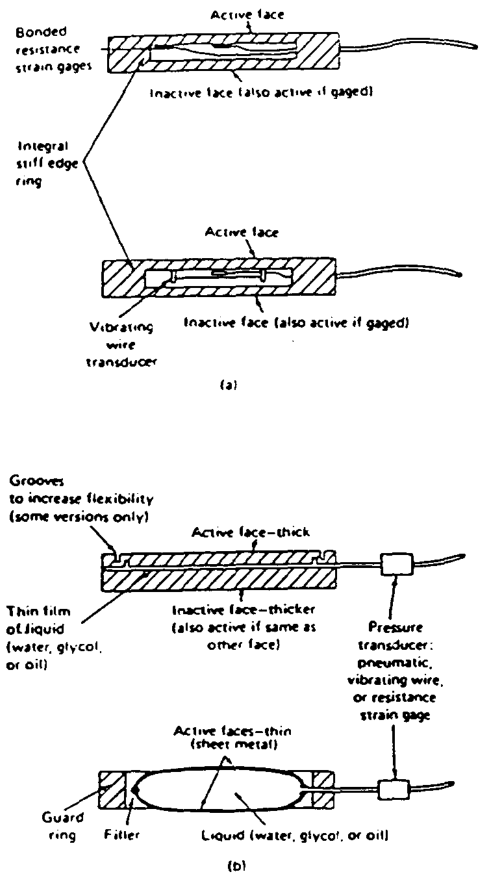

Figure 4-26. Basic types of earth pressure cell: (a) diaphragm cells and (b) hydraulic cells (Dunnicliff 1988)

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

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

c. Contact earth pressure cells.

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

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

4-6. Measurement of Temperature

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

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

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

4-7. Measurement of Seismic Events

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

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

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

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

Source: Dunnicliff (1988)

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

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

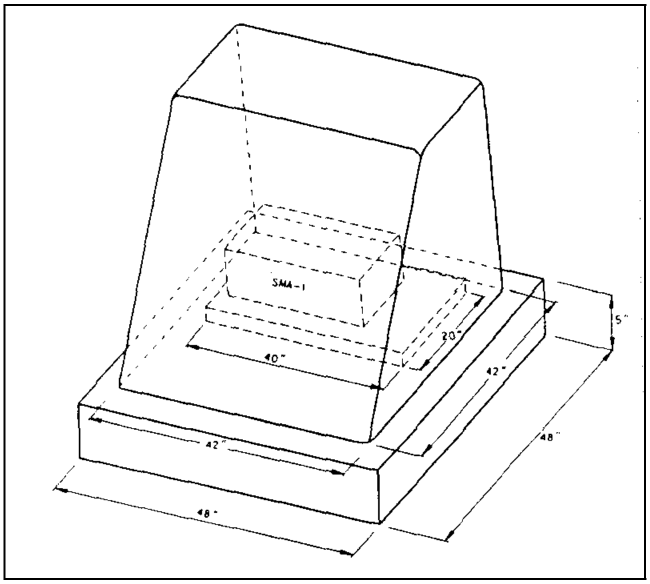

Figure 4-27. 41-2 shelter on a concrete pad for housing accelerograph

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

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

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

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

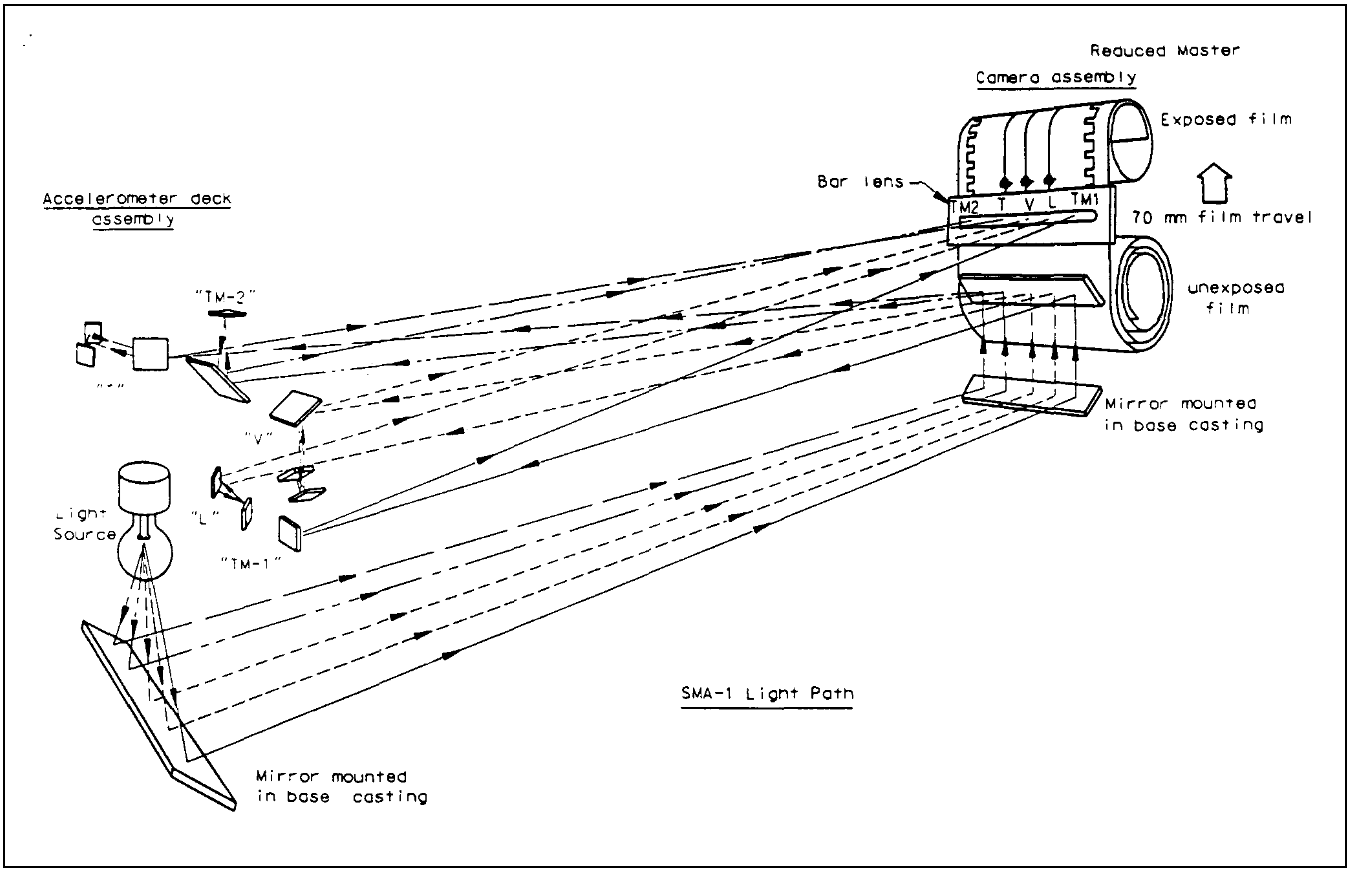

Figure 4-28. Analog/accelerograph component diagram (courtesy of Kinemetrics, Inc., Pasadena, CA)

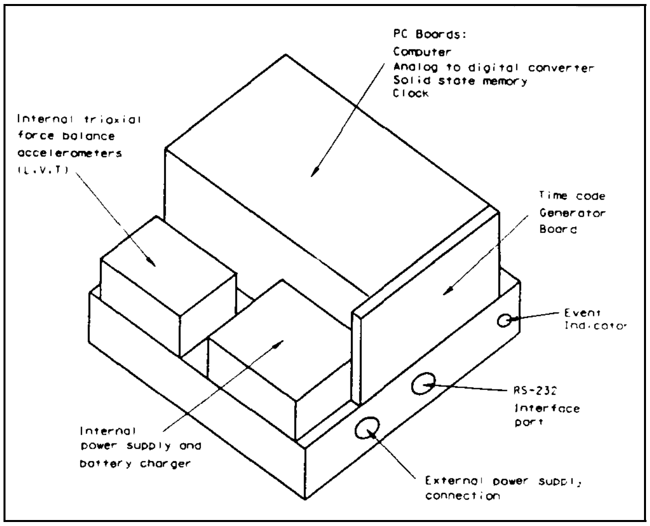

Figure 4-29. Digital accelerograph component diagram

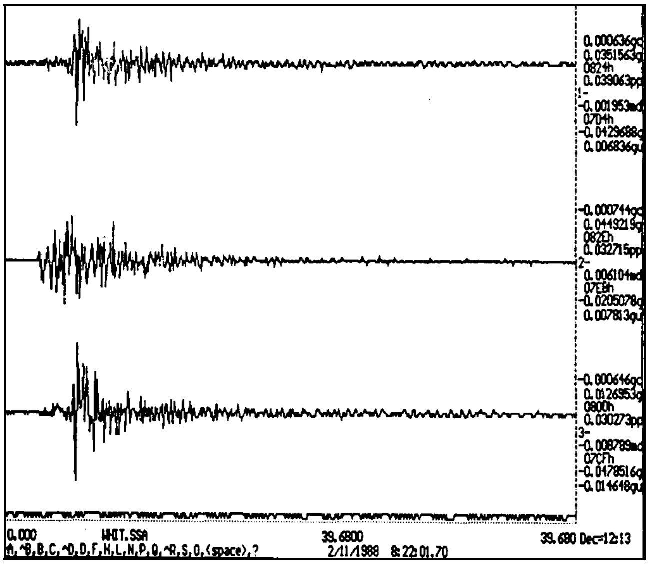

Figure 4-30. Digital accelerograph data plot

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

4-8. Measurement of Seepage Emerging Downstream

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

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

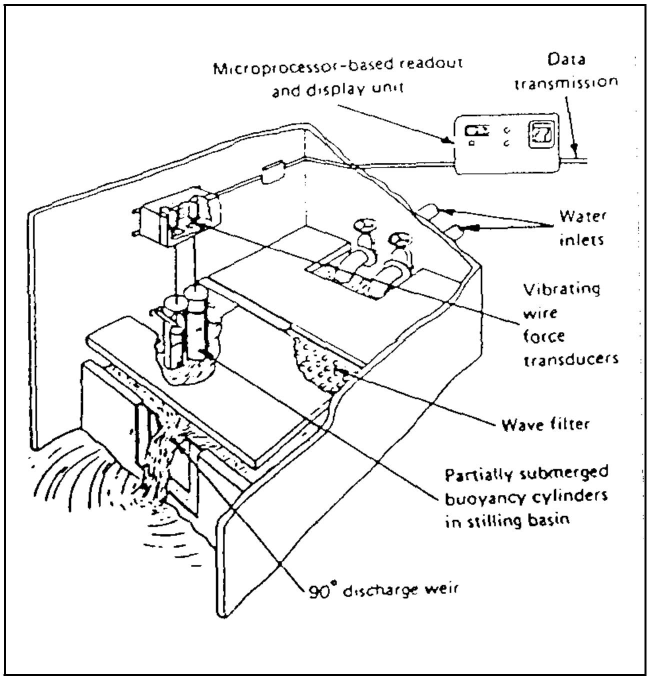

Figure 4-31. Remote-reading weir for monitoring leakage quantities (courtesy of GEONOR, Inc.)

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

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

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

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

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

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

Chapter 5
Automation Considerations

5-1. Introduction

Automation of instrumentation can assist in the assessment of the safety of dams and levees. This is particularly true for monitoring that requires rapid and frequent data collection or for instruments that are inaccessible. In recent years, the technology of devices for measuring seepage, stresses, and movements in dams and levees has improved significantly with respect to accuracy, reliability, and economics. Although the initial installation of an automated data acquisition system (ADAS) may appear to be more expensive than traditional instrumentation systems, the overall long-term cost, in many cases, is now economically competitive. Automation should receive consideration for all systems that are to be installed during new dam construction, major rehabilitations, structural modifications, or any major effort that would support a major instrumentation system. Instrument upgrades and replacements could be justified on a case-by-case basis. The trends of decreasing manpower and resources that are allocated for dam safety efforts within the Corps of Engineers suggest that engineers consider the automation technology to accomplish the tasks required. The instrument automation concept generally includes an instrument or transducer that is linked to a datalogger or computer with communication capability that allows data retrieval locally or from a remote location. Figure 5-1 shows a general schematic of a typical ADAS. This chapter addresses areas that are characteristically unique for automation.

5-2. Applications

The monitoring of any project or feature can be automated depending on instrument type and feasibility. Automation is not limited to new installations related to new construction, research, or specific investigation. Existing systems can be retrofitted. However, it is not appropriate to automate in all cases. Sufficient engineering justification is necessary. The following situations are examples of justifiable applications for automating instrumentation.

a. Historical movement or pressure trends exceed the established thresholds, or trends are raising concerns that warrant frequent measurement.

b. Formal studies or investigations have identified specific or potential problem (stability, performance) areas warranting frequent measurement.

c. High hazard potential in the event of uncontrolled releases and timeliness of response to performance changes is critical to public safety. (Consequences of failure or partial failure)

d. Structural or foundation features are required to perform in a manner that was not anticipated in the original design.

e. Complexity of design and/or complexity of construction requires that design considerations be verified.

f. Abnormal extent or frequency of remedial measures has been or is required.

g. Instruments or systems have met their useful life, failed to perform satisfactorily, or have degraded with time and are required for performance assessment.

h. Timely response to unusual developments is adversely affected by remoteness of geographic location, inaccessibility, or lack of qualified onsite personnel.

i. Increased reliability and/or high frequency of monitoring is critical to the assessment of conditions.

5-3. Advantages and Limitations of Automation

The advantages and limitations of an automated system follow. The limitations can be minimized with appropriate attention to planning and use of the system.

a. *Advantages.*

- Increased accuracy-reduced human error.
- Increased frequency-more data, less system error.
- Increased data reliability and consistency.
- Replaces lost manpower.
- Timeliness of information-obtain data whenever needed.
- Data and system validity checks enhance data quality.
- Alarms for exceeding data thresholds and system health.
- Remote diagnostics, calibrations, and programming.

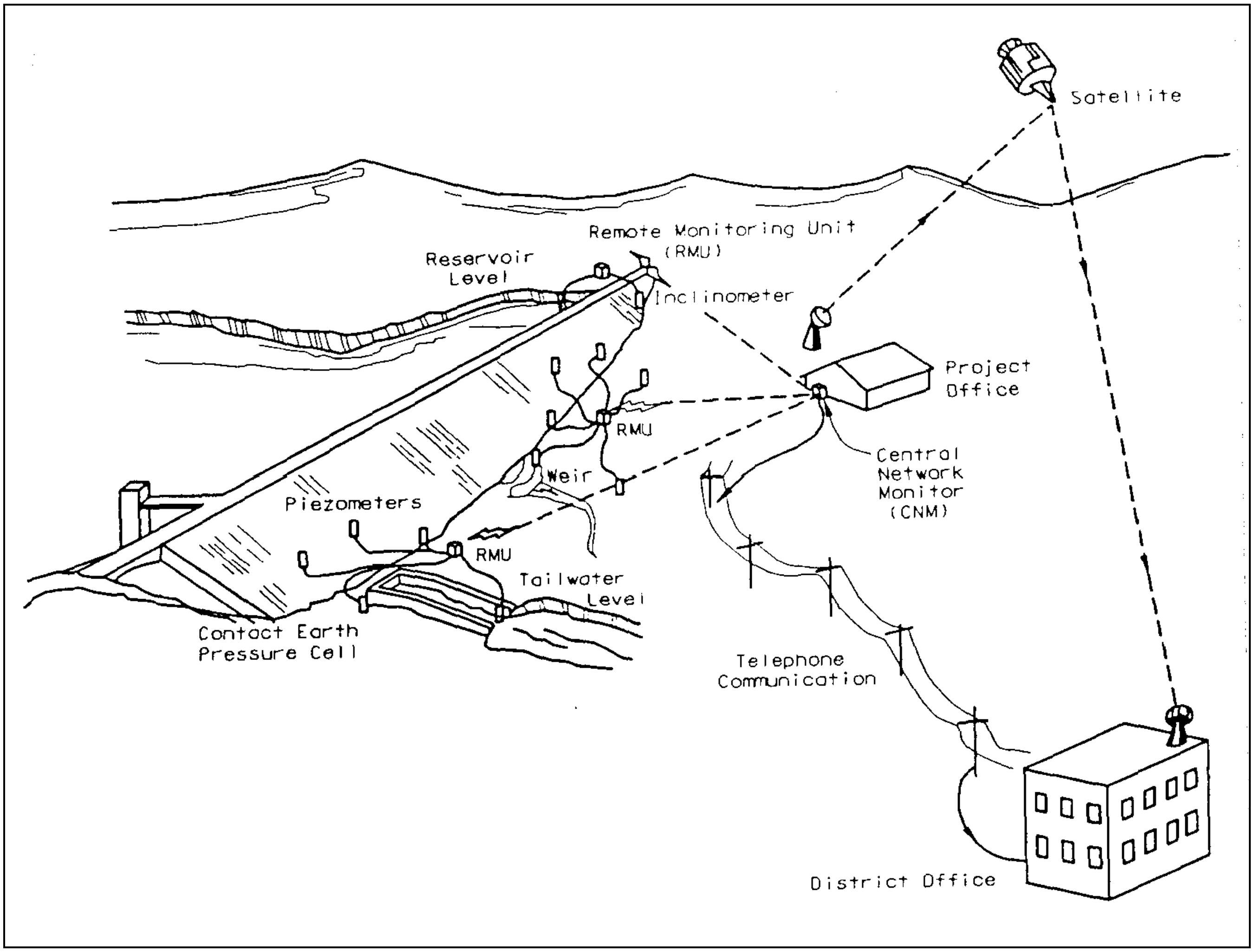

Figure 5-1. Automatic data acquisition system geotechnical instrumentation

b. Limitations.

