Part 1

Introduction

Part 1 is intended to serve as a general introduction. Chapter 1 sets the stage for the book, describing the role of geotechnical instrumentation and giving a historical perspective and a look into the future. It is hoped that Chapter 1 will motivate the reader toward a deeper study of the subject. Chapter 2 presents an overview of key aspects of soil and rock behavior, targeted for the practitioners who become involved with geotechnical instrumentation programs and who do not have formal training in soil or rock mechanics.

CHAPTER 1

GEOTECHNICAL INSTRUMENTATION: AN OVERVIEW

1.1. WHAT IS GEOTECHNICAL INSTRUMENTATION?

The engineering practice of geotechnical instrumentation involves a marriage between the capabilities of measuring instruments and the capabilities of people.

There are two general categories of measuring instruments. The first category is used for in situ determination of soil or rock properties, for example, strength, compressibility, and permeability, normally during the design phase of a project. Examples are shown in Figure 1.1. The second category is used for monitoring performance, normally during the construction or operation phase of a project, and may involve measurement of groundwater pressure, total stress, deformation, load, or strain. Examples are shown in Figure 1.2. This book is concerned only with the second category.

During the past few decades, manufacturers of geotechnical instrumentation have developed a large assortment of valuable and versatile products for the monitoring of geotechnically related parameters. Those unfamiliar with instrumentation might believe that obtaining needed information entails nothing more than pulling an instrument from a shelf, installing it, and taking readings. Although successful utilization may at first appear simple and straightforward, considerable engineering and planning are required to obtain the desired end results. The use of geotechnical instrumentation is not merely the selection of instruments but a comprehensive step-by-step engineering process beginning with a definition of the objective and ending with implementation of the data. Each step is critical to the success or failure of the entire program, and the engineering process involves combining the capabilities of instruments and people.

1.2. WHY DO WE NEED TO MONITOR FIELD PERFORMANCE?

The term *geotechnical construction* can be used for construction requiring consideration of the engineering properties of soil or rock. In the design of a surface facility, the ability of the ground to support the construction must be considered. In the design of a subsurface facility, consideration must also be given to the ability of the ground to support itself or be supported by other means. In both cases, the engineering properties of the soil or rock are the factors of interest. The designer of geotechnical construction works with a wide variety of naturally occurring heterogeneous materials, which may be altered to make them more suitable, but exact numerical values of their engineering

Figure 1.1. Examples of measuring instruments for in situ determination of soil or rock properties: (a) Piezocone: combined static cone and pore pressure probe (courtesy of Geotechniques International, Inc., Middleton, MA); (b) vane shear equipment (courtesy of Geonor A/S, Oslo, Norway); (c) self-boring pressuremeter (courtesy of Cambridge Insitu, Cambridge, England); and (d) borehole deformation gage (courtesy of Geokon, Inc., Lebanon, NH).

properties cannot be assigned. Laboratory or field tests may be performed on selected samples to obtain values for engineering properties, but these tests will only provide a range of possible values.

The significance of these statements about geotechnical construction can be demonstrated by comparison with steel construction. A designer of a steel structure works with manufactured materials. The materials are specified, their manufacture is controlled, and fairly exact numerical values of engineering properties are available for design. An accurate analysis can be made and design plans and specifications prepared. Then, provided construction is in accordance with those plans, the structure will perform as designed. There will generally be no need to monitor field performance. Similar remarks apply to reinforced concrete. In contrast, the design of geotechnical construction will be based on judgment in selecting the most probable values within the ranges of possible values for engineering properties. As construction progresses and geotechnical conditions are observed or behavior monitored, the design judgments can be evaluated and, if necessary, updated. Thus, engineering observations during geotechnical construction are often an integral part of the design process, and geotechnical instrumentation is a tool to assist with these observations.

1.3. WHAT CAPABILITIES MUST THE PEOPLE HAVE?

Basic capabilities required for instrumentation personnel are reliability and patience, perseverance, a background in the fundamentals of geotechnical engineering, mechanical and electrical ability, attention to detail, and a high degree of motivation.

1.4. WHAT CAPABILITIES MUST THE INSTRUMENTS HAVE?

Reliability is the overriding desirable capability for instruments. Inherent in reliability is maximum simplicity, and in general the order of decreasing simplicity and reliability is optical, mechanical, hydraulic, pneumatic, electrical. Also inherent in reliability is maximum quality. Lowest cost of an instrument is rarely a valid reason for its choice, and unless high quality can be specified adequately, instrument procurement on a low-bid basis will remain a stumbling block to good field performance.

1.5. WHERE HAVE WE BEEN?

Figures 1.3–1.15 show examples of past uses of geotechnical instrumentation.

The birth of geotechnical instrumentation, as a tool to assist with field observations, occurred in the 1930s and 1940s. During the first 50 years of its life, a general trend can be observed. In the early years, simple mechanical and hydraulic instruments predominated, and most instrumentation programs were in the hands of diligent engineers who had a clear sense of purpose and the motivation to make the programs succeed. There were successes and failures, but the marriage between instruments and people was generally sound. In more recent years, as technology has advanced and the role of geotechnical instrumentation has become more secure, more complex devices with electrical and pneumatic transducers have become commonplace. Some of these devices have performed well, while others have not. At the same time, the technology has attracted an increasingly large proportion of the geotechnical engineering profession, and an increasing number of instrumentation programs have been in the hands of people with incomplete motivation and sense of purpose. There have continued to be successes and failures but, in contrast to the early years, a significant number of the failures can be attributed to an unsound marriage between instruments and people.