- Produces large volumes of data; overtaxes storage medium.
- Installation could be expensive.
- Removes personal attention from the field.
- Lightning; variable voltage potential is destructive.
- Excessive downtime with overly complex integrations.
- Sufficient computer and electronics expertise not available.
- Potentially higher maintenance costs.
- Requires a constant electrical power source.
- Requires use of electronic transducers which have least long-term reliability of any type used.

5-4. Description of Automated Systems

Automation is the integration of the electronics, computer, and communications technologies that is applied to geotechnical and structural engineering concerns of water resources projects. It performs a variety of tasks that contribute to efficient and effective performance analyses. EM 1110-2-2300, Appendix D, very generally describes the features and capabilities of an automated system. The appendix contains examples of networks and communications alternatives. It also recommends an approach to choosing the features of a structure to be monitored and selecting the sensors that are appropriate to automate.

a. Configurations. Configurations of automated systems can be categorized as one of three basic types as follows:

(1) Datalogger. An electronic component collects data from attached instruments upon command from a personal operator. The system can include modems for remote communication, but generally requires that the intelligence and operation be external to the system. Figure 5-2 shows a stand-alone datalogger configuration.

(2) Scada. Scada (supervisory control and data acquisition) is a host computer that controls remote monitoring units (RMUs) which are intelligent dataloggers. RMUs acquire data and report those data upon command from the host computer. The remote unit can carry out the acquisition of data and store the information until communication with the host computer is established. The host computer is the system intelligence. It is programmed for frequency and scheduling of data acquisition. Personal intervention is not required for this system to operate. Figure 5-3 shows a Scada configuration.

(3) Distributed intelligence. Computers are located at each remote monitoring unit in the network. All are linked to a central computer; central network monitor (CNM) and communications can be established with the central computer as well as with each other. The remote units are fully responsible for the frequency and scheduling of data acquisition as well as initiating communications. Raw data can be reduced and certain other decisions can be made at these remote points without personal or central computer intervention. Figure 5-4 shows a distributed intelligence configuration.

b. Communications. Communication of information occurs at three different locations: sensor to datalogger, remote dataloggers to central computer, and central computer to remote office. The most common modes of communicating from the sensor to the datalogger are electrical transmission through cables and sound transmission (acoustics) through the air. The most common local communication, linking the remote units to the host or central computer, is electrical cabling or radio transmissions. Remote communication from the project site to the district office is commonly by telephone, microwave, radio, or satellite. All modes of communication are not appropriate for any one application. Consideration must be given to lightning, presence of water, and other conditions which would affect the selection of a mode of communication. Design criteria will assist in making that determination.

c. Power supply. Automated systems can be energized by alternating current, battery, or solar panels and are normally supplemented by uninterruptible power supplies or emergency generators. Each of these alternatives have positive and negative characteristics for various applications. The sizing and maintenance of the primary supplies and backups should be addressed early in the planning process.

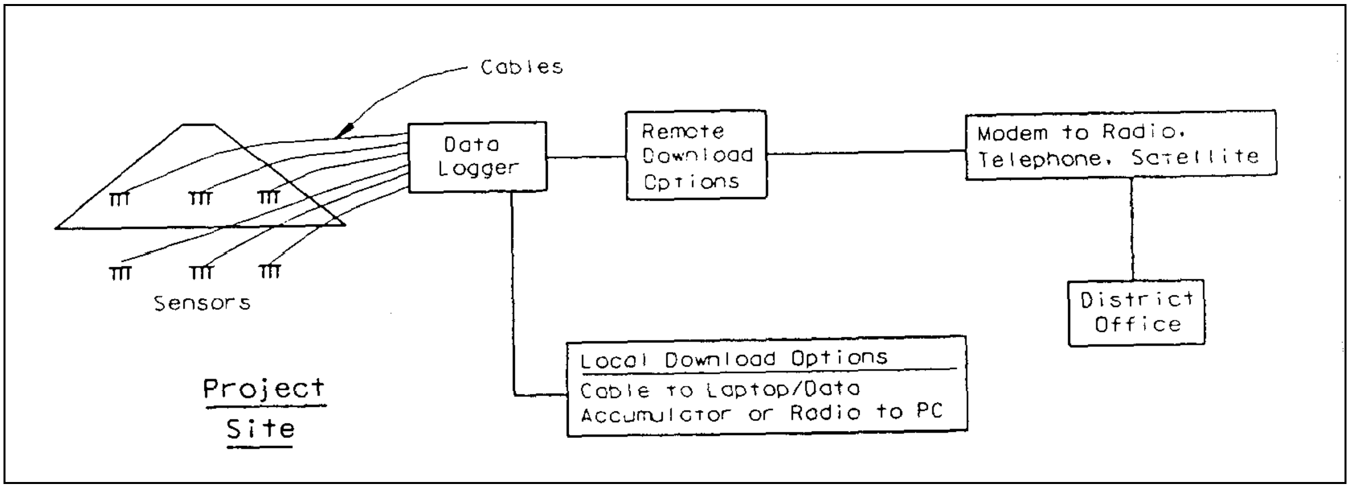

Figure 5-2. Stand-alone datalogger configuration

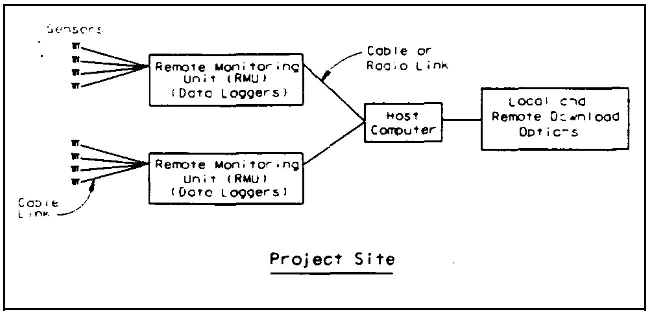

Figure 5-3. Scada configuration

5-5. Planning a System

All of the Corps of Engineers guidance and documentation that have been published emphasize that the proper approach to planning a system that is reliable and cost-effective include: obtaining the appropriate information, applying good engineering judgment, using Corps expertise when available, and learning from the experience that has been gained by others. The specific guidance is described below:

a. Detailed planning. Experience has shown that dam safety engineers must have some knowledge of project management and procurement issues to be successful with their automation endeavors. Experience has also shown that there are certain characteristics inherent in automation that must be understood to enhance the success of the project. This planning tool addresses the following major issues: assessing in-house resources, determining contracting mechanism, preparing Commerce Business Daily announcements and bid documents, technical design considerations, estimating, and others. Refer to USCOLD 1993 for more detail in each of these areas. It is important that the planner follow the suggested order of the tasks in the procedure to avoid complications at later stages of the planning process.

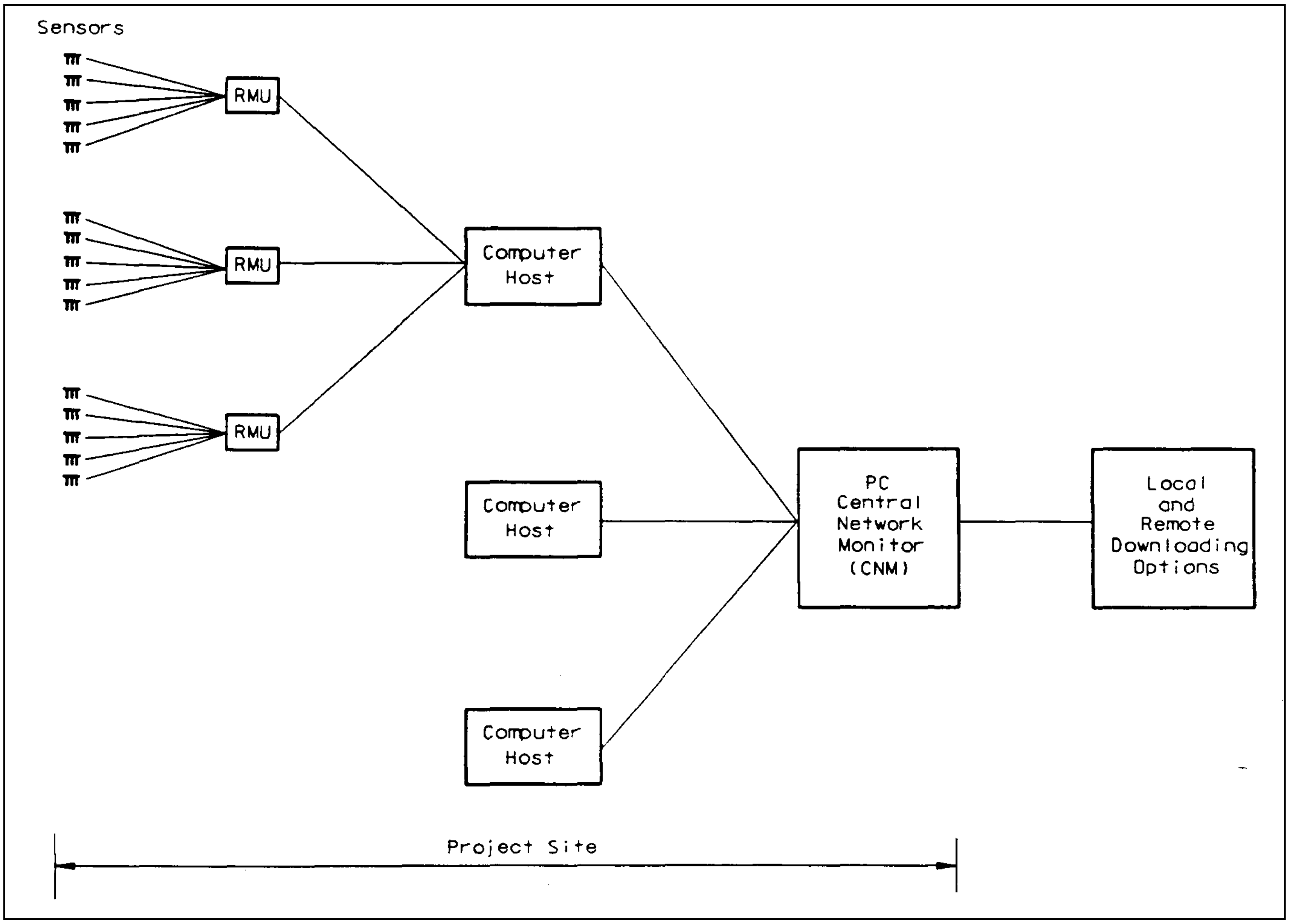

Figure 5-4. Distributed intelligence configuration

b. Automation experience. USCOLD 1993, Appendix D, is a summary of automation experience in Federal and private sectors. It lists dam projects and various features of dams that have been automated, the equipment used, the sensors installed, and persons that can be contacted for each of the projects listed. This document is valuable to designers that are interested in learning about the performance of systems that they are considering. Contacts with those persons listed should be an early step in the planning process to identify the feasibility of proceeding with the project and the appropriate direction.

c. Technical expertise. The majority of automation design, operation, and routine maintenance can be accomplished by conscientious geotechnical engineers, and moderate levels of computer and electronic expertise, most of which is available within the Corps installation. New automation developments and complex applications will often require a higher level of expertise which may only be available through contractor support. Lack of in-house computer and electronic expertise may also require a dependency on consultants and manufacturers to design, install, troubleshoot malfunctions, and implement corrections. Because of this contractor dependency it is highly desirable to specify a number of performance tests of all features of the system. Simultaneous manual and electronic data acquisition should also be accomplished during system performance testing. An increased level of cost will be proportional to the degree of dependency on outside expertise. This should be considered when planning and designing automated systems. Several Corps of Engineers Districts as well as WES have a significant amount of expertise in planning, design, and system operation and maintenance. Emphasis is placed on the use of in-house expertise as a priority with outside assistance (consultants, manufacturers, etc.) used as necessary.

d. Selection of instruments. If there is sufficient justification for automation (see paragraph 5-2), and preliminary assessments indicate that automation is feasible, judgment must be applied to the selection of instruments to be automated. Table 5-1 lists the methods and relative ease of automating various dam safety instruments. The following criteria should be considered when choosing instruments to be automated:

(1) Performance. Instrument performance is acceptable. Data are consistent and meaningful. Maintenance/calibration has not been excessive or ineffective.

(2) Longevity. The instrument is expected to continue to function for at least 5 years.

(3) Location. The physical location of the sensor (including the tip elevation and material type) is appropriate to monitor the feature/condition of interest.

(4) Ability to be automated. The instrument is able to be automated. Sensors are available and compatible with the current installation such that manual reading capability can be retained as backup. The new sensor will satisfactorily perform in an automated environment (response frequency, electronic conversions, communications media, etc.).

5-6. Designing an Automation System

CWGS 16740 is technical guidance for the instrument system designer. It addresses important issues that are characteristic of automated systems that demand attention, i.e., grounding techniques for lightning protection, the use of shielded cable, proper power supplies, etc. The guide specification is not a specific recipe but design and installation considerations for engineering judgment.

5-7. Implementation

Obtaining funding support for automation is often a concern. The best opportunities for implementing automation is for projects that are under construction (new projects, dam safety remedial efforts) and approved structural modifications, investigations, and research. Smaller projects may be accomplished with routine allocations of operations and maintenance (O&M) funds which are normally limited.

5-8. Data Acquisition, Management, Analysis, and Reporting

These issues are discussed in Chapter 7. That information is applicable to automated systems. In addition to that discussed, automated systems can provide large quantities of data at no additional cost. Discrete management of this volume of information is necessary to keep it from exceeding storage, to reduce time involved with communications, and to prevent it from becoming cumbersome when processing, analyzing, and reporting.

5-9. Maintenance

Utilizing data to determine the need for maintenance is discussed in Chapter 7. That approach is also applicable to automated systems. Automated systems can produce a large volume of data that are accessible on a very frequent basis. This provides greater opportunity to assess

Table 5-1
Methods and Ease of Automating Various Instruments (Adapted from USCOLD 1993) (Continued)

	Category					
Instrument[1]	1	2	3	4	Automation Method	Manual Backup
Piezometers						
Open standpipe		•			Pressure transducer down standpipe	Usually straightforward by measuring to water surface
Twin-tube hydraulic		•			Pressure transducers connected to lines	Straightforward, by existing pressure gages
Pneumatic			•		Pressure actuating and meas. system	Straightforward, with manually operated readout
Vibrating wire		•			Frequency counter	Ditto
Electrical res. strain gage		•			Strain gage, completion circuitry	Ditto
4-20 mA pressure transducer	•	•			Current readout	Ditto
Sonic		•			Time readout	Ditto
Deformation Gages						
Tiltmeter[2]	•	•			See footnote 2	Ditto
Probe extensometer				•	N/A	N/A
Embankment and borehole extensometer[2]	•	•			See footnote 2	Straightforward, with manually operated readout
Inclinometer, probe type				•	N/A	N/A
Inclinometer, in-place type[2]		•			See footnote 2	Straightforward, with manually operated readout
Plumb line and inverted pendulum[2]			•	•	Infrared or light sensor line position transducers	Ditto
Liquid level gage[2]	•	•			Pressure transducer	Ditto
Earth Pressure Cells						
Pneumatic			•		Pressure actuating and meas. system	Ditto
Electrical res. strain gage		•			Strain gage completion circuitry	Ditto
Load Cells and Strain Gages						
Electrical res. strain gage		•			Strain gage completion circuitry	Ditto
Vibrating wire		•			Frequency counter	Ditto
Hydraulic load cell		•			Pressure transducer	Ditto
Temperature						
Thermistor	•	•			Resistance readout	Ditto
Thermocouple		•			Low level voltage readout	Ditto
Resistance temperature device	•	•			Resistance readout	Ditto

There are four categories in order of increasing difficulty, specialization, and cost of automation:

CATEGORY 1: Straightforward. Category 1 can be done by numerous manufacturers of laboratory and industrial ADAS.

CATEGORY 2: More Specialized Requirements. Thermally unconditioned environments, inaccessible power, nonstandard signal conditioning, low level voltage measurement, wide common mode voltage range.

CATEGORY 3: Most Specialized Requirements. Hostile outdoor environment, hard-wire communication unavailable - radio network required, difficult sensors to automate like plumb lines and pneumatic piezometers, sensors which communicate via serial or parallel interface.

CATEGORY 4: Usually Not Practicable to Automate. Technical complexity or cost outweighs benefits, significant reliability problems in hostile environment, customized automation hardware required, impracticable to automate.

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[1] For a definition of instrument terms, see this manual and Dunnicliff (1988).
[2] Depends on type of transducer.

Table 5-1 (Concluded)

	Category					
Instrument	1	2	3	4	Automation Method	Manual Backup
Miscellaneous						
Reservoir and tailwater elevation, rainfall gage[2]	•	•			See footnote 2	Ditto
Weir for measuring water flow[2]	•	•			See footnote 2	Ditto
Seismograph analog				•	N/A	Seismographic chart record
Seismograph digital		•			N/A	Seismographic chart record

instrument performance easily and often. Additional discussion regarding calibration is in Chapter 8 and it is also applicable to automated systems. Some components can be calibrated with expertise already existing at many Corps installations; other calibrations can be accomplished with minimal training and additional equipment. Calibration of custom-developed components could require the attention of outside expertise.

a. Planning. Automation experience has indicated that maintenance can be minimized with proper planning and forethought. The following is suggested:

(1) Determine the person(s) responsible and the means of accomplishing the maintenance as early as the planning and design phases of the project.

(2) Obtain clear, simple documentation, O&M manuals, as-installed drawings, and electronic schematics from the contractor and/or manufacturer.

(3) Involve the operation and maintenance personnel in the planning and design phases as well as during the installation and acceptance phases.

(4) Use the component concept to facilitate changing malfunctioning devices with spares and/or replacement parts as necessary. Use equipment that has standard connectors, parts, and operating procedures to assure compatibility with a variety of manufacturers of similar components.

(5) Obtain manufacturer-recommended spare parts with the initial system. Revise the inventory as consumption rate is learned.

(6) Train the maintenance staff and system operators. Retrain them as personnel turnover and/or system changes necessitate.

(7) Learn the performance characteristics that are unique to the system and utilize the remote diagnostics.

(8) Use project blanket purchase agreements (bpa's) or other existing mechanism for components already being maintained on site (radios, personal computers, telephones, etc.)

(9) Take advantage of warranties. Check the performance of all features of the system before the warranty period expires. Remote calibration, diagnostics, reprogramming, and troubleshooting are examples of system features that may be rarely or infrequently used. Unsatisfactory performance of such features may escape warranty attention if not checked.

b. Implementation. Indefinite delivery contracts and maintenance agreements with manufacturers are the most expensive means of maintaining systems and they tend to remove the system users from thoroughly understanding the system.

Chapter 6
Installation

6-1. Introduction

Installation of geotechnical instrumentation, whether during construction of a project or in an existing structure, requires special attention to detail. Faulty installation of instruments not only can lead to erroneous and misleading performance data, but could also affect the integrity of a structure. Methods of installation are dependent on the parameters to be monitored, site conditions, and selected instruments. Therefore, qualified, experienced, and competent personnel are essential if an installation is to be successful. An installation of an instrumentation system is not considered routine; therefore this chapter includes guidelines and recommendations rather than step-by-step procedures.

6-2. Personnel Issues

The purpose of geotechnical instrumentation is to provide accurate and timely data so that performance evaluations of a project can be made by personnel responsible for safety of an embankment dam or levee. The quality and accuracy of the evaluations are highly dependent on proper instrumentation installation. In addition, District and project personnel will be responsible for the maintenance of the instrumentation system (see Chapter 8). Therefore it is highly recommended that in-house personnel perform as much of the actual installation as possible, and that the design and installation of an instrumentation system be the responsibility of the instrumentation program manager (see Chapter 3).

6-3. Contracting Issues

Although in-house expertise is preferred, contracting may be necessary. Work such as trenching, conduit installation, and other site work can be performed by general construction contractors. Drilling contractors require close supervision by a geotechnical engineer during installation. However, a great deal of the work requires an instrumentation specialist (who will usually be the instrumentation program manager) who is familiar with the particular instruments and has a good working knowledge of geotechnical engineering and the local site conditions. If a contractor is to be responsible for the installation of an instrumentation system, the specifications should include the following items:

- Purpose of the geotechnical instrumentation program.
- Responsibilities of the contractor.
- Instrumentation system performance criteria.
- Qualifications of contractor’s instrumentation personnel.
- Quality assurance.
- Submittals.
- Scheduling work.
- Storage of instruments.
- Materials (provide a detailed description of all types of instruments included in the contract).
- Factory calibration requirements.
- Pre-installation acceptance tests.
- Installation instructions (provide a detailed step-by-step procedure for the installation of each type of instrument included in the contract).
- Instructions for changed site conditions.
- Field calibration and maintenance requirements.
- Protection of instruments.

6-4. Instrumentation of New Structures

Various options exist when planning installation of an instrumentation system in a new structure. Instrument casing can be installed upward in the embankment as the fill rises. However, it is generally not advisable to extend the casing vertically through the core material of an embankment. Horizontal runs of tubes and cables must not extend horizontally fully through the core (see Figure 6-1d) and must exit the downstream face of the embankment. Vertical runs of tubes and cables can run upward through any zone of the embankment except the core. The installation of vertical runs of tubes and wires through the core of an embankment is not acceptable and must be avoided. Obtaining adequate compaction, due to difficult access around the casing, is very difficult, resulting in the creation of a poorly compacted zone. An alternative to installing an instrument which requires casing is to use an instrument which requires tubes or cables. In addition, the inclusion of instrumentation in an

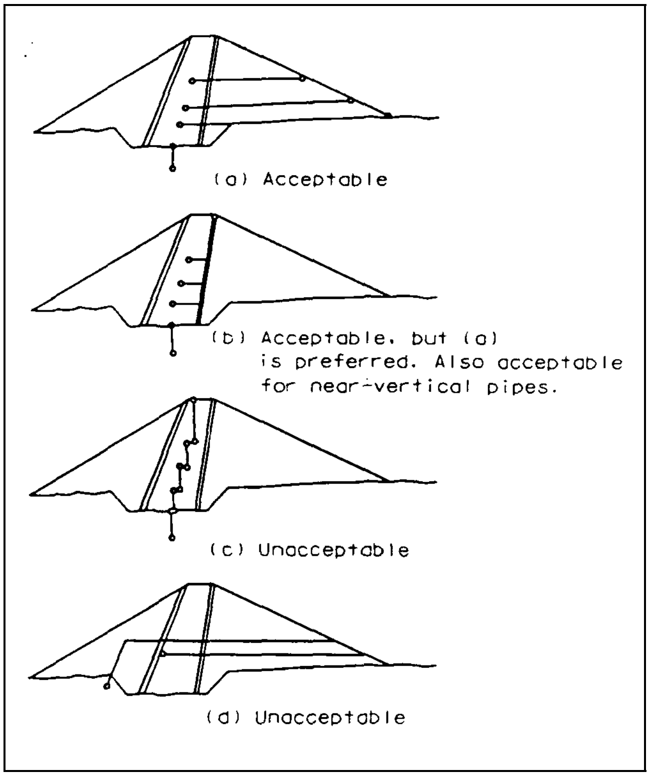

Figure 6-1. Examples of acceptable and unacceptable routings for instrumentation tubes and cables (after Dunnicliff 1988)

embankment construction will, almost inevitably, cause delays and require a general contractor to pay special attention to details and provide protection when working around an instrument that is being installed. Scheduling of cable installation must be coordinated with other activities to avoid damage to cables by construction equipment. Instruments should be sufficiently protected and located with highly visible survey stakes and flagging.

6-5. Instrumentation of Existing Structures

Surface installations, retrofits, or replacements of nonembedded sensors do not generally create installation difficulties. However, drilling may be the only option available when the installation or replacement of a subsurface instrument is necessary in an existing structure. Great care must be taken when selecting a drilling method to be used in an existing embankment. Water or air pressure used during drilling of a borehole can damage the embankment by hydrofracturing. A hydrofracture is a crack, shear plane, seepage path, and/or other detrimental condition that can develop during the drilling process. Impervious cores are especially susceptible to damage and extreme care must be used in drilling in these zones. For this reason, the practice of drilling in embankments or foundations using air (including air with foam) is prohibited per ER 1110-2-1807. A summary of drilling methods is included in Appendix B.

6-6. Drilling Fluids

There are two purposes for using drilling fluids when performing a boring: first, to have a medium through which the drill cuttings are moved from the cutting head at the bottom of the boring to the top; second, to stabilize the sidewalls of the boring from collapse. The viscosity of the drilling fluid can be thickened as necessary to prevent collapse. The drilling fluid adheres to the sidewalls and creates a residual skim coat. The standard bentonite mud is an unacceptable drilling fluid for piezometers because it seals the soil and inhibits piezometric response. Biodegradable mud composed of an organic polymer is acceptable as a drilling fluid because it reverts back to water through enzyme breakdown, leaving no residue. The selection of a drilling fluid must be made with the compatibility of the installed instrument in mind. If there is any possibility of collapse of the walls of the boring, drilling fluid should not be used. Casing is often the preferred method for support.

6-7. General Installation Procedures

Instruments are often installed in boreholes located in either abutments or embankments. Many of the instruments installed in boreholes have minimum and maximum diameter requirements. Drilling specifications should clearly spell out required diameters, depths, alignments, drilling and sampling requirements, instrument requirements, construction details, and special requirements. The information provided below is suggested guidance for instrumentation installation. Each system to be installed should be evaluated on a case-by-case basis. It is the responsibility of the instrumentation program manager or geotechnical engineer to write detailed procedures for the installation of an instrument. When deformations are expected to occur, special considerations are often required so that pipes, tubes, and wires are not damaged as deformation occurs.

a. Planning. Prior to the actual installation of the instrumentation, time should be invested in planning the installation. Planning includes preparation of site-specific detailed step-by-step installation procedures and of a list of required materials and installation tools, preparation of an installation schedule, and coordination of installation with other parties. Additionally, the lead time necessary for the procurement of the instruments should be investigated. Many instruments are manufactured when ordered, and large orders may require significant lead time before delivery to the site. Installation of instrumentation may require support from utility companies (electricity or telephone) which may require long lead time before service is available. Possible road closures while cables cross routes of access may be necessary. The routes which will be used for pulling instrument cables through conduits should be decided. Other ongoing operations or construction activities may impact on the planning of an installation. The necessity for automation (see Chapter 5) must have previously been addressed, since cable runs may change to match hardware limitations and using radio for communication may be less expensive than hardwire options.

b. Pre-installation acceptance tests. When the instruments are received at the site, instrumentation personnel should perform pre-installation acceptance tests to ensure that the instruments and readout units are functioning properly. Where electrical components are irretrievable and must function below the water table, consideration must be given to pressure-testing of instruments for leaks. Pre-installation acceptance tests should include relevant items from the following list:

- Examine factory calibration data to verify completeness (factory calibration and documentation should be specified).
- Examine manufacturer's quality assurance inspection check list to verify completeness (quality assurance procedures and documentation should be specified).
- Check cable length.
- Check tag numbers on instrument and cable.
- Check, by comparing with procurement documents, that the model, dimensions, materials, product performance criteria, etc. are correct.
- Bend cable back and forth at point of connection to the instrument while reading the instrument to verify connection integrity.
- Check water pressure or humidity test components as appropriate for the service entity to identify leaks.
- Verify that instrument reading as required compares favorably with factory reading.
- Perform resistance and insulation testing, in accordance with criteria provided by the instrument manufacturer.
- Verify that all components fit together in the correct configuration.
- Check all components for signs of damage in transit.
- Check that quantities received correspond to quantities ordered.

Results of the tests should be documented and include the following items:

- Project name.
- Instrument type and number.
- Identification of any testing or readout equipment used during testing.
- Personnel responsible for testing.
- Date and time of testing.
- Measurement and observations made during testing, as listed above.
- Test results, pass or fail.

c. Installation documentation. In addition to recording pre-installation information, a record of installation should be documented and include the following items:

- Project name.
- Contract name and number.
- Instrument type and number, including readout unit.
- Planned location, orientation, depth, length, and backfill volume data.
- Personnel responsible for installation.
- Plant and equipment used, including diameter and depth of any drill casings or augers used.
- Method of trenching and backfilling.

- Date and time of start and completion.
- Measurements or readings required during installation to ensure that all previous steps have been followed correctly.
- A log of subsurface data indicating the elevations of strata changes encountered in the borehole.
- A determination if the strata at the transducer location was or was not that anticipated in the instrumentation plan.
- Type of backfill used.
- As-built location, orientation, depth, length, and backfill volume data.
- Three-dimension schematic of utility runs to instrument, locating all junction boxes (buried and surface access).
- Results of post-installation acceptance test (see below).
- Weather conditions at the time of installation.
- Miscellaneous notes, including problems encountered, delays, unusual features of the installation, and details of any events that may have a bearing on instrument behavior.

d. Post-installation acceptance test. Upon completion of the instrument installation, installation personnel should demonstrate that the instrument was correctly installed and is functioning properly. The details of the test will depend on the type of instrument, and all possible quality checks should be made. A series of readings should be made (minimum of three) during a short span of time to demonstrate that the instrument reading can be repeated. The installation may have an effect on the parameter which is to be measured and the instrument should be allowed to stabilize and the acceptance test repeated. The details of the test should be included with the installation report.

e. Care and handling. To ensure satisfactory performance of an instrument, it should be protected from the elements prior to installation. The manufacturers will usually describe conditions which are unsuitable for their devices. All instruments should be kept free from dirt and dust. Some instruments or their cables degrade in direct sunlight. Some instruments are sensitive to electric or magnetic fields. Others should be protected from extreme temperatures, humidity, water, shock, and/or chemical precipitates. All instruments should be handled carefully. Cables and tubes should be protected from nicking, bending, and kinking.

6-8. Installation Procedures for Piezometers in Boreholes

Installation of a piezometer in a borehole is not a routine process. Many factors must be considered if the piezometer is to function properly.

a. Example of detailed issues when planning installation. As an example of the thought process that is necessary when preparing detailed installation procedures, the following questions should be answered when selecting a method for installing a piezometer in a borehole in soil: (adapted from Dunnicliff 1988)

(1) What are the soil types?

(2) Is sufficient lead time necessary for procuring special piezometers?

(3) Are there artesian conditions?

(4) Are there excess pore water pressures?

(5) What drilling methods are available?

(6) What skill/care/experience is available among personnel who will be responsible for installations?

(7) How much vertical compression will occur in the soil above the instrument?

(8) Are soil samples required?

(9) How can the borehole be supported?

(10) How much time is available between completion of installation and the need to establish zero readings?

(11) What are the requirements of response time?

(12) What borehole diameter will be used?

(13) How will the casing or augers be prepared, cleaned, backfilled, and/or pulled?

(14) Is a sounding hammer required?

(15) What type of bentonite will be used?

(16) What is the required waiting time for swell?

(17) Is a swelling retardant needed? If yes, what method will be used?

(18) Where will the seals be located?

(19) What will be the required depths of the seals?

(20) Will centralizers be required?

(21) Which method of installation is most appropriate?

b. Selection and placement of sand filters. The filter material to be placed around an open standpipe piezometer must be designed to meet filter criteria with respect to the screen and to the gradation of the soil layer in which it is being installed. Filter material for all types of piezometers should be generally clean from fines and not restrict the response of the instrument. Filter material can be placed by pouring the material in the top of the boring or tremied into place. If the material is poured from the top, it should be saturated with water and poured slowly to avoid bridging in the annular cavity of the boring. If the tremie method is used, water should be used to flush the material through the tremie pipe. The tremie pipe is gradually raised as the material builds up in the hole. A sounding hammer (Dunnicliff 1988) should be used to verify depths of placement.

c. Selection and placement of seals. Seals are needed above (and below if necessary) filter zones to ensure that representative readings are collected from single soil stratum. The seal should be constructed of bentonite. A method of compressing slightly moist bentonite into pellets was developed in the Sixties. However, the pellets bridge easily within the casing if they are poured through fluid. Bentonite now exists in the form of angular gravel. This is usually a pit-run graded material, which does not start to hydrate and swell as quickly as compressed bentonite pellets, and if poured slowly, falls to the bottom of the borehole without bridging. If a soil stratum is to be sealed off below the location of a piezometer, great care must be taken with the bentonite to avoid making contact against the sidewalls at the location of the sand filter by using casing. Installation of the bentonite in powdered or slurry form should not be allowed as these methods will coat the casing on the way down and possibly foul the filter below.

d. Multiple-stage piezometers. Multiple-stage piezometers (more than one piezometer in a borehole) are generally not recommended due to the possibility of vertical flow of water between sealed zones. If multiple-stage piezometers are necessary, extreme care must be taken when installing the bentonite seals and the number of stages should be limited to two.

e. Lengths of screens in embankments. Screens are normally minimal in length and situated in aquifers in order to measure the actual pore pressure. In an embankment, the magnitude of pore pressure may be less important than noticing that changes are occurring over the long-term life of a project. If these conditions exist, it may be necessary to install screens of much greater lengths, as indicators of changing conditions.

6-9. Installation Procedures for Other Instruments

Many of the same or similar questions must be answered (see paragraph 6-8*a*) when developing installation procedures for other types of instruments. Manufacturers of inclinometers and borehole extensometers normally supply good instructions for the installation of the downhole components. However, care must always be taken since variable site conditions might alter these procedures. Additional information can be found in Dunnicliff (1988).

6-10. Backfilling Boreholes

Various materials may be used to backfill a borehole. Grout, granular fills such as sand and pea gravel, and bentonite gravel may be used. Grout has the advantage that it readily fills all the void spaces. However, grout should not be used if it will bleed off into the surrounding ground, and in this situation a pregrouting step may be appropriate. Grouting guidance is available in EM 1110-2-3506 and Driscoll (1986). Grout mixes should be tested to determine appropriate ratios of water, cement, bentonite, and sand (rarely used) that will ensure good performance between the instrument and the surrounding soil or rock.

6-11. Protective Housings

Each installed instrument must be protected with a protective housing that is provided with a vented locking cap. Protective housings should be grouted into place not only to secure the cap but also to prevent surface water from flowing into the instrument. Unfortunately, instrument housings protruding above the ground are often a target for vandals. In extreme cases or in roadways, an instrument may be flush-mounted with the surface, and surrounded with a gate box similar to those used by utility companies. The drawbacks of this method are that the boxes are hard to find with a snow covering and drainage must be considered so that surface water does not flow down the instrument.

6-12. Documentation

After completion of the installation of all instruments, the following documents should be bound and placed in a report:

- Description of instruments, readout units, and automation equipment.
- Plans and sections sufficient to show instrument numbers and locations.
- Appropriate surface and subsurface stratigraphic and geotechnical data.
- Instrument calibration and maintenance procedures.
- Instrument installation procedures.
- Instrumentation and/or automation documentation from manufacturers, including calibration data and warranty information.
- Pre-installation acceptance test documents.
- Post-installation acceptance tests.
- Instrument installation reports.
- A list of suggested spare parts needed for repair or maintenance.
- Procedures for data collection and processing.
- Names, addresses, and phone numbers of maintenance/repair sources.

It is recommended that at least two copies of the documentation be prepared. One should be maintained on file at the project site. The other should be filed in the District office.

Chapter 7
Data Management, Analysis, and Reporting

7-1. Introduction

Data management and analysis are crucial to understanding the behavior of a monitored structure, for detecting unsafe developments, and for determining the performance of the instrument systems. The major aspects of the instrumentation planning process are data management, engineering analysis, and formal reporting. A plan for the management and analysis of data should be in place before the instruments are installed. The plan should indicate the frequency of data collection, the extent and timeliness of processing, the level of analysis, the reporting requirements for in-house engineers and reviewing authorities, and the people responsible for accomplishing each of these tasks.