1.6. WHERE ARE WE NOW?

The state of the art of instrument design is now far ahead of the state of the practice by users, and many more imperfections in current instrumentation programs result from user-caused people problems rather than from manufacturer-caused instrument problems. As users we are fortunate in having access to such a wide variety of good instruments. It is **our** responsibility to develop an adequate level of understanding of the instruments that we select and to maximize the quality of our own work if we are to take full advantage of instrumentation technology. The greatest shortcoming in the state of the practice is failure to plan monitoring programs in a

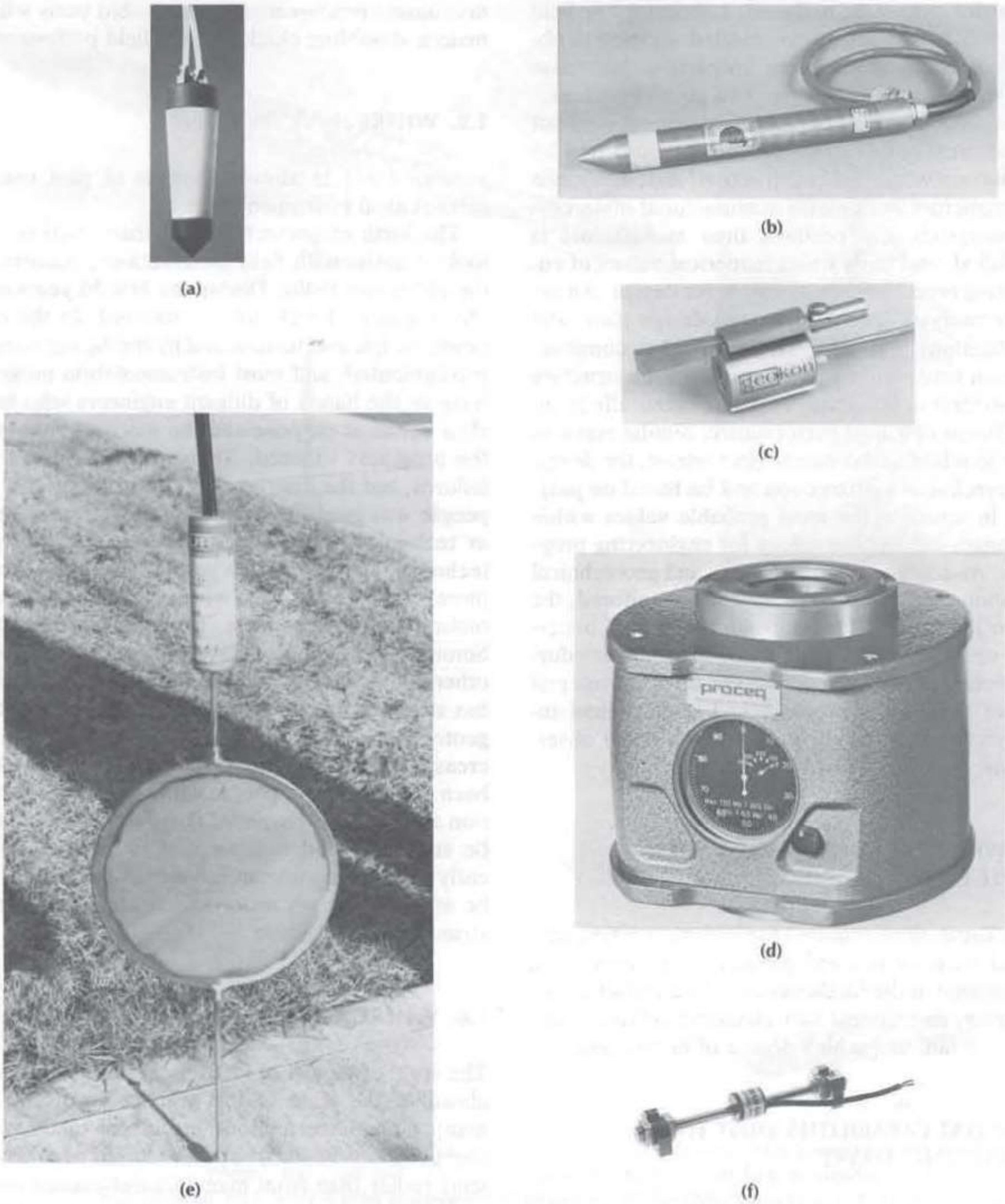
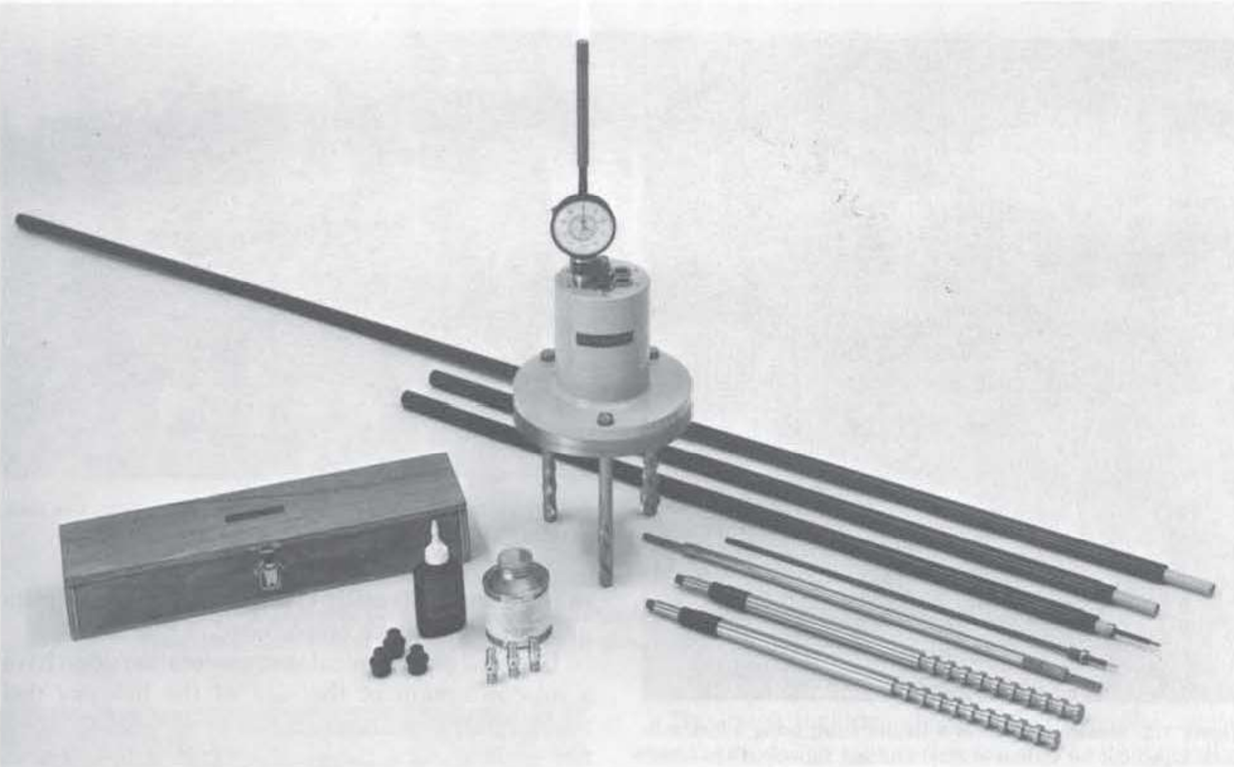


Figure 1.2. Examples of measuring instruments for monitoring field performance: (a) twin-tube hydraulic piezometer (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England); (b) vibrating wire piezometer (courtesy of Telemac, Asnières, France); (c) vibrating wire stressmeter (courtesy of Geokon, Inc., Lebanon, NH); (d) load cell (courtesy of Proceq SA, Zürich, Switzerland); (e) embedment earth pressure cell (courtesy of Thor International, Inc., Seattle, WA); (f) surface-mounted vibrating wire strain gage (courtesy of Irad Gage, a Division of Klein Associates, Inc., Salem, NH); (g) multipoint fixed borehole extensometer (courtesy of Soil Instruments Ltd., Uckfield, England); and (h) inclinometer (courtesy of Slope Indicator Company, Seattle, WA).



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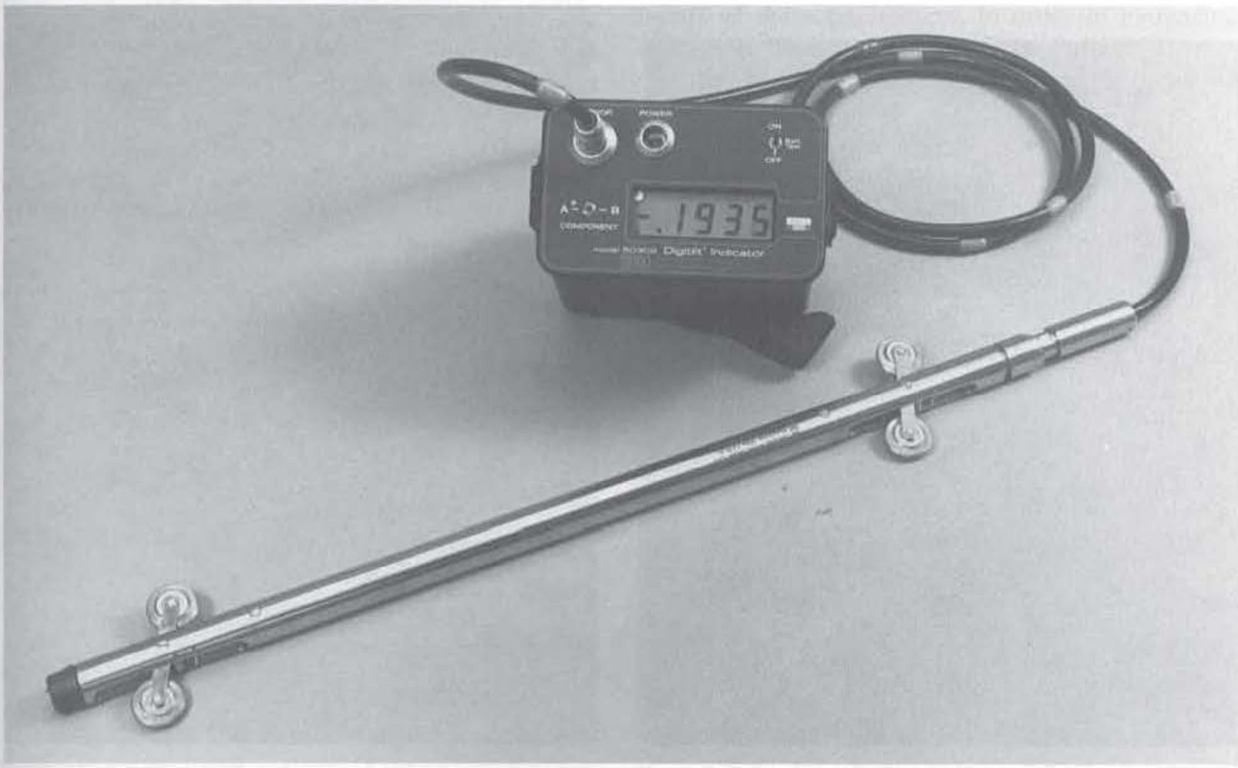

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Figure 1.3. Measuring load in a timber strut, using a hydraulic jack. Open cut for station in clay. Chicago Subway, 1940 (courtesy of Ralph B. Peck).