7-2. Data Management

The management of data consists of data collection, reduction and processing, and presentation.

a. Data collection. Data collection should begin with a well-defined established schedule. The schedule is dependent on project-specific requirements. The requirements are dependent upon instrument characteristics, site conditions, construction activity, or the occurrence of unusual events. The schedule should be updated whenever these conditions or instrument readings indicate the need. Data collection procedures should adhere to the following guidelines:

(1) Personnel consistency. Data will be most consistent if collected by the same person. If this is not possible the designated instrument reader should have a backup instrument reader who is also familiar with the instruments. Data collection personnel should read the instruments in the same manner every time.

(2) Instrument consistency. Using the same readout unit to read an instrument every time will give the most consistent readings. The readout instrument should be connected or aligned the same way for every reading. Readout units should not be interchanged, because readings can be dependent on readout unit and transducer combinations.

(3) Multiple readings. Multiple readings should be taken to the most representative value.

(4) Coordination of instrument readings. Instrumentation systems should be designed to have different types of instruments show changes under the same conditions and in the same time frame. Therefore, the instrument whose values, which need to be compared, should be read as close to the same time as possible.

(5) Data records. Instrumentation data should include the instrument reading and also any information that identifies the project, instrument, readout unit, reader, date, visual observations, climate, remarks, and any site conditions that might affect the value of the reading. All calibration checks, averaging, or median values should be shown. Data from field books or field data sheets should be transferred to data calculation sheets or data computer files and the originals filed.

(6) Data entry. Recording readings in field books allows for comparison of current readings with previous readings at the time the readings are collected. This early or initial comparison of the data aids in assuring the correctness of the readings and also allows for early detection of problems with instruments so that corrective action can be implemented without delay. The readings in field books should be transferred to data sheets or computer files as soon as possible after being obtained, to avoid losing data if the field book is lost or destroyed. The transfer should be checked for transposition errors. Field data sheets used to record field readings directly should be forms with spaces for recording all the factors necessary. Field data sheets should include previous readings for immediate comparison with current readings, or a copy of previous readings should be available for current reading comparison, as a first step in data management. Portable data acquisition recording devices are helpful in transmitting data. These devices may save time and minimize errors.

(7) Communication. Communication among personnel responsible for data collection, data processing, data reviewing, and data analysis is vital to the data acquisition process. The data collection personnel should communicate to the data review and analysis personnel all conditions that could affect the readings. The data review and analysis personnel should communicate the results of their work to the data collection personnel to indicate whether the instruments are being read correctly, if the instrument is operating correctly, if the reading schedule is adequate, etc.

(8) Warning of unusual conditions. Readings that exceed established threshold levels should be reported

immediately. Appropriate personnel should be notified when an instrumentation reading, changed condition, activity, or visual observation reveals that a problem or dangerous situation has occurred, or is occurring, and implement the steps listed in the Project Operation and Maintenance Manual, Emergency Contingency Plan. Communication and cooperation among all parties involved in data acquisition is essential, especially when problems arise.

(9) Special considerations of automated data collection. Automated data collection allows for the adjustment of the data collection frequency to capture the behavior during a significant event. For example, if an event at a project causes a rapidly fluctuating reservoir elevation, the data collection frequency should be altered to record the effect of the event. Automatically recorded readings that are beyond threshold values should be checked. This early or initial check of the data aids in ensuring the accuracy or correctness of the readings and also allows for early detection of problems with instruments so that corrective action can be implemented without delay.

b. Data reduction and processing. Data processing and reduction consists of converting the raw field data into meaningful engineering values necessary for graphical presentation, analysis, and interpretation. Several calibration constants may be needed to convert the field readings to engineering values. In the past, these conversions were performed by hand, but currently can and should be performed by computers to eliminate conversion errors. Where possible, initial and preliminary reduction and processing of instrumentation data should be accomplished in the field, where anomalous readings, errors, or malfunctioning instruments can be readily identified and/or corrected.

(1) Timeliness of data reduction and processing. Expeditious transfer of instrumentation readings from the project site to the reducing/processing/reviewing office is essential in timely data management. Facsimile machines, local computer networks, or express mail services should be used to expedite data transfer. All instrumentation data should be reduced and processed as soon as possible, preferably while the conditions under which the data were obtained still exist (e.g., reservoir stages, high velocity flows). Backlogging or stockpiling of instrumentation data for later reduction and processing prior to preparation for annual data submittal or scheduled inspections is unacceptable.

(2) Error checking. Checking for errors in instrumentation data should be accomplished at each level of collection and processing (from reading of instruments in the field to final interpretation of the instrumentation data). Checking should commence with proofreading of data values to ensure that readings have been properly recorded on field data sheets or notebooks and transcribed correctly from field data sheets or notebooks to reporting forms or summary tabulations. Instrument readings should be compared with ranges specified by the reviewing office and with previous readings under similar conditions. Conformance with previously established trends should be determined. Anomalous readings should be identified and checked as necessary. Data sheets should reflect the anomalous readings and possible causes of such readings.

(3) Reduction and processing methods. Simple computer programs should be used to expedite data reduction. Careful proofreading of input values is recommended, and a standardized input format should be used. Programs which are used to reduce instrumentation data should be carefully tested and verified by the user to ensure that they are operating correctly throughout the expected range of instrument values. These computer programs range from simple programs which perform only data reduction calculations to complex databases designed for data reduction of many different types of instruments. The more complex databases can be used for data storage on electronic media, production of plotted data, some preliminary analyses, and maintaining history files of instrument readings. It is recommended that computer programs be used for data reduction, data storage, and graphical plots. Regardless of the computer program used, periodic manual checking of data calculations and results by knowledgeable instrumentation personnel is essential. As with any computer system, a procedure or time frame for backing-up the data is an essential step in data processing. A relational database, such as the Instrumentation Database Package developed by the Corps of Engineers, is helpful in all phases of data management.

c. Data presentation. Numerically tabulated data are not conducive to detecting trends, evaluating unanticipated behavior, and comparison with design values. Plots of the data are needed to provide visual comparisons between actual and predicted behavior, a visual means to detect data acquisition errors, to determine trends or cyclic effects, to compare behavior with other instruments, to predict future behavior, and to determine instrumentation maintenance requirement needs. Plotting enables data to be compared readily with events that cause changes in the data, such as construction activities and environmental changes. Plotting also provides a visual means to evaluate unanticipated behavior, and to determine the effectiveness of remedial correction.

(1) Types of plots. Several types of plots can aid in evaluating various project conditions. Some examples are given below.

(a) Time history plot. Time history plots display time versus the change in parameter (see Figure 7-1). Parameters such as water level, seepage, pore water pressure, deformation, and temperature can be plotted against time. Dual Y-axis time history plots allow the plotting of a second parameter, such as pool, tailwater, or rainfall, with the first parameter.

(b) Positional plot. Positional plots show a change in parameter (water level, temperature, deflection, etc.) versus the position of an instrument (see Figure 7-2). These positions can be shown as cross section, X-Y coordinate, station, offset or depth. An example of a positional plot is an inclinometer plot as shown in Figure 7-2. This type of inclinometer plot shows horizontal deformation versus depth and changes with time.

(c) Other plots. Multiple plots and plotting of multiple parameters is possible. An example is Figure 7-3. Plotting multiple parameters can be useful in examining questionable conditions.

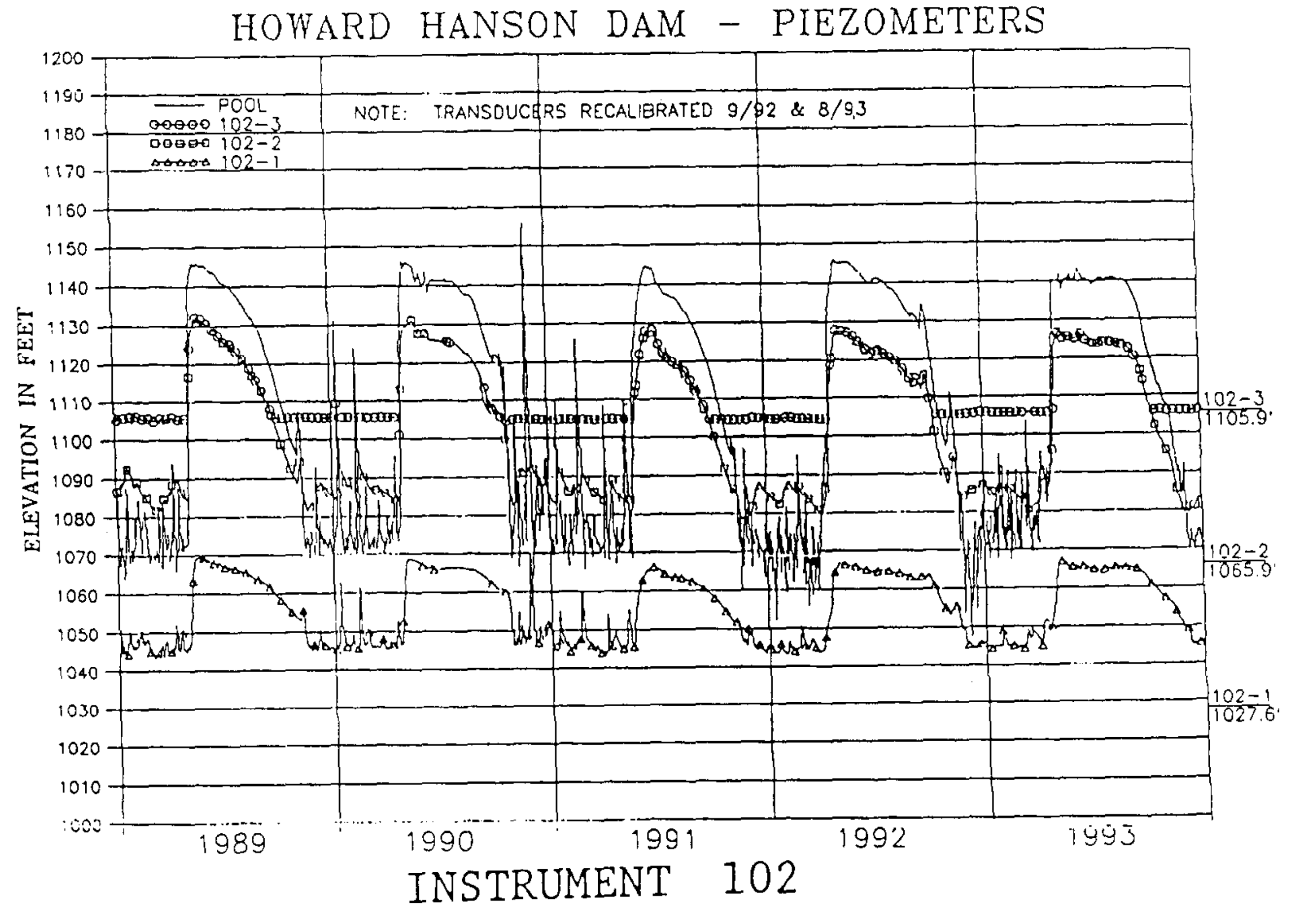

Figure 7-1. Example of a time history plot

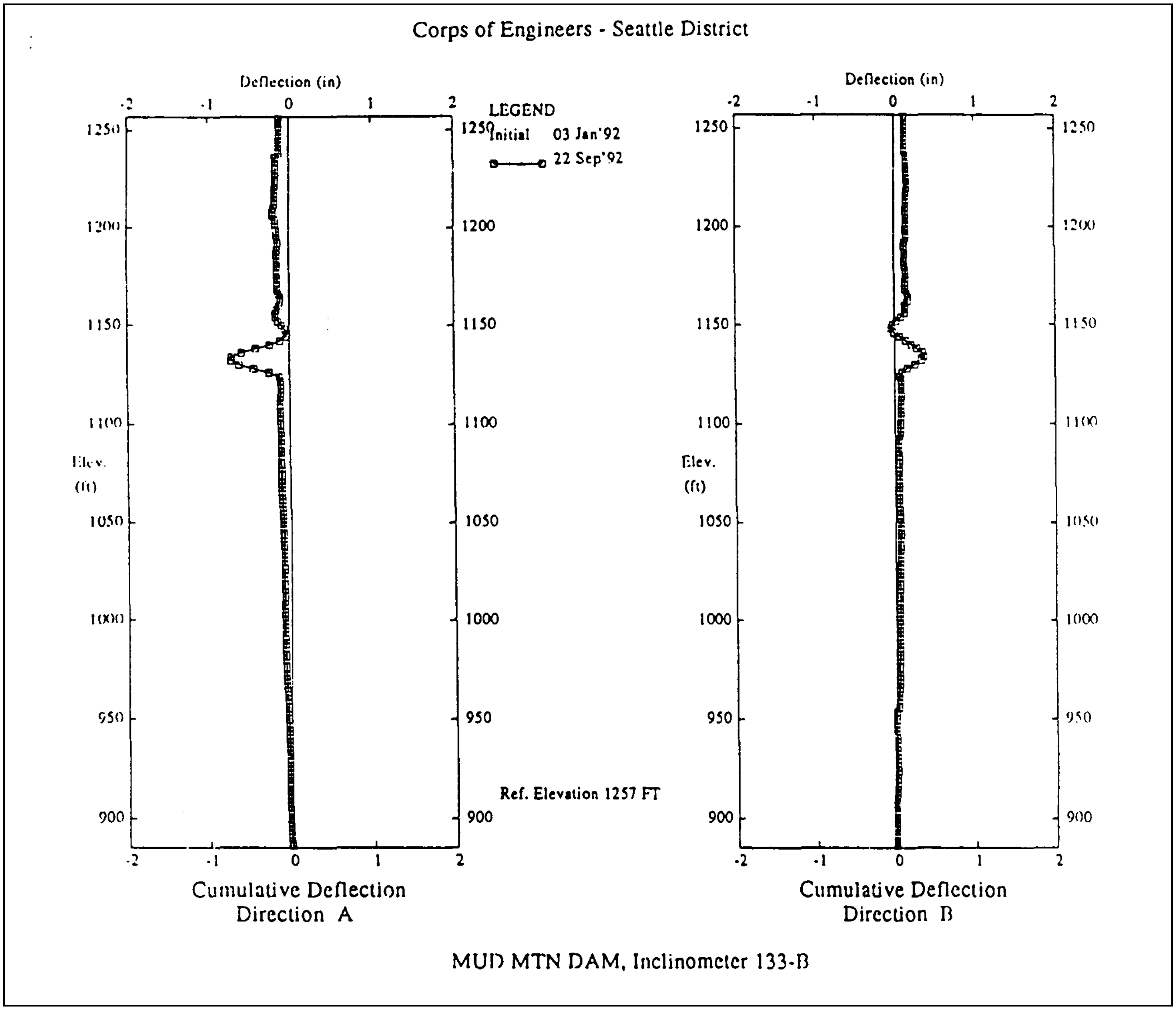

Figure 7-2. Example of a positional plot

(2) Guidelines for plotting. Some guidelines for plotting follow:

(a) Appropriate scale should be chosen for the analysis. Determination of minute changes requires a scale of small increments. Scales with increments so large that they would not show the data trends should not be used. Exaggerated scales that would magnify minor changes to make them appear alarmingly large should not be used.

(b) Standardize the graph formats and scales for all the projects or features as much as possible to minimize confusion and effort of interpretation.

(c) Location and cross-sectional sketches should be included on the graph to orient the reader to the subject area.

(d) Multiple graphs should be used to explain a situation by showing related conditions.

(e) If appropriate, the predicted behavior and/or limits of safety values should be shown along with the actual monitored behavior.

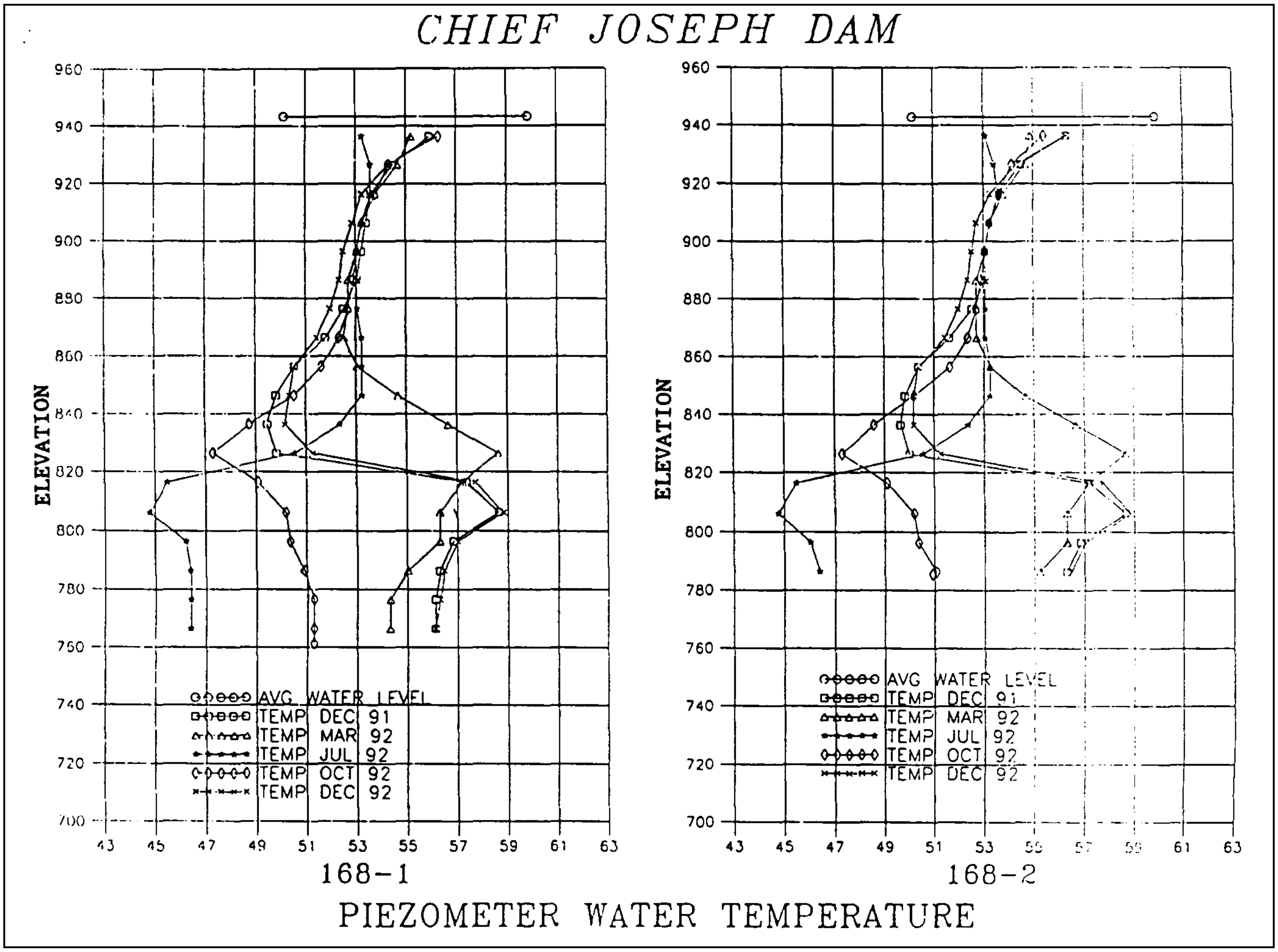

Figure 7-3. Example of a multiple parameter plot

(f) Significant influences of the measurements should be noted (i.e., construction activities, reservoir level on piezometer level plots, temperature on expansion/contraction plots).