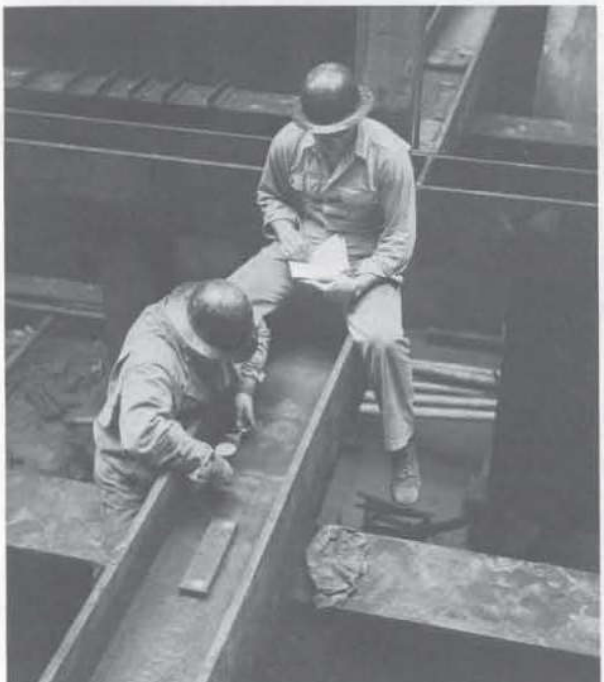


Figure 1.4. Determination of load in a steel strut, using a mechanical strain gage. Open cut for station in clay. Chicago Subway, 1948 (courtesy of Ralph B. Peck).

Figure 1.5. Installing twin-tube hydraulic piezometers. Usk Dam, England, 1952 (courtesy of Arthur D. M. Penman).

rational and systematic manner, and therefore planning procedures are emphasized in this book.

Users of geotechnical instrumentation often have a misconception of the size of the industry that manufactures instruments for performance monitoring. It is **not** a large industry: it is in fact very small. The manufacturing industry employs between 300 and 400 people worldwide, and the total annual volume of sales is about 30 million U.S. dollars. This misconception sometimes leads to unreasonable expectations on the part of users: we cannot expect the manufacturers to make large expenditures on research, development, and testing of special instruments, unless justified by the size of the market. If the market is small, special funding is needed.

Figure 1.6. Installing fixed embankment extensometer with vibrating wire transducer. Balderhead Dam, England, 1963 (courtesy of Arthur D. M. Penman).

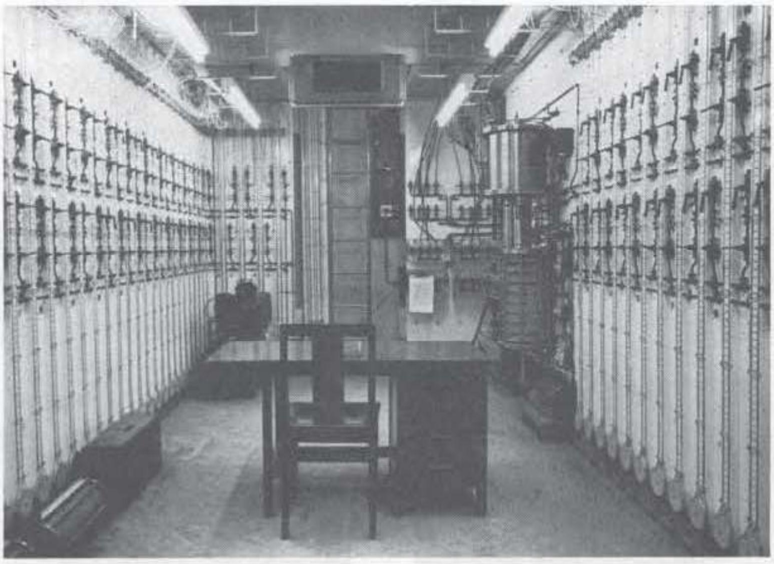


Figure 1.7. Manometer panels for twin-tube hydraulic piezometers. Plover Cove Main Dam, Hong Kong, 1965 (after Dunnicliff, 1968). Reprinted by permission of Institution of Civil Engineers, London.

Figure 1.8. Installing fixed embankment extensometers in embankment dam. Ludington Pumped Storage Project, Ludington, MI, 1972.

This book includes chapters that describe available methods for monitoring various geotechnically related parameters. The following is a summary rating of our current ability to obtain reliable measurements of these parameters, in order of increasing reliability:

- Total stress in soil and stress change in rock
- Groundwater pressure
- Load and strain in structural members
- Deformation
- Temperature

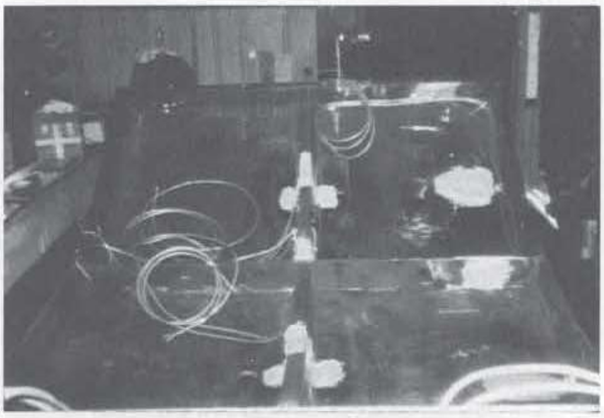


Figure 1.9. Bonded resistance strain gages on segmented steel liner for soft ground tunnel. Port Richmond Water Pollution Control Project, Staten Island, NY, 1974.

Figure 1.10. Installing multipoint fixed borehole extensometer above alignment of rock tunnel. East 63rd Street Subway, New York, NY, 1976.

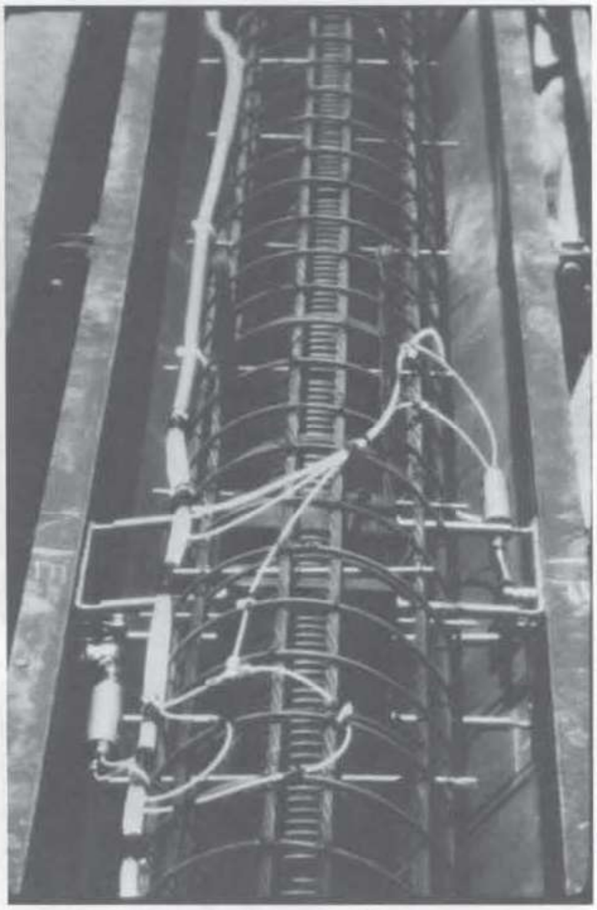


Figure 1.11. Pneumatic piezometer and earth pressure cell on opposite faces of precast concrete pile, prior to concreting. Keehi Interchange, Honolulu, HI, 1977.

Reliability is strongly influenced by the extent to which measurements are dependent on local characteristics of the zone in which the instruments are installed. Most measurements of pressure, stress, load, strain, and temperature are influenced by conditions within a very small zone and are therefore dependent on local characteristics of that zone. They are often essentially *point* measurements, subject to any variability in geologic or other characteristics, and may therefore not represent conditions on a larger scale. When this is the case, a large number of measurement points may be required before confidence can be placed in the data. On the other hand, many deformation measuring devices respond to movements within a large and representative zone. Data provided by a single instrument can therefore be meaningful, and deformation measurements are generally the most reliable and least ambiguous.

1.7. WHERE ARE WE GOING?

As we look ahead, there is no reason to believe in a decreasing role for geotechnical instrumentation. Geotechnical design and construction will always be subject to uncertainties, and instrumentation will continue to be an important item in our tool box. However, several current trends can be identified, each of which will continue in the future and change the state of the practice.

First, there is the advent of automatic data acquisition systems and computerized data processing and presentation procedures. Clearly, these systems and procedures have many advantages, yet we must remain aware of their limitations. No automatic system can replace engineering judgment. When automatic data acquisition systems are used,

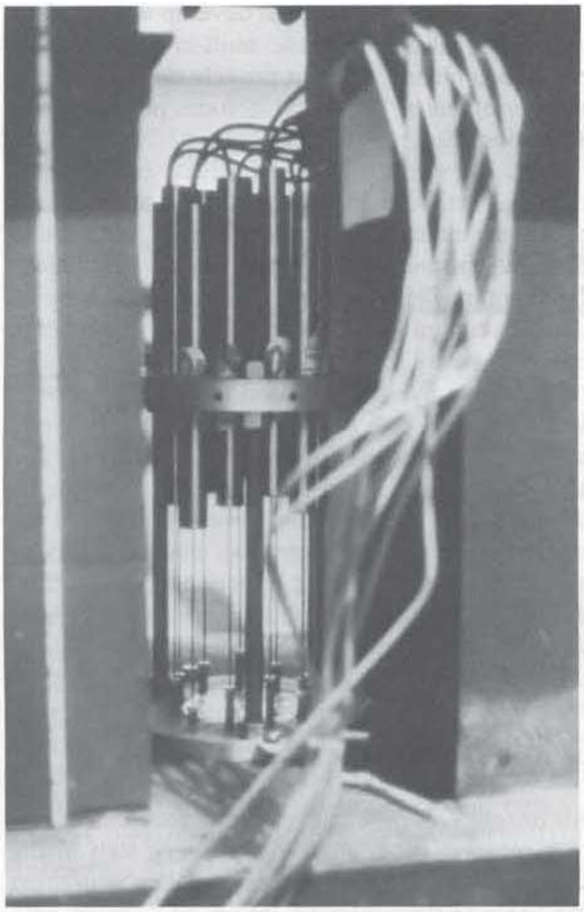


Figure 1.12. Electrical transducers for monitoring movement of multiple telltales during load test of precast concrete pile. Keehi Interchange, Honolulu, HI, 1977.