7-3. Engineering Analysis

Data analysis is the interpretation and evaluation of the data as affected by various conditions. It is a continuous process from data collection through reporting. At every step of the analysis, the evaluator should be conscious of the potential for invalid data and the improper use of the calculations, so that incorrect interpretations are not made. Proper analysis will address two basic aspects of dam safety monitoring: the performance of the instrument system, and the performance of the structure or feature that is being monitored.

a. *Timeliness of data.* The field reading should be compared to the previous data set as it is recorded in the field. Data should be entered into the computer by electronic transfer or immediately upon returning to the office. The computer should have an automatic check to determine the significance of value variations upon entry. Questionable results of either of these two procedures should be brought to the immediate attention of the instrumentation program manager. Reduced data in plot format should be immediately reviewed upon completion of processing. In-depth analyses should be accomplished commensurate with the degree of concern associated with the monitored feature. Reduced data should be provided to other involved offices (hydraulics, structures, operations, etc.) as appropriate. Under normal circumstances with conscientious attention by qualified personnel, significant dam safety concerns can be detected within hours;

valid and meaningful information and preliminary analyses can be made available within one day, two days maximum. The severity of the situation can accelerate the assessment.

b. Analysis techniques. An analytical technique can be considered the viewing of the current information in the context of past experience. It should also consider the predicted behavior of the monitored feature. The review and analysis personnel should consider the following techniques when analyzing the data.

(1) Compare current data with the most recent data set to detect anomalies, discernible short-term behavioral changes, and instrument malfunctions.

(2) Compare the current data point with historical performance over a significant period of time to ascertain consistency of instrument performance for the monitored feature. This can also indicate compliance of the new information with an established trend.

(3) Compare current data point with the initial reading for that point to determine the magnitude of change over time. This can indicate instrument drift or fundamental characteristic behavior of the structure.

(4) Compare trends of behavior over time with trends predicted during design, with values relating to calculated factors of safety, and/or with any other predicted behavior. Note that the historic behavior of a structure becomes the base for comparison of future behavior and the performance predicted during design becomes less relevant.

(5) Compare the results of one instrument system with those of complementary systems to confirm or deny an implied physical change (e.g., consolidation settlements with dissipation of pore water pressure, pore water pressures with functioning of drains).

(6) Use statistical analyses to assess the performance of instruments. Automated systems can acquire a large quantity of data which is conducive to calculating standard deviations and variance of instrument response. This is also helpful in determining calibration frequency.

c. Outcome of data analysis. There are many outcomes of data analysis. The appropriate personnel should consider the following:

(1) Determine when to test, calibrate, or abandon instruments.

(2) Determine if the schedule of observation should be altered.

(3) Reevaluate which areas of the project require priority attention.

(4) Determine the need for further study (slope stability, seepage, and other structural performance analysis).

(5) Confirm or refute previous studies.

(6) Prepare the processed data for formal presentation and develop the engineering position that will be reported.

d. Pitfalls to avoid. The following are some data pitfalls to avoid:

(1) Lack of data comparison in the field resulting in invalid data.

(2) Delaying data entry, analysis of processed data, and the dissemination of information to involved offices.

(3) Assuming data are valid and calculations were executed properly. Software calculation and calibration factors should be periodically checked.

(4) Assuming that change in data is reason for concern. Instrument may be appropriately responding to a condition.

(5) Assuming no change is satisfactory. Instrument may not be operating.

(6) Failing to recognize or incorporate all factors that influence the data (e.g., seasonal temperature changes affecting structural movement, temperature, rainfall, reservoir level values).

(7) Assuming contour plots are accurate. Those plots developed by automation or computer software should not be used without a careful review by an experienced geotechnical engineer or geologist who should be thoroughly familiar with the software.

7-4. Formal Reporting and Documentation

Formal presentation of data may be quite different than the plotting prepared for data analysis. Formal presentations summarize and present data to show trends, enable comparison of predicted design behavior with actual behavior, document key aspects of the instrumentation monitoring program, and identify necessary remedial measures. Reporting requirements are contained in a variety of regulations and formal reporting guidance. As the reporter complies with these regulations, consideration should be given to the following:

a. Choose the aspect of performance that is to be portrayed.

b. Identify all conditions and information that significantly enhance the portrayal.

c. Group instruments that are pertinent (e.g., cross section of foundation piezometers only) to relate to cutoff effectiveness.

d. Refrain from using formal reports to serve as a depository for permanent filing of all data ever acquired. The focus should be on reporting the condition that is monitored.

e. Scales for the data presentation used for analysis (see 7-2*c*(2)) may show detailed changes over a short period of time. Detailed changes over a short period of time may be desirable for analytical purposes. However, formally reported assessment of the same information may show an acceptable trend in the long-term which would require a different scale. Scales for analysis may be chosen for seeing, but the final reported assessment of the behavior may be insignificant change and in compliance with an accepted behavioral trend in the long term.

f. Focus on clarity and significance of information on plots.

g. The text of the report should discuss changes, and identify trends and rate of change with time. Specific values should be stated in units that are meaningful and understandable. A specific statement should be made with regard to the engineering judgment of the situation, the acceptability of the condition, and the intentions for followup.

h. Guidelines for plotting in paragraph 7-2*c* are also relevant for formal reporting.

Chapter 8
Instrumentation Maintenance

8-1. Introduction

Proper design and installation of instruments provides a reliable and functional system. With usage and the passage of time the instrumentation system must be maintained to continue its reliable and useful function. This chapter deals with maintenance including recalibration of instrumentation systems during service life. Maintenance and recalibration of general instrument types and most commonly used instruments are discussed. The basic maintenance and recalibration concepts discussed for these types of instruments can be applied to all other types of instruments.

8-2. Importance of Maintenance and Recalibration

Careful attention to factory calibration, pre-installation acceptance tests, installation, and post-installation acceptance tests should ensure that instrumentation systems are operationally satisfactory to monitor the performance of the dam or levee. However, to ensure that the systems remain in a satisfactory operating condition during their service life, regular maintenance and recalibration are necessary. Lack of regular maintenance and recalibration will result in invalid data which can lead to incorrect conclusions. Lack of maintenance will also jeopardize the functioning of the system, and risk the loss of individual instruments, which in many cases cannot be replaced.

a. General concepts. Maintenance is the responsibility of the owning agency. The agency's maintenance requirements and procedures should be planned during the design of the instrumentation system and outlined in the project Operation and Maintenance (O&M) Manual. Planning for maintenance and recalibration is discussed in Chapter 3. Although it may not be practicable to develop a project-specific maintenance manual because of cost, the O&M Manual should include as many guidelines as possible, and should include the instrument manufacturer's instruction manuals. Maintenance procedures should be based on the manufacturer's instruction manual and on the project-specific site conditions, and include such needs as preventative maintenance program schedules, troubleshooting, cleaning, drying, lubricating, battery servicing, disassembly, and repair and replacement instructions for each type of instrument.

b. Maintenance contracts. Maintenance and recalibration are best accomplished by the owning agency's personnel, and the first option should be to use District personnel before contracting out services. However, instrumentation systems and components usually have limited warranty periods, and a maintenance contract with the manufacturer could be a wise investment. Government contracting procedures, specifications, and guidance should be followed for any contractual agreements. Any contractual agreements for regular maintenance and recalibration should define scope of work, requirements, procedures, schedules, contractor qualifications, experience, and personnel qualifications and experience.

c. Personnel responsible for maintenance and recalibration. Personnel should be reliable, dedicated, and motivated people who will pay attention to detail. They should have a background in the fundamentals of geotechnical engineering and have mechanical and electrical ability. They should be able to understand how the dam or levee functions and how the instruments function. The maintenance and recalibration checks of an instrumentation system during service life are best supervised by or accomplished by the data collection personnel, who are in the position to notice potential problems and to observe malfunctions, deterioration, or damage. Qualifications for data collection personnel are discussed in Chapter 3. They should be trained to perform scheduled preventative maintenance and to initiate corrective action, repair, or replacement without delay. Their training should also include all personal safety training required for conditions, equipment, and materials related to the performance of their duties. If maintenance, recalibration checks, or corrective action are not routine or are beyond the capability of data collection personnel, the data collection personnel should communicate this to the office responsible for inspection and analysis, so that arrangements can be made for action to be taken by the instrumentation program manager.

d. Service history. A service history record of maintenance, recalibration, repair, and replacement of the components of the system should be kept and communicated to the personnel responsible for analysis. The record should include dates, observations, what the problems were, what was done, how it was accomplished, who was involved, and anything else that will help to understand or interpret the instrumentation data. A service history establishes the general behavior that is characteristic of the system and suggests what frequency of maintenance is needed. The service history also facilitates the transfer of responsibility due to turnover in personnel.

e. Spare parts. Appropriate spare parts and interchangeable components should be available for replacing failed or questionable components without interrupting system operation during service life. An inventory of spare parts and instruments should be available and revised as necessary. Spare readout units should also be available in case of malfunction of primary readout units.

8-3. Recalibration During Service Life

After instruments are in service, they will require regular recalibration to maintain proper operational characteristics. However, some instruments such as an embedded transducer cannot be recalibrated. As a general rule recalibration should be performed on a well-defined schedule. Formal schedules and reporting requirements for routine recalibration are necessary to ensure that the readings obtained are reliable. Routine recalibration of instrumentation system components is best performed by personnel responsible for data collection, and coordinated with the data analyses personnel. Instrumentation data will have to be interpreted for indications that recalibration is needed. The data should be watched for abrupt reading changes for no apparent reason. If the data are showing a long-term change, it should be verified whether or not the change is actual or is due to a malfunctioning instrument, which may need to be recalibrated. Procedures for recalibration during service life should be included in the O&M Manual. Components of most instrumentation systems can be classified into three groups: portable readout units, retrievable components at field terminals, and embedded components. Maintenance of these three components are discussed below. Other instruments that do not fit into the three-component classification are discussed later in this chapter.

a. Portable readout units. Portable readout units generally are vulnerable to mishandling and subject to calibration changes. Some readout units can be checked and recalibrated by following procedures provided by the manufacturers. If they cannot be checked in this way, they should be sent to the manufacturer for calibration, adjustment, or repair. Local commercial calibration companies that use equipment traceable to the National Institute of Standards and Technology are also capable of calibrating many types of portable readout units. Frequent field calibration checks can be accomplished on some portable readout units; for example, inclinometer probes can be checked by examining repeatability at the bottom immovable length of an installed inclinometer casing.

b. Retrievable components. Retrievable components are components that are mounted to a field terminal that can be removed for recalibration or replacement. For this reason, components should be mounted in the field terminal with shutoff valves or disconnect plugs in such a way as to allow for easy removal and replacement. Some components can be recalibrated without removal by using standard recalibration equipment located in or brought to the field terminal.

c. Embedded components. Embedded components are those that are buried or installed so that they are normally inaccessible. Many of these embedded components cannot be recalibrated because of their inaccessibility. For those that can be recalibrated, standard procedures should be developed for recalibrating the instrument types in question. To develop standard procedures, contact the manufacturers or other personnel with experience (see USCOLD 1993). Embedded components that can be recalibrated should be included in a routine recalibration schedule.

d. Calibration equipment. Calibration test equipment should be traceable to the National Institute of Standards and Technology. Test equipment used to recalibrate components of an instrumentation system must be maintained in good working order so that recalibration of the components can be made with accuracy.

e. Recalibration frequency. The recalibration frequency should depend on the type of instrument, the application of the instrument, and the operating environment. Some instruments require recalibration checks frequently during each day of readings, others require recalibration checks daily, weekly, monthly, or yearly. As a general rule, recalibrations should be made on a frequent schedule rather than an infrequent schedule. A more frequent schedule will allow data collection personnel to find any changes in calibration sooner, so that a minimum amount of erroneous data will be collected, processed, and reviewed before the instrument is recalibrated. A more frequent schedule could also aid in finding a malfunctioning instrument before it is damaged.

8-4. Maintenance During Service Life

a. Portable readout units. Portable readout units should be protected from mishandling, and be kept clean and dry. Attention should be given to all connection ports, O-rings, seals, accessory wires, and plug-in connectors. Protective plugs and caps should be in place when instruments are not being read, to protect the connectors and to keep them clean and dry. If protective plugs and caps are not provided by the manufacturer, they should be added to the instrument. Preferably, the plugs and caps should be attached to the units to avoid loss, and to make them easy for data collection personnel to use. All moving parts should be checked for tightness, damage or wear; worn or damaged parts should be replaced. Cables should be checked for damage to the outer coating and any cable markings. If there is moisture present in the readout unit, it should be removed by drying. Many units are supplied with desiccant that changes color when moisture is present. Batteries should be replaced as needed. Nickel-cadmium (nicad) batteries and lead-acid batteries are rechargeable batteries that require two different recharging procedures. The manufacturers' instructions for checking, maintaining, and recharging batteries should be followed.

b. Retrievable components. Retrievable components such as in-place inclinometers, electrical transducers, and thermistors can be installed as retrievable instruments so that they can be removed for maintenance and recalibration, and reinstalled or replaced. Protective barricades and protective enclosures should be maintained in good condition. Retrievable components, any wires, tubes, cables, and their enclosures should be kept clean, dry, and protected from rodents, vandals, and transient voltage surges. All plugs, caps, and covers should be maintained in good order and used properly. Maintenance inspections of the retrievable components and their protective structures should include inspections of wires, cables, tubes, etc. where they exit from the ground or structure. These areas are vulnerable to damage by accidents, weather, vandals, etc. When retrievable components are to be removed, observations of the existing installation and physical conditions should be noted. The instrument should be read before removal and after reinstallation. Any maintenance, recalibration, or replacement should be documented and communicated to the data management, reporting, and plotting personnel. Recommended follow-up checks and readings should be made to verify success of maintenance and to validate readings.

c. Embedded components. Embedded components are normally inaccessible and maintenance is not possible. However, there are various embedded components that require maintenance. Inclinometer casings, open standpipes, and relief wells can be inspected by downhole video cameras to determine if maintenance is required. Chemical analysis of water samples taken from these types of embedded components can be used to determine what maintenance treatment procedures are required for bacterial or chemical contamination.

d. Maintenance frequency. Maintenance should be preformed on a regular schedule and in accordance with procedures in the project O&M Manual or the manufacturer's instructions. Maintenance frequency should depend on the type of instrument, the application of the instrument, and the operating environment. A more frequent maintenance schedule may allow data collection personnel to find a malfunctioning instrument before it is damaged.

8-5. Instruments Requiring Specific Maintenance

Instruments that require more than the basic maintenance for portable readout units, retrievable components, or embedded components are discussed below.

a. Twin-tube hydraulic piezometers.

(1) To determine if maintenance is required for twin-tube hydraulic piezometers, the data collection personnel should compare current readings with previous readings to observe trends. The two gages can be compared to see if the pressures are equal. Under normal conditions the gages will indicate similar pressures. If they do not, flushing then rehabilitation is needed. The data collection personnel should observe the tubes and gages for bubbles and water clarity. Sediment or mineral deposits derived from the piezometer liquid may also be present. When flushing is performed, the data collection personnel should check to see if the discharged water contains gas, sediment, or mineral deposits.

(2) Maintenance tasks required for twin-tube hydraulic piezometers include flushing with de-aired liquid to clean the lines of any mineral deposits, and to remove accumulated gas bubbles from the tubing and manifold system (Dunnicliff 1988). When de-airing a piezometer, water under pressure may pass through the filter into the surrounding soil, causing excess pore water pressure in the soil that requires time to dissipate. In order to minimize or eliminate the buildup of pore water pressure in the soil when de-airing piezometers, a vacuum should be applied to one tube of the piezometer while de-aired water under a minimum pressure (calculated as shown by Dunnicliff 1988) sufficient to dislodge and move the air bubbles is applied to the other tube. Flushing procedures and pressure calculations are described in Dunnicliff (1988). The system should be checked frequently for

blockage and/or presence of gas. Sediment and mineral deposits derived from the liquid in the system must be flushed from the system if they are present. If deposits are allowed to accumulate in the system they will eventually plug the system and the instruments will be lost. Pressure gages should be checked periodically by comparing them with a master gage. Master gages and individual gages should be maintained and recalibrated and inaccurate or damaged gages should be replaced. For twin-tube hydraulic piezometers located in terminal structures above the frost line, protection from freezing is required, preferably by heating the structure. Maintenance of the heating equipment and control of moisture in the structure will be necessary.

b. Pneumatic piezometers. Data collection personnel should observe the instruments and readings to detect symptoms that may indicate that maintenance is needed. Unusual readings, sticking flow meters, evidence of moisture, leaking gas sounds, and valve malfunctioning are typical symptoms indicating that maintenance is needed. Pressure gages in pneumatic piezometer readout units require occasional calibration checks. Flowmeters will occasionally have to be cleaned to remove moisture or residue. The tubing may occasionally have to be flushed with purified, dry nitrogen gas to evaporate moisture from the tubing. O-rings and valves may have to be replaced if leaks are detected in the system.

c. Open standpipe piezometers. The hydrostatic time lag, frequently called response time, of each open standpipe piezometer should be established by performing a rising or falling head test at the time of installation. Test data may be converted to hydrostatic time lag for the piezometer by the method described in Chapter 2. The hydrostatic time lag for the piezometers should be reestablished periodically for a comparison with the initially established hydrostatic time lag. Such comparisons give an indication of the condition of the piezometer. Open-standpipe-type piezometers require periodic response tests to determine if the piezometer is effective or if maintenance is needed. In soils of low permeability, piezometer equalization can be obtained by adding or removing water in increments and observing the rate of rise or fall. The piezometers should be sounded periodically to determine if the tips contain sediments. If sediments are found, the piezometer should be flushed to remove sediment deposits from the bottom of the piezometer. Periodic disinfecting treatments may be required in piezometers that are located in environments that allow bacterial growth in the piezometers. Care should be taken when obtaining measurements to avoid introducing contaminants into the piezometer from the readout probe.

(1) In open standpipe piezometers where the water level rises above the frost line a nontoxic low-freezing-point fluid should be used to protect the piezometer from freezing. Maintenance may be required to replace the fluid so that it does not freeze and break the standpipe. Regardless of type of fluid used, the difference in specific gravities of the low-freezing-point fluid and the in situ pore water must be taken into account in adjusting the hydrostatic pressure shown by the piezometer.

(2) Observation wells are similar to open standpipe piezometers except they have no subsurface seals, therefore strata are vertically connected. Observation wells have limited use; however, their maintenance is basically the same as that for open standpipe piezometers.

d. Relief wells. Relief wells are outside the scope of this manual. Information on relief wells can be found in EM 1110-2-1914 and Driscoll (1986).

e. Probe extensometers. Probe extensometer readout devices must be kept clean and free of grit. Measuring tapes and cables should be inspected for kinks and kept dry. The riser pipes may require flushing to remove silt, corrosion, or plugging material.

f. Fixed borehole extensometers. The extensometer reference head must be kept clean of dust, grit, and moisture. The reference head may have to be reset if movement has occurred by following the manufacturer's instructions. Protection from direct sunlight or physical damage is required.

g. Inclinometers. The inclinometer probe, cable, and readout unit should be sent to the manufacturer for factory calibration and/or repair when either the check sums, the internal diagnostics, a malfunction, or unusual readings indicate that there is a problem with the instrument. Inclinometer casings may require occasional flushing to remove debris or sediment deposits from the bottom of the casing. Mechanical brushing can be used to remove biological or chemical residue or incrustation from the casing grooves. Inclinometer casings that have corroded, deteriorated, or deflected to such a state that readings can no longer be obtained, can sometimes be re-lined with a smaller inclinometer casing so that the inclinometer can still be used. Other types of instruments can also be installed in deteriorated inclinometer casings such as a slope extensometer or possibly a shear strip. These methods of instrumenting and re-using an existing inclinometer casing are normally much less expensive than drilling a new hole and installing a new inclinometer casing.

h. Seismic (strong motion) instruments. Maintenance of seismic (strong motion) instruments should be performed on a regular basis. Strong motion instrumentation is covered in ER 1110-2-103. A technician trained by the United States Geological Survey (USGS) or WES should check strong motion instruments on a periodic basis. The technician should check to see if the instrument has been tripped, check the operation of the instrument, and make sure the instrument has an ample amount of film. If it has been tripped, the exposed portion of the film should be removed for development and analysis.

i. Seepage measurement sevices. Routine maintenance is basically similar for most open-channel seepage measuring devices such as weirs, flumes, or seepage pipes. The channel and channel banks, or pool and pool banks near the device should be cleaned of weeds and debris. The sides, crest, outlets, and any measuring devices such as scales or staff gages should be cleaned of dirt, scum, mineral deposits, and bacterial or vegetation growth. The channel or pool should be cleaned of silt and sand deposits as they accumulate. If the cleaning has to be accomplished before the flow reading is taken, the flow reading should not be taken until the flow returns to its normal state.

(1) Weirs and flumes should be checked to make sure that they remain level and are at the same elevation as the zero reading on the staff gage. Weir notches or crests should be checked for nicks or dents that reduce their accuracy. Nicks or dents should be dressed or repaired if it can be done without changing the shape of the weir opening. If it cannot be repaired, the weir notch or crest should be replaced.

(2) Regular maintenance of flow or velocity meters includes keeping all moving parts clean, lubricated, free of corrosion, and in good working condition. Electrodes of electromagnetic instruments should be cleaned of any film buildup. The calibration of velocity meters should be checked frequently and recalibrated as needed.

8-6. Automation Equipment

The portable readout units, field terminals, and embedded components of an automated instrumentation system are basically the same as any instrumentation system and should receive the same care and maintenance. Automation equipment is discussed in Chapter 5. Automated instrumentation systems, communications systems, electronic equipment, dataloggers, data controllers, and computers contain sophisticated electronic components and will usually require the care of experienced electronics personnel.

Chapter 9
Continual Reassessment for Long-Term Monitoring

9-1. Introduction

This chapter addresses factors unique to long-term monitoring. Historical experience of dam designers, constructors, and engineers responsible for dam safety has shown first that: the function of a project changes with age, second that deterioration can be progressive with time, and third that problems can develop and occur at any time during the history of a structure. Engineers responsible for the dam safety of the embankment dams and levees must learn and understand the characteristic behavior of each embankment and other structure so that this knowledge can be applied in any future investigations, recommendations, and remedial actions. Ensuring safety is a continuing process, the responsibility for which must be accepted for the entire life of a project.

9-2. Long-term vs Construction-Related Instruments

The initial design of an instrumentation system should consider not only construction-related instruments, but also long-term instruments. Long-term instrumentation may be needed to provide data to validate design assumptions, to provide information on the continuing behavior of the foundation, embankment, or abutments, and to observe the performance of unique features. If deemed necessary, a well-planned system of instruments (see paragraph 3-6) should be installed to provide data on flows, pore water pressures, and/or deformations at structurally significant locations in the foundation, embankment, and/or abutments during construction, first filling, and long-term operation. A careful examination of instrumentation data on a continual basis may identify a new condition, or may play a role in reassuring the reviewer that an observed condition does not require immediate remedial measures.

9-3. Primary, Secondary, and Tertiary Instruments

The classification of instruments into primary, secondary, and tertiary categories usually relates to piezometers, but may apply to all other instruments installed at a project. Figure 9-1 illustrates an example of instrument classification and sample locations. The primary instruments include all instruments located along a typical cross section at or near the maximum structural vertical section. Also included are piezometers installed to monitor structurally significant features or suspect areas in the foundation, embankment, and/or abutments. Secondary instruments are those located in less critical sections or areas. Tertiary instruments include other instruments that have been installed to verify that other areas of the project behave in a similar way to the areas where the primary and secondary instruments are located. If automation is a consideration (see Chapter 5), the primary instruments would be the first to be included in the automation system.

9-4. The Evolving Instrumentation System

One of the early steps in the planning of an instrumentation system (see Chapter 3) is to define the geotechnical questions that need to be answered. For a long-term monitoring system, the questions that need to be answered are normally associated with developing trends over time and response under major pool conditions (which for a flood-control project may not occur for many years after construction). Construction-related instruments must not be maintained unless they can assist in answering long-term questions. Typical questions relating to long-term monitoring might be: *Is the feature responding as assumed in design under high pool conditions? Is the seepage flow increasing with time?*

a. Changing conditions. Design criteria or existing conditions can change. For example, filter criteria for a dam designed and constructed in the 1930's are no longer accepted. Additional piezometers might be warranted to verify that pore water pressures are constant and that core material is not being lost. Siltation of the reservoir can occur with time, affecting the hydraulic gradient of the structure.

b. Effects of aging. As an embankment dam or levee ages, new problems or concerns may develop. It may be necessary to instrument potential problem areas to verify that conditions are not deteriorating.

c. Reading schedules. Reading schedules may vary depending on locations of instruments and associated factors such as reservoir level.

9-5. Steps for Continual Reassessment

Paragraph 3-6 provides a step-by-step procedure for planning a monitoring program. These steps were designed for a new structure, but they also apply to an existing

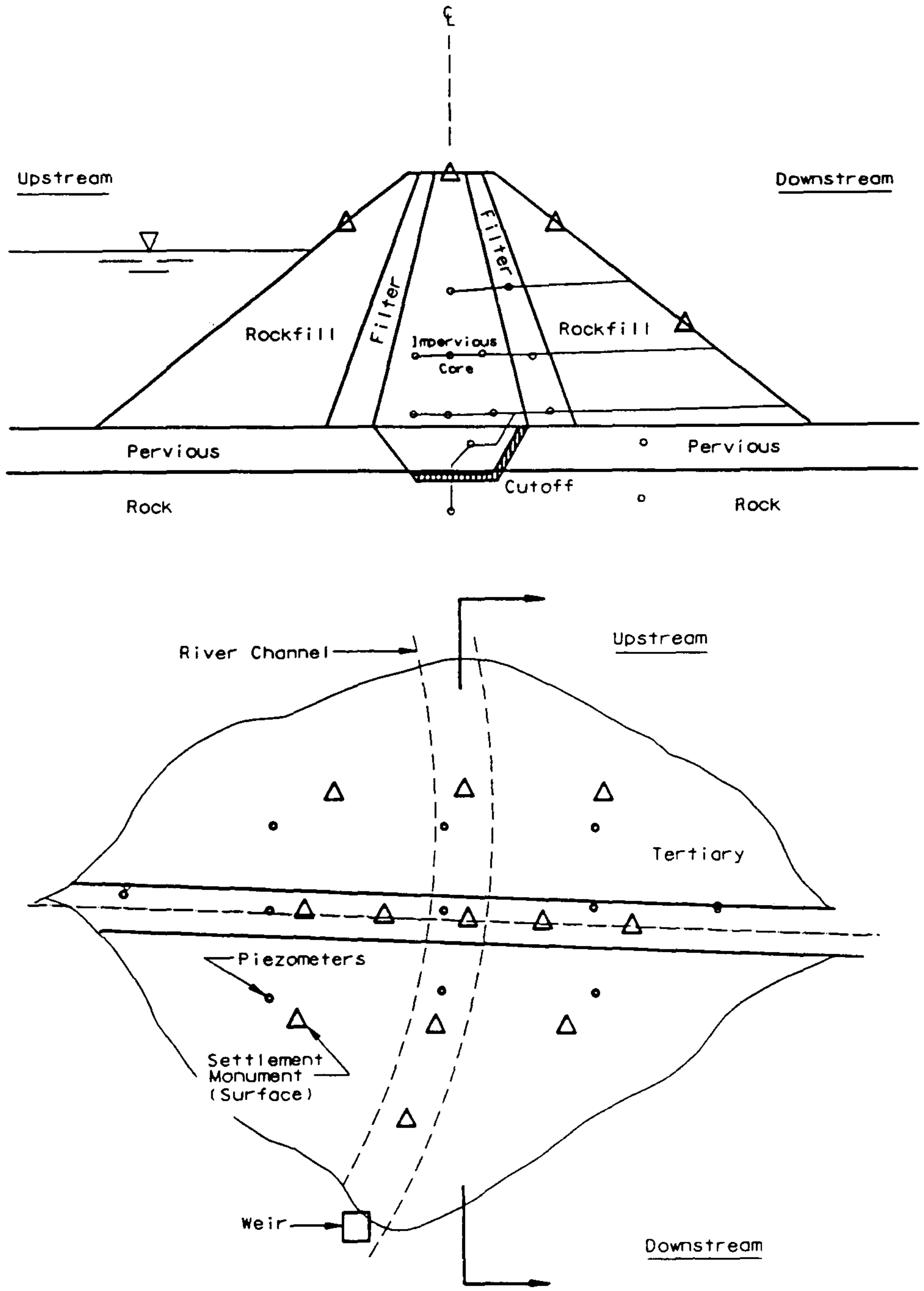

Figure 9-1. Instrument classification and sample locations

structure. The process for planning and executing a monitoring program for an existing structure should begin at the appropriate step. As with a new instrumentation system, the steps to follow for modifying or upgrading an existing system can vary, and are up to the discretion of the designer, or a senior-level geotechnical or instrumentation engineer. The terms *retrofit, rehabilitate, upgrade, and replace* have slightly different meanings with respect to instrumentation. The following paragraphs indicate these differences.

a. Retrofit. The term retrofit signifies changing or adding to an instrument that already exists. An example would be the installation of an electronic pressure transducer in an open standpipe piezometer.

b. Rehabilitate. The term rehabilitate is normally used in conjunction with the repair of an individual instrument or system. An example would be re-establishing a new initial for a settlement monument after the necessary repairs.

c. Upgrade. The upgrading of an existing instrument or system usually refers to the enhancement of a functioning instrument or system so that more reliable or frequent data can be obtained. The automation of existing instrumentation would be considered an upgrade. The upgrade of an instrumentation system may include the addition of instruments in order to monitor newly observed conditions.

d. Replace. Replacement signifies the installation of a new instrument or component and the abandonment of an existing instrument which cannot be repaired. It can also refer to the removal of a malfunctioning component, which is sent in for repair, replacement, or the installation of a spare part.

9-6. Selection of Parameters to Monitor

Table 9-1 gives, in priority order, measurements which are applicable for the long-term monitoring of embankment dams and levees, together with recommended instruments. It must be restated that the selection of instruments is dependent upon the unique characteristics of each structure or associated feature. For example, lateral subsurface deformation within a typical embankment dam will be less important than monitoring seepage, but it may be more critical in a potentially unstable abutment. Pore water pressures and subsurface settlement may rank higher if core material was placed and compacted too wet.

a. Visual observations. Dr. Ralph Peck has often stated that the human eye attached to an intelligent brain is the single most important instrument at a project site. Automation is sometimes criticized because of a concern that visual observations will not be made. The solution is to schedule regular visual inspections of all areas of a project, and not to rely solely on the automation equipment and instruments for warnings of potential problems. Moreover, if a major problem were to occur, it is very possible that the instruments in place would not give enough advance warning, simply because the instruments may not be located close enough to the problem area to detect the change, or simply because of the delay in data processing and review.

b. Seepage. Regular monitoring of seepage which appears downstream of an embankment dam or abutment is essential in assessing the behavior of a structure, not only during first filling, but also for monitoring long-term trends (see paragraph 4-8). The long-term monitoring should also include solids content. Relief wells for dams or levees have specific problems associated with the plugging of the filter packs or the accumulation of bacteria or carbonates (see EM 1110-2-1914). It is often necessary to install piezometers adjacent to relief wells to carefully monitor the pressure increases associated with clogged wells.

c. Pore water pressures within the embankment or abutments. For long-term monitoring, pore water pressures are measured in embankments or abutments to verify design assumptions and to monitor changes which could be an indication of a deteriorating core or stratum. Paragraph 4-3 includes a discussion of the various types of piezometers. The most reliable type for long-term monitoring is the open standpipe, possibly retrofitted with a retrievable transducer.

d. Seismic instrumentation. Seismic instrumentation is often installed at medium to large dams to guide decisions on remedial actions which may be necessary if a structure has been affected by a seismic event. Also the data can be a very important research tool, benefitting the design of future projects.

e. Vertical deformation. Measurements of surface settlement and horizontal movement at various points along the crest and on the slopes should be considered for monitoring long-term deformations. Measurements of subsurface vertical deformations can be of importance especially for large dams or for structures located on unique or soft foundations. Liquid level gages, horizontal inclinometers, subsurface settlement points, and probe exentsometers can all be used, depending on the circumstance (see paragraph 4-3).

f. Lateral deformation. Measurements of surface lateral deformations may be required, but they can often be terminated within a few years after first filling unless special conditions exist. Similarly, subsurface lateral

Table 9-1
Measurements and Instruments for Long-Term Performance Monitoring

Measurement, in Priority Order	Recommended Instruments
Condition of entire structure	Visual observations
Seepage	Seepage weirs or flumes Precipitation gage Pool elevation
Pore water pressure[1]	Open standpipe piezometers Twin-tube hydraulic piezometers Vibrating wire piezometers Pneumatic piezometers Electrical resistance piezometers
Seismic events	Strong motion accelerographs Microseismographs
Surface vertical or lateral deformations	Surveying techniques Global positioning system
Subsurface vertical or lateral deformations	Liquid level gages Inclinometers Extensometers Subsurface settlement points
Total stress at structure contacts	Contact earth pressure cells

[1] Listed in priority order, vibrating wire, pneumatic, and electrical resistance piezometers are only used in special cases.

Source: Dunnicliff (1988).

deformation measurements may be required only if there are special concerns. Probe extensometers, fixed embankment extensometers, and inclinometers are options for monitoring subsurface lateral deformation (see paragraph 4-4).

g. Additional instrumentation. Thermotic survey/ thermal monitoring (see paragraph 4-8*f*) of seepage water can be a useful tool for the long-term monitoring of seepage paths within an embankment or abutment. Temperature measurements are especially suitable for abutments with nonhomogeneous soil conditions, allowing the monitoring of strata where the seepage is occurring. Earth pressure cells can be used but generally are useful only when contact pressures between an embankment and an appurtenant structure are required (see paragraph 4-5).

h. Associated parameters. Various other parameters are often monitored. The purpose for monitoring reservoir, tailwater, and river levels needs no explanation. Rainfall affects surface runoff, which in turn affects weir and flume measurements. Air and water temperatures can affect transducer readings, and these measurements are also necessary as part of groundwater thermal studies. Barometric pressure can also affect certain transducer readings. Other conditions should always be noted when possible, such as general weather conditions and construction activities in the area. Reviewers are often searching for possible causes for unexplainable readings, and answers can often be found if the miscellaneous data are recorded.