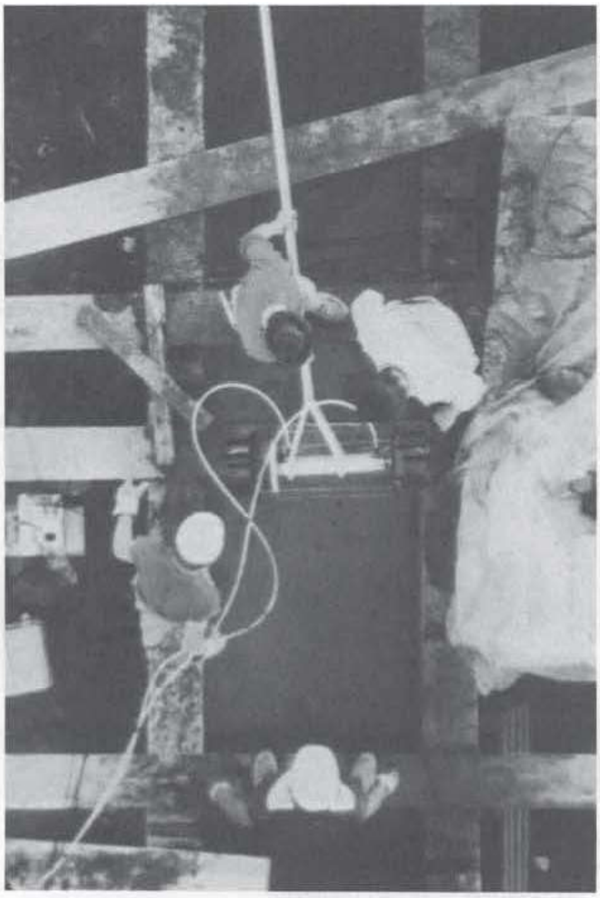


Figure 1.13. Installing gage with induction coil transducers, for monitoring convergence of slurry trench test panel in soft clay, Alewife Station, Cambridge, MA, 1978.

there is a real possibility that visual observations will not be made, that other factors influencing measured data will not be recorded, and that information will therefore not be available for relating measured effects to their likely causes. When computerized data processing and presentation procedures are used, there is a real possibility that engineering judgment will be given second place and that correlations between causes and effects will not be made. We should take all possible advantage of this exciting new technology but should never forget that judgment plays an important and often overriding role in the practice of geotechnical engineering.

Second, increasing labor costs in many countries have sharply reduced the availability of competent personnel. This trend of course encourages the use of automatic systems and procedures, yet reduces

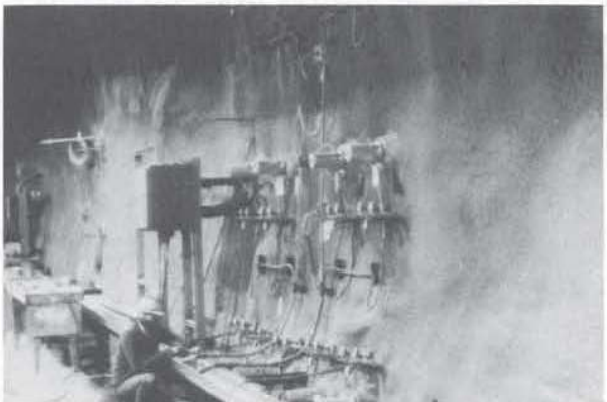


Figure 1.14. Heads of multipoint fixed borehole extensometers, installed to monitor rock movements during full-scale heater test for studies relating to disposal of high-level nuclear waste. Basalt Waste Isolation Program, Hanford, WA, 1980 (courtesy of Department of Energy).

Figure 1.15. Reading inclinometer during construction of underwater test fill. Chek Lap Kok Replacement Airport, Hong Kong, 1981 (courtesy of Leo D. Handfelt).

the number of personnel available for exercising engineering judgment.

Third, the use of design tools such as finite and boundary element modeling techniques leads to a need for field verification. Geotechnical instrumentation is likely to play an increasing role in providing a check on these advanced analytic predictions.

Fourth, there is a trend to develop and improve transducers and to include built-in features that create redundancy and that provide direct output in engineering units. The trend includes provisions for calibrations and zero checks.

Fifth, there is a trend toward use of new construction methods. Examples of innovations in the recent past include earth reinforcement, lateral support, and ground modification. These innovations often require field verification before they become widely accepted, and geotechnical instrumentation will always play a role.

The above five trends, good or bad, are inevitable. There is a sixth trend, which the author views as wholly bad: the procurement of instruments and the awarding of field instrumentation service contracts on the basis of the lowest bid. If an instrumentation program sets cost above quality of instruments, or fee above experience, dedication, and motivation of people, it deserves to be a failure. We must work hard to reverse this trend.

1.8. THE KEY TO SUCCESS

Full benefit can be achieved from geotechnical instrumentation programs only if every step in the planning and execution process is taken with great care. The analogy can be drawn to a chain with many potential weak links: this chain breaks down with greater facility and frequency than in most other geotechnical engineering endeavors. The links in the chain are defined in Chapter 26: their strength depends both on the capabilities of measuring instruments and the capabilities of people. The success of performance monitoring will be maximized by maximizing the strength of each link.

CHAPTER 2

BEHAVIOR OF SOIL AND ROCK

Many practitioners who become involved with geotechnical instrumentation programs do not have formal training in soil or rock mechanics. The purpose of this chapter is to present a brief and simple overview of the key aspects of soil and rock behavior that relate to the use of geotechnical instrumentation. For a thorough treatment of soil behavior readers are referred to Holtz and Kovacs (1981) and Terzaghi and Peck (1967). McCarthy (1977) presents similar material oriented for students at technical colleges. Rock behavior is well described by Blyth and DeFreitas (1974) and Franklin (1988).

2.1. BEHAVIOR OF SOIL

2.1.1. Constituents of Soil

Soil is composed of solid particles with intervening spaces. As shown in Figure 2.1, the particles are referred to as the *mineral skeleton* and the spaces as *pore spaces, pores,* or *voids*. The pore spaces are usually filled with air and/or water. A soil in which the pore spaces are completely filled with water is called a *saturated soil*. If any gas is present in the pore spaces, the soil is called an *unsaturated soil*. The term *partially saturated* is sometimes used, but because *it's either saturated or it isn't*, this is not a satisfactory term.