9-7. Management

a. Data collection schedules. Data collection schedules must be reviewed within a few years after first filling. The number of instruments read at unchanged frequencies should generally be reduced to a few primary instruments. Readings of other instruments should either continue on a reduced schedule or be terminated. For example, the frequency of piezometer readings within a dam with a rapidly fluctuating pool should be more frequent than the pool cycle. If the pool elevation can cycle dramatically within a few days, a monthly reading schedule for the piezometers and seepage instruments may be useless. However, depending on the feature being monitored and the complexities involved, the original monitoring schedule may have to be continued for the life of the project for numerous instruments. In summary, the reading schedule should be matched to the conditions. Chapter 7 includes additional information.

b. Maintenance. The maintenance of instruments and automation equipment must be scheduled and budgeted for annually. Additional guidance is included in Chapters 5 and 8.

c. Data collection. The manual reading if instruments over the long-term has historically been difficult. Available project labor is becoming scarce, and when labor is available, temporary or untrained personnel are often used. Rapid turnover of temporary personnel makes training difficult. Despite the problems, quality of readings and observations must be maintained. The options available are dependent on the project, personnel, and required reading frequencies. Options can include the automation of instrument and/or the permanent hiring of an instrumentation technician. Paragraph 3-8*c* includes additional information.

d. Data processing and presentation. This topic is discussed in detail in Chapter 7. For long-term monitoring purposes, the data processing and presentation capabilities should be available at the project as well as in the District office. This allows personnel to respond to a major event more effectively, especially if communication to the District is affected. In addition, a complete record of instrumentation in plot format should be maintained at each project office. Historical data must be maintained for the life of the project.

e. Data interpretation, reporting, and analysis. Review and analysis schedules are dependent upon the individual projects and features. Minimum schedules are given in ER 1110-2-100 and ER 1110-2-110. Additional guidance is included in Chapter 7.

Appendix A
References

A-1. Required Publications

ER 1110-2-100
Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures

ER 1110-2-103
Strong Motion Instruments for Recording Earthquake Motions in Dams

ER 1110-2-110
Instrumentation for Safety-Evaluations of Civil Works Projects

ER 1110-2-1806
Earthquake Design and Analysis for Corps of Engineers Projects

ER 1110-2-1807
Use of Air Drilling in Embankments and Their Foundations

EM 1110-2-1907
Soil Sampling

EM 1110-2-1913
Design and Construction of Levees

EM 1110-2-1914
Design, Construction and Maintenance of Relief Wells

EM 1110-2-2300
Earth and Rock-fill Dams--General Design and Construction Considerations

EM 1110-2-3506
Grouting Technology

EM 1110-2-4300
Instrumentation for Concrete Structures

CWGS 16740
Automated Data Acquisition System

TR REMR-CS-5
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A-2. Related Publications

ER 1110-2-101
Reporting of Evidence of Distress of Civil Works Structures

ER 1110-2-1150
Engineering and Design for Civil Works Projects

ER 1110-2-1802
Reporting Earthquake Effects

ER 1110-2-1901
Embankment Criteria and Performance Report

ER 1110-2-1925
Field Control Data for Earth and Rockfill Dams

ER 1110-2-1942
Inspection, Monitoring, and Maintenance of Relief Wells

ER 1130-2-419
Dam Operations Management Policy

EM 1110-2-1911
Construction Control for Earth and Rock-fill Dams

Dunnicliff 1990
Dunnicliff, J. 1990. "Twenty-five steps to successful performance monitoring of dams," *Hydro-Review*, IX (4).

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Gibson, R. E. 1963. "An analysis of system flexibility and its effect on time-lag in pore-water pressure measurements," *Geotechnique,* 13 (1), 1-11.

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Holtz, R. D., and Kovacs, W. D. 1981. *An introduction to geotechnical engineering.* Prentice-Hall, Englewood Cliffs, NJ.

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Kallstenius, T., and Wallgren, A. 1956. "Pore pressure measurements in field investigations." *Proceedings, Royal Swedish Geotechnical Institute,* No. 13.

Terzaghi and Peck 1967
Terzaghi K., and Peck, R. B. 1967. *Soil mechanics in engineering practice.* 2nd., John Wiley & Sons, Inc., New York.

Appendix B
Drilling Methods

B-1. Introduction

A brief discussion of available drilling methods is included below. It is not the intent of this manual to include a detailed description of these methods. Neither is it intended to list all the methods available to the drilling industry. Most of the methods listed below may be good options for drilling in native soil or rock. When drilling in embankments extreme care must be taken to avoid damage to the core, as discussed in paragraph 6-5.

B-2. Hollow Stem Auger Drilling

The hole is advanced by turning sections of auger casing, called auger flights, into the subsurface (see Figure B-1). Rotating of the auger flights carries the soil to the surface. Soil samples can be taken off the flights of the augers as the soil comes to the surface. For accurate locations of samples, the auger pilot bit can be removed and split-spoon sampling can be performed through the augers ahead of the auger cutter head. This method is most effective when used in stable soil conditions which are generally free from cobbles and boulders. A detailed description of soil sampling procedures can be found in EM 1110-2-1907. The advantages of this method are that the hole is drilled and cased simultaneously, and the hole can be advanced without the introduction of fluids. Some of the disadvantages are that drilling difficulty significantly increases with depth and the auger flights must be removed from the hole without rotating to avoid damaging the installed instrument.

B-3. Cable Tool Drilling

a. The cable tool (churn drill or percussion drill) method of drilling involves the use of percussion by repeatedly lifting and dropping a heavy string of drilling tools or weight into a borehole (see Figure B-2). The material is pulverized at the bottom of the hole forming a slurry which is then removed with a bailer (see Figure B-3) when the penetration rate becomes unacceptable. The sides of the borehole can be supported with drill casing as needed. This method is useful for deep holes when a hydrostatic head from drilling mud is unacceptable. The main drawback is that it is relatively slow.

b. Continuous sampling may be accomplished with a cable tool if the chopping bit is replaced by a steel barrel or open-drive sampler and the short-stroke drilling jars attached between the sampler and drill bar are replaced by long-stroke fishing jars. The long jars facilitate driving without any upward motion. The hole is advanced by the sampling operation itself and is cleaned out by bailing each time the casing is advanced. Samples must be taken below the bottom of the casings. It is difficult, however, and often impossible to advance the borehole ahead of the casing when sampling in soft or cohesionless soils.

B-4. Direct Mud (Water) Rotary Drilling

Mud rotary drilling is a commonly used method of drilling that is suitable in rock as well as overburden but cannot be used in situations where excess hydrostatic heads cannot be tolerated such as in some earth embankment dams. As the name describes, a drill bit on the bottom of a string of drill rods is rotated in a borehole. Drilling fluid is circulated in the borehole by pumping down through the string of rods, where it picks up the drill cuttings and carries them to the surface of the borehole (see Figure B-4). As discussed in paragraph 6-6, selection of the proper drilling fluid is essential for the proper installation of some instruments. For most instrumentation installations the sides of the borehole should be supported with drill casing. The casing also prevents the drilling fluid from contacting the sidewalls of the borehole. The disadvantage of using drilling mud is that the fluid can seal the sides of the borehole where an instrument may be installed.

B-5. Air Drilling Systems

Air rotary drilling is similar to direct mud rotary drilling except that compressed air is used to transport the cuttings to the surface. An air-operated downhole casing advancement system is sometimes used. This casing advancement system consists of an air-operated down-the-hole hammer drill that is fitted with a specialized bit that has an eccentric reamer that cuts the hole large enough for the casing to follow. The hammer drill is designed to be used inside and at the bottom of the drill casing so that the bit and eccentric reamer are below the casing. Using compressed air, the hammer pulverizes the material below the casing, then blows it back through the casing to the top of the hole. As the hammer drives through material it also reacts against an interior shoulder bevelled on the drill casing shoe, which pulls the casing down the hole as the hammer drill is advanced. This method is well suited for drilling through difficult material such as rock fill. The major drawback is the high air pressure and large air volume required for operation and it is prohibited on embankment dams (see paragraph 6-5).

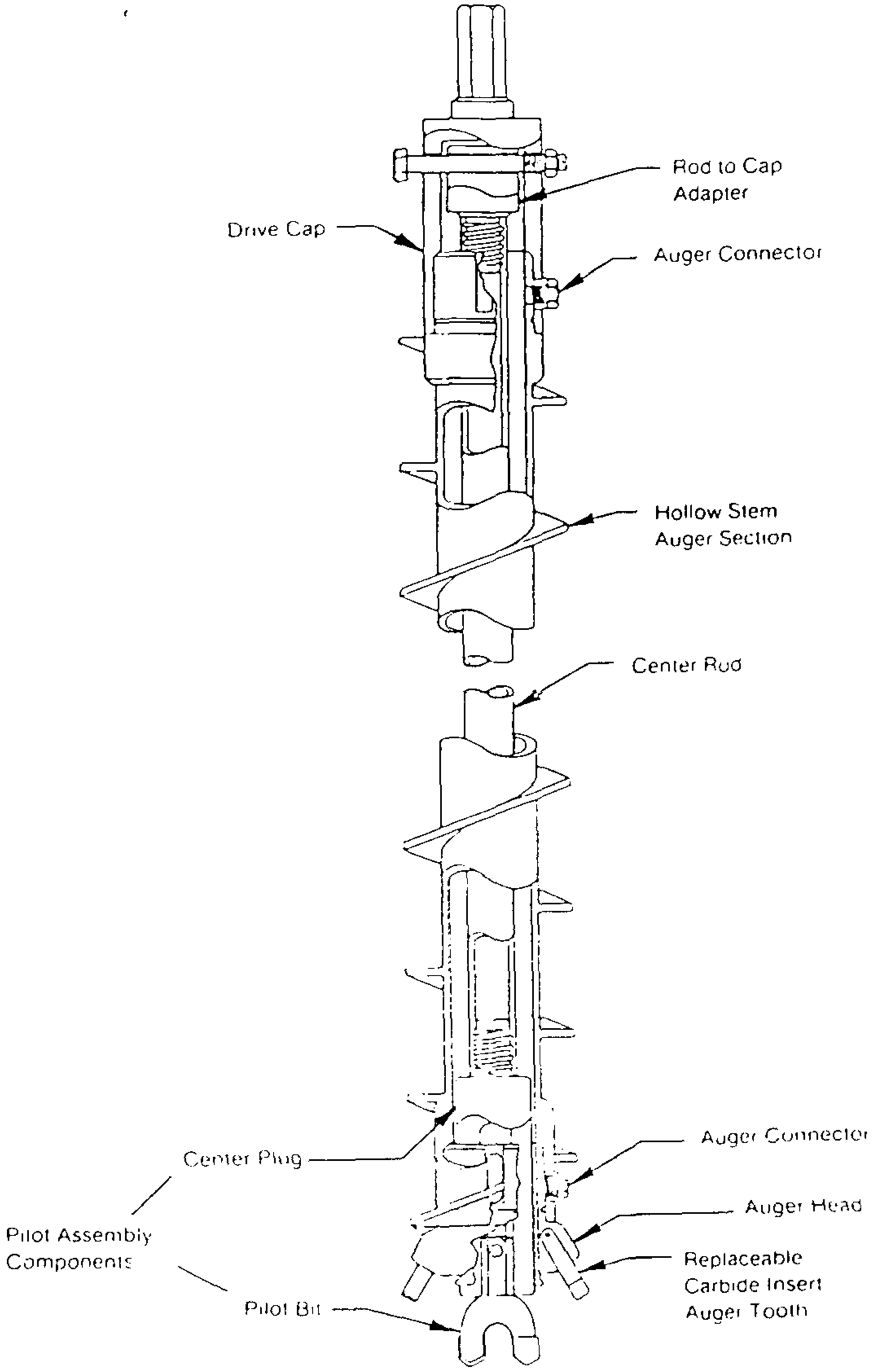

Figure B-1. Typical components of a hollow-stem auger. (Courtesy of National Ground Water Association)

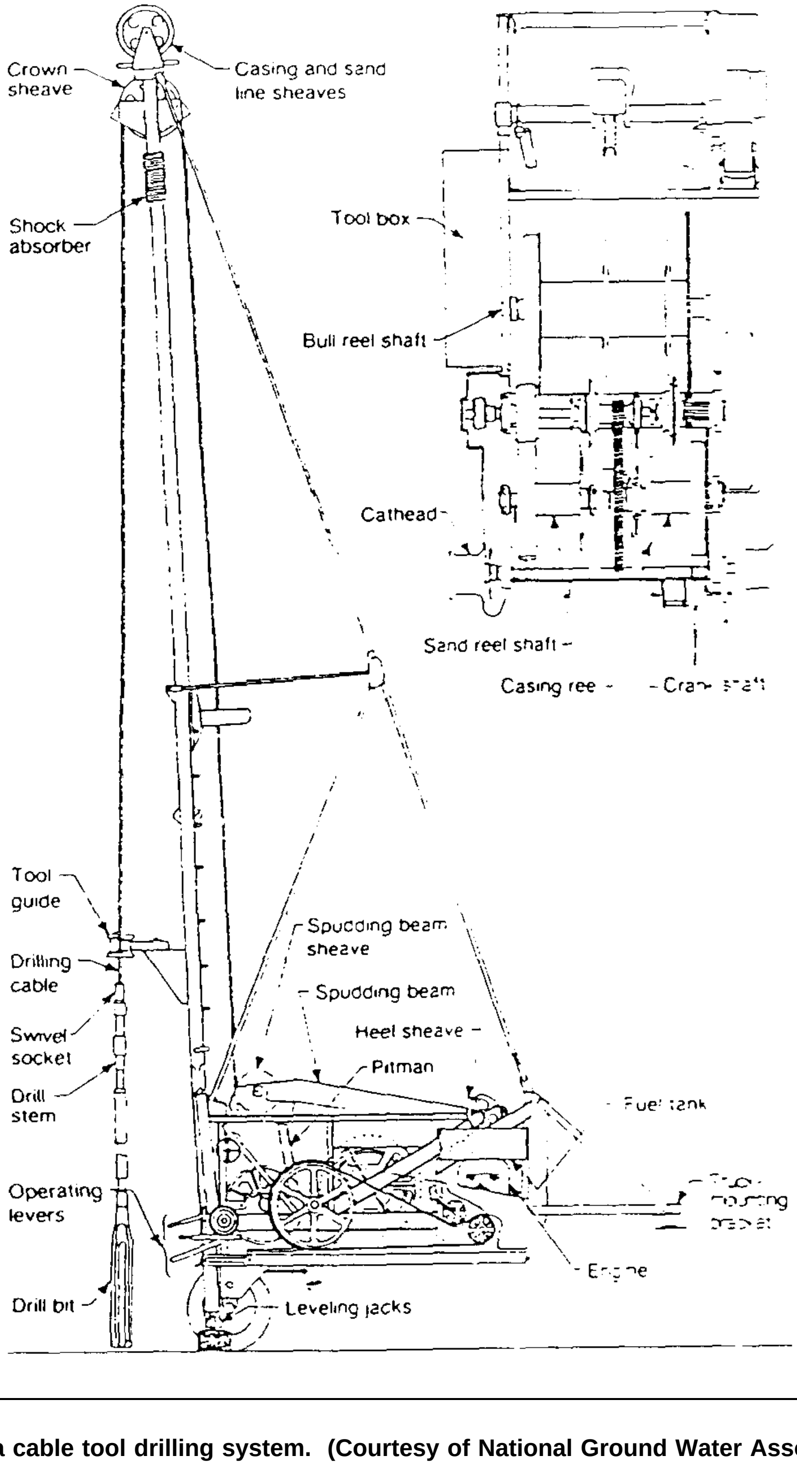

Figure B-2. Diagram of a cable tool drilling system. (Courtesy of National Ground Water Association)

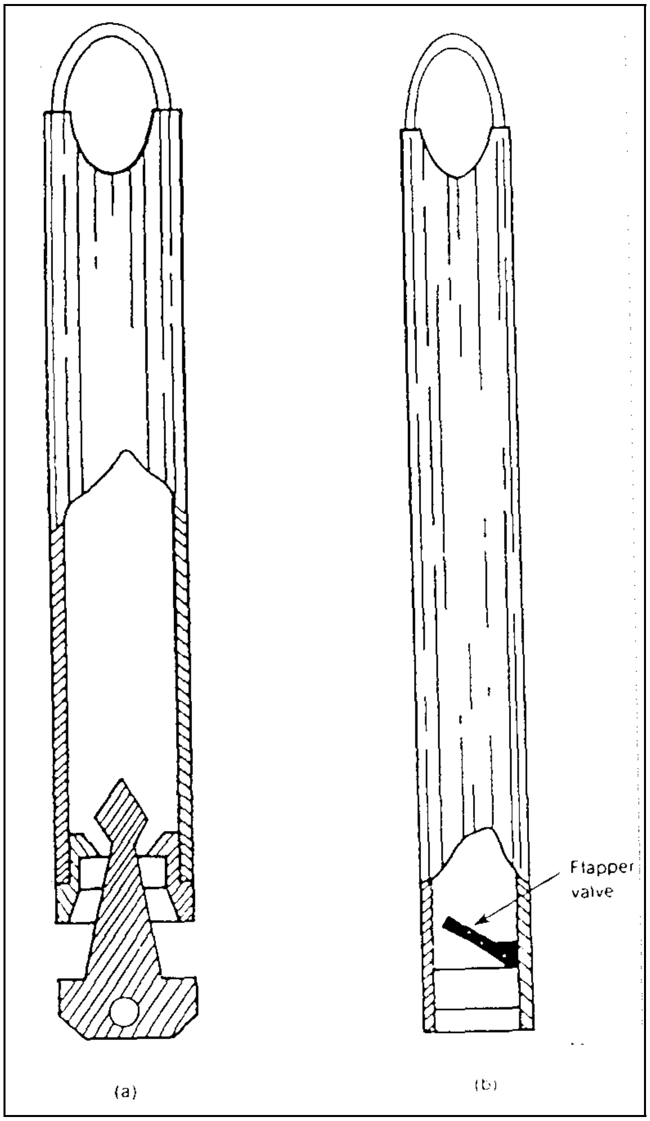

Figure B-3. Diagrams of two types of bailers: (a) dart valve and (b) flat bottom. (Courtesy of National Ground Water Association)

B-6. Core Drilling

Core drilling involves use of a core barrel, attached at the bottom of a string of rods, which is rotated and advanced through soil or rock to obtain a core sample of the material. Water or drill fluid is used to cool the cutting bit and to carry cuttings to the surface. The cutting bits are usually constructed of steel with carbide inserts or with impregnated diamonds. There are two types of core barrels: conventional (Figure B-5) and wire line (Figure B-6). To retrieve a core cut with a conventional core barrel, the entire string of drill rods must be removed from the hole. The wire line core barrel has an inner barrel which holds the core, that can be pulled up through the drill rods thereby eliminating the need to remove the entire string of drill rods.