2.1.2. Basic Types of Soil

Soil can be categorized into two broad groups: *cohesionless soil* and *cohesive soil*. Cohesionless soils include sand and gravel, which consist of fragments of rocks or minerals that have not been altered by chemical decomposition. Inorganic silt is a fine-grained soil with little or no plasticity and can generally be classified as cohesionless. Organic silt is a fine-grained soil with an admixture of organic particles and behaves as a plastic cohesive soil. Clay is a cohesive soil consisting of microscopic and submicroscopic particles derived from the chemical decomposition of rock constituents.

2.1.3. Stress and Pressure

Stress and *pressure* are defined as force per unit area, with typical units of pounds per square inch (lb/in.^{2}) or pascals (Pa). Strictly, pressure is a general term meaning force per unit area, and stress is the force per unit area that exists *within* a mass. However, in geotechnical engineering, the terms

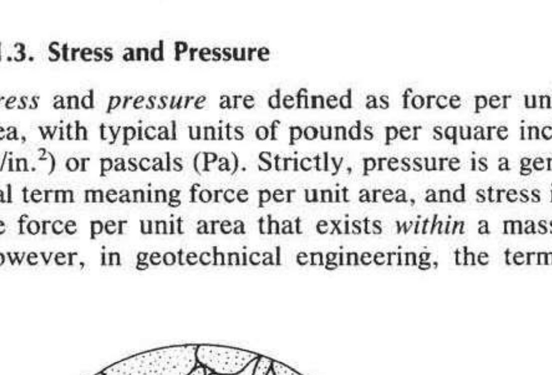


Figure 2.1. Constituents of soil.

are applied more loosely; for example, as will be discussed later, *earth pressure* and *soil stress* are used as synonyms.

2.1.4. Pore Water Pressure

When the pore spaces are filled with water (saturated soil), the pressure in the water is called the *pore water pressure* (Figure 2.2). It acts in all directions with equal intensity.

Figure 2.2. Pore water pressure caught in 10^{-6} fill (after Partially Integrated, 1962).

2.1.5. Total and Effective Stresses

Total stress is the total force transmitted across a given area, divided by that area. Thus, if a 2-foot square piece of wood is placed on the ground surface and a person weighing 200 pounds stands on the wood, the total stress in the ground immediately below the wood is increased by 50 lb/ft^2.

Effective stress can be explained by use of an analogy. Figure 2.3a shows saturated soil placed in a cylindrical container with a cross-sectional area, in plan, of 1 square inch. Figure 2.3b shows an analogy in which the resistance of the mineral skeleton to compression is represented by a spring, and the porous piston is replaced by an impermeable piston with a valved orifice. The orifice represents the resistance to the flow of water through the soil. The piston is assumed to be weightless, and the water is incompressible. Initially, the valve is closed. The spring has a stiffness of 10 lb/in., meaning that a force of 10 pounds is required to produce an axial

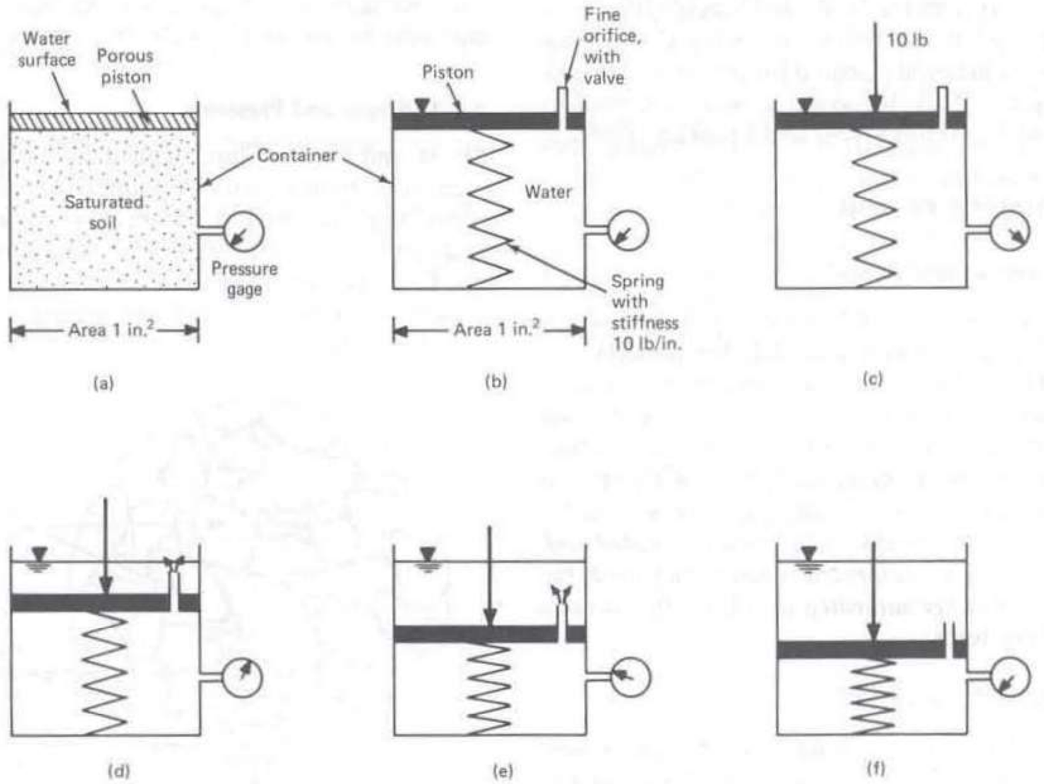


Figure 2.3. Spring analogy for soil behavior.