B-7. Dual-Wall Reverse Circulation Drilling

Dual-wall reverse circulation drilling (see Figure B-7) can be used with either mud or air rotary drilling. The direction of flow is reversed and the transport medium is pumped down between the outer casing and the inner drill rods, through the drill bit, and up through the drill rods. This allows for rapid drilling through both unconsolidated and consolidated formations, and allows for continuous collection of the cuttings.

B-8. Wash Boring

The wash boring method is frequently used in sands and silts to either advance a casing or collect soil samples. Water is pumped down the drill rods under pressure and discharges through ports in the drill bit and carries the soil up to the surface in the annulus between the rod and the boring wall or casing. A washing or wedge-shaped chopping bit is normally used.

B-9. Other Drilling Methods

Other drilling methods include hand augers, driven wells (wellpoint) (see Figure B-8), and sonic (see Figure B-9). The major limitation of hand augers and driven wells is that they are normally restricted to shallow depths, although in sandy material wellpoints have been driven in excess of 15.24 m (50 ft). Solid-flight auger holes are difficult to instrument in most unconsolidated aquifers because of borehole caving upon auger removal. Sonic drilling uses a hydraulically activated unit that imparts high frequency sinusoidal wave vibrations into a drill string to achieve a cutting action at the bit face. The resultant cutting action forces a circular continuous core of the formation up into the drill rods. No cuttings are generated in the drilling process since excess material, generated by the cutting face of the bit, is redistributed into the borehole wall. For this reason sonic drilling should be evaluated before it is used as a drilling method for the purpose of installing instrumentation.

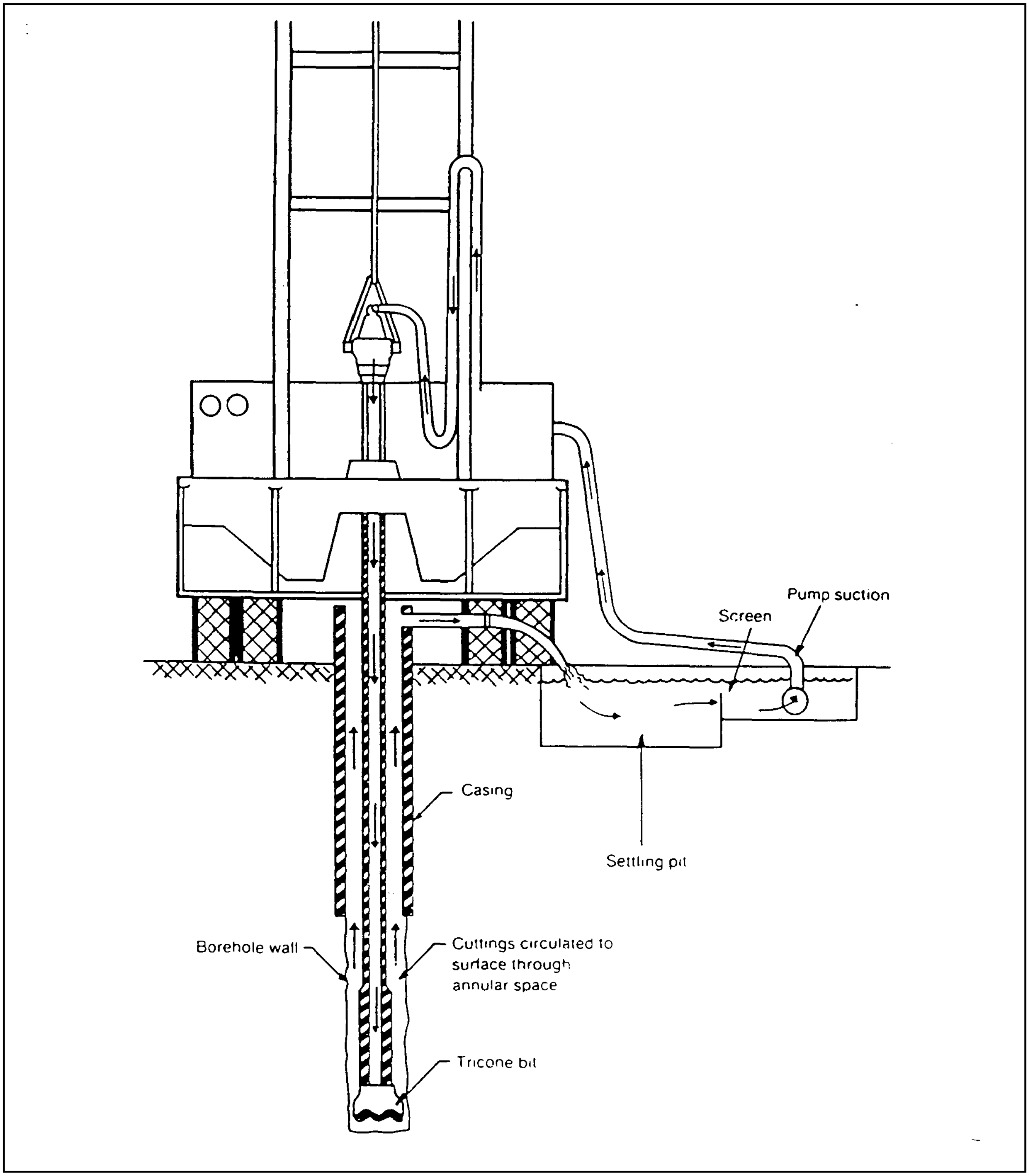

Figure B-4. Diagram of a direct rotary circulation system. (Courtesy of National Ground Water Association)

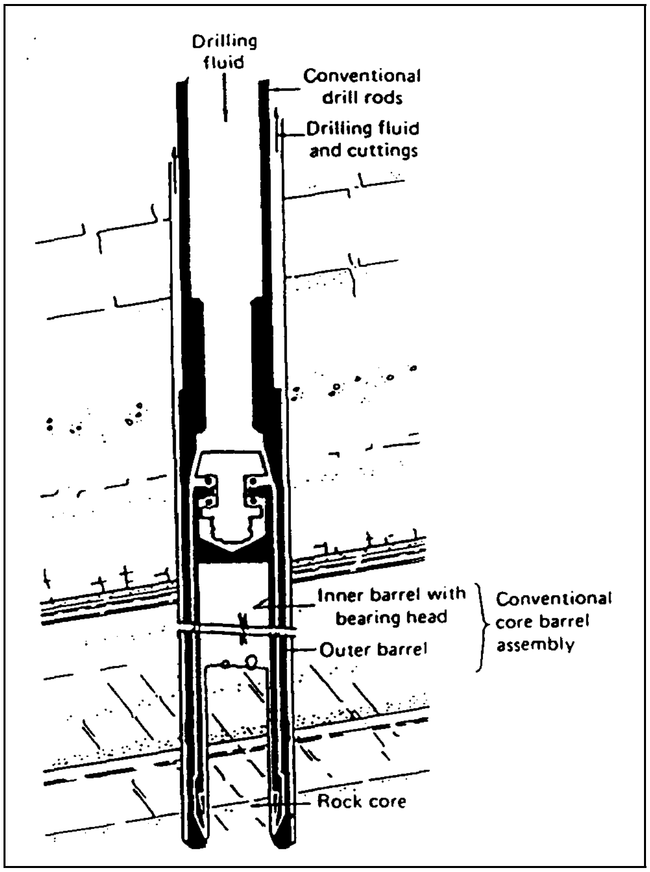

Figure B-5. Conventional core drilling (Dunnicliff 1988)

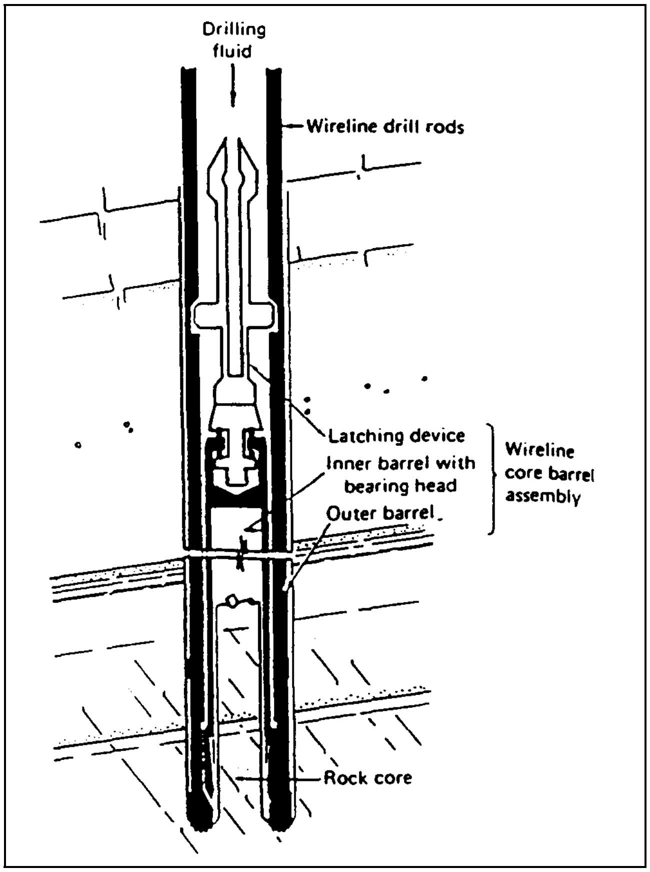

Figure B-6. Wireline core drilling (Dunnicliff, 1988)

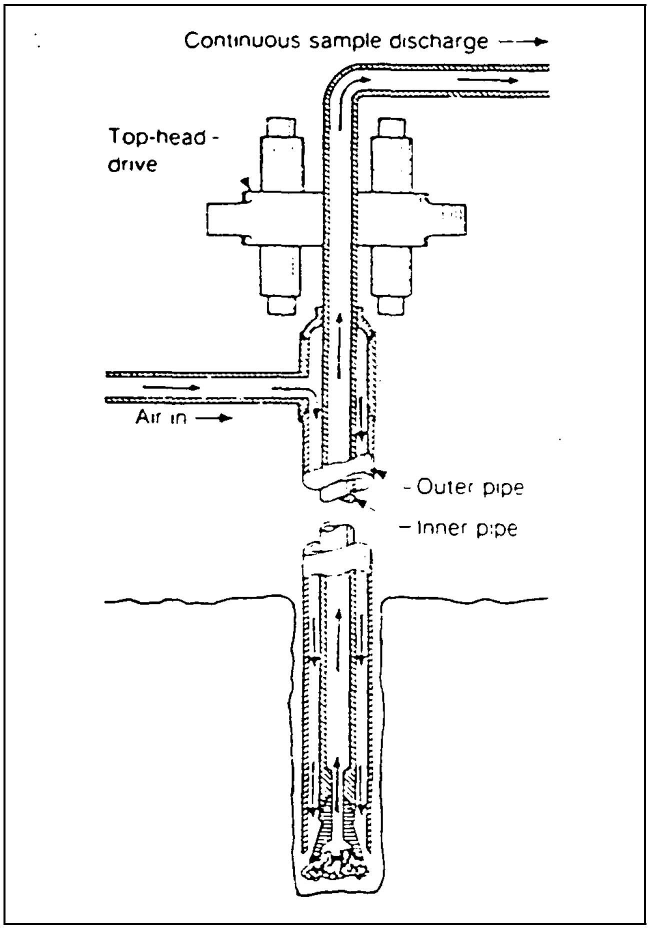

Figure B-7. Diagram of dual-wall reverse-circulation rotary method (Driscoll 1986)

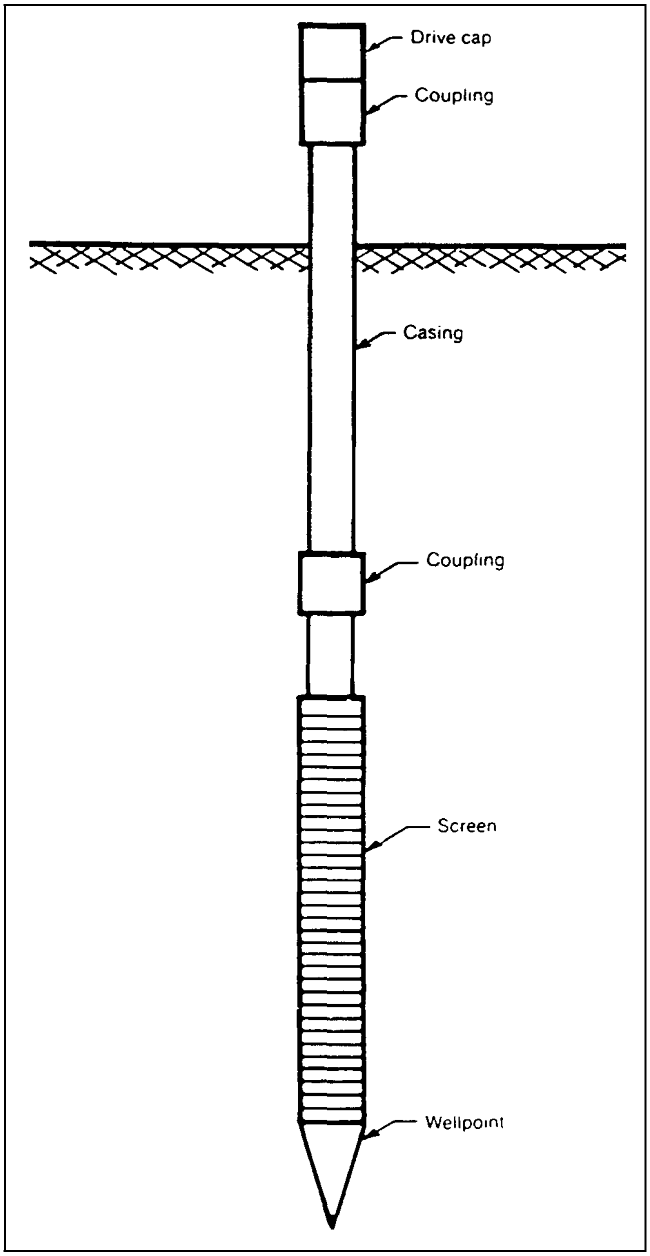

Figure B-8. Diagram of a wellpoint. (Courtesy of National Ground Water Association)

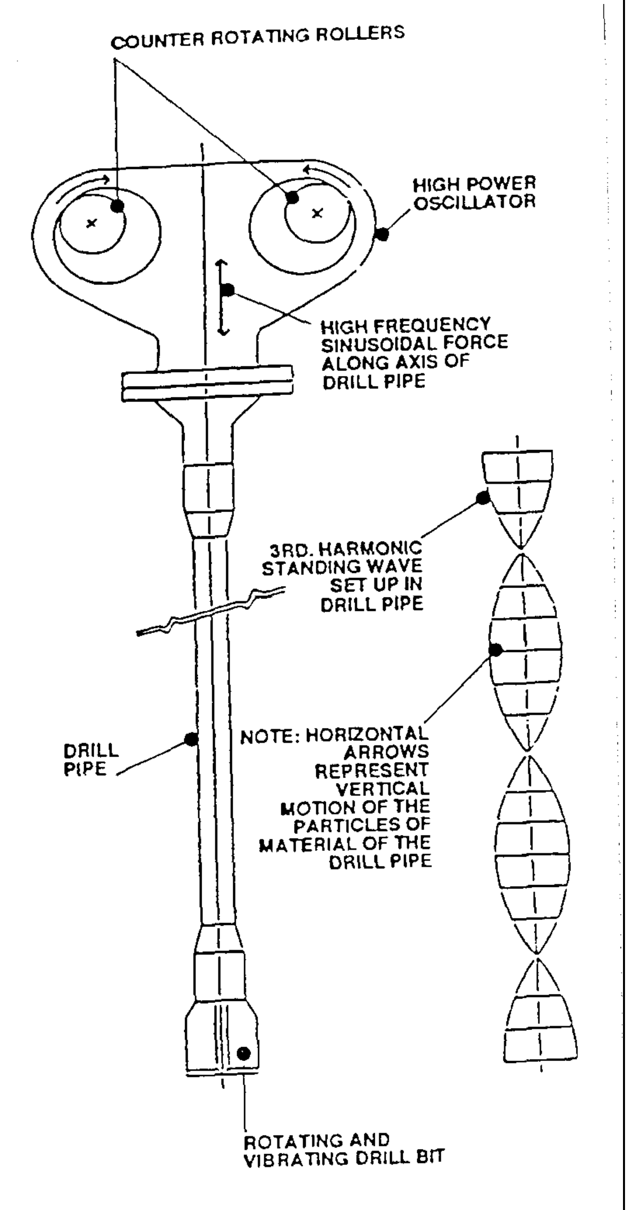

Figure B-9. Sonic drilling. (Courtesy of National Ground Water Association)