Table 2.1. Sharing of Applied Force

Figure 2.3	Condition	Valve Position	Force on Piston (lb)	Force Carried by Spring (lb)	Force Carried by Water (lb)
(b)	Initial	Closed	0	0	0
(c)	10 lb force applied	Closed	10	0	10
(d)	Piston descended 0.4 in.	Open	10	4	6
(e)	Piston descended 0.8 in.	Open	10	8	2
(f)	Piston descended 1.0 in.	Open	10	10	0

deflection of 1 inch. In Figure 2.3c, a 10-pound force has been applied to the piston. The water is not free to escape; therefore, the spring cannot compress and cannot carry the newly applied force. The water must therefore carry **all** the force, and the pressure gage will show an increase immediately as the force is applied. If the valve is now opened, water will pass through the orifice and the piston will descend. Figures 2.3d and 2.3e show intermediate steps, and Figure 2.3f shows the condition when the piston has descended 1 inch and there is no further flow of water. Because the spring has now been compressed 1 inch, it must be carrying a force of 10 pounds. The spring is now carrying **all** the force, and the pressure gage has returned to the same reading as in Figure 2.3b. Table 2.1 summarizes the steps and shows the sharing of applied force between the spring and water. It can be seen from the table that the sum of the forces carried by the spring and the water is always equal to the force on the piston.

Effective stress is defined as the force acting between the points of the mineral skeleton **per total area.** Because a cross-sectional area of 1 square inch has been chosen in the above analogy, all the forces in Table 2.1 are numerically equal to stresses in lb/in.^{2} if a real soil is considered. By thinking now in terms of stresses, it can be seen that the force on the piston represents the total stress, the force carried by the spring represents the effective stress, and the force carried by the water represents the pore water pressure. The following relationship always applies:

total stress = effective stress + pore water pressure.

This is Terzaghi's *principle of effective stress.* The following symbols are normally used:

Total stress, σ
Effective stress, σ'
Pore water pressure, u

Thus,

$$\sigma = \sigma' + u.$$

Forces and stresses are plotted in Figure 2.4a. It can be seen from the figure that the rates of pressure change decrease as time increases: this is consistent with the observation that the flow of water through the orifice in the piston decreases as the water pressure in the container decreases.

2.1.6. Consolidation

The process of gradual squeezing out of water, with the accompanying transfer of total stress to effective stress and decrease in pore water pressure, is called *consolidation.* Figure 2.4b shows the volume change that occurs during consolidation. The amount by which the pore water pressure exceeds the equilibrium pore water pressure is called the *excess pore water pressure,* and the gradual decrease of this pressure is often referred to as *dissipation* of pore water pressure.

As a practical example of consolidation, consider

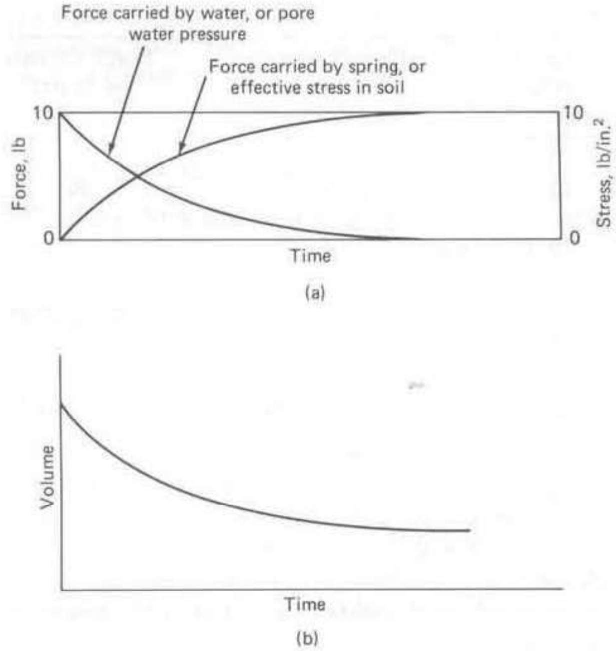


Figure 2.4. (a) Sharing of applied force and stress. (b) Volume change.

a layer of fill for a highway embankment, placed on a clayey foundation soil. As the fill is placed, pore water pressure in the foundation immediately increases and then starts to dissipate, resulting in *settlement*. The rate of settlement depends primarily on the *permeability* of the foundation soil. Permeability is a measure of the rate at which water can move through the soil. Cohesive soils have lower permeability than cohesionless soils, and therefore consolidation and settlement of cohesive soils occur more slowly.

2.1.7. Shear Strength

It has been shown above that effective stresses increase as consolidation progresses. Because an increase of effective stress means that the grains within the mineral skeleton are pressing more tightly together, it becomes increasingly harder to cause sliding between the grains. As an analogy, a brick can be placed on a concrete floor and pushed sideways to cause it to slide. If a second brick is now placed on top of the first brick, it takes more sideways force to cause sliding. It is therefore evident that the ability of a soil to resist sliding is related to the effective stress: the larger the effective stress in a particular soil, the greater is its *shear strength*. The shear strength is a measure of the resistance to sliding between grains that are trying to move laterally past each other.

It can now be seen that the gain in shear strength during the consolidation process can be monitored by measuring pore water pressure.

2.1.8. Normally Consolidated and Overconsolidated Soil

A *normally consolidated* soil is one that has never been subjected to an effective stress greater than the existing overburden pressure. Examples include ocean and lake-bed clays. An *overconsolidated* soil is one that has been subjected to an effective stress greater than the existing overburden pressure. Examples include clays such as London clay, where thousands of feet of overburden have been eroded.

2.1.9. Difference Between Pore Water Pressure and Groundwater Level

The *groundwater level* is defined as the upper surface of a body of groundwater at which the pressure is atmospheric.

Figure 2.5 shows three perforated pipes installed in a soil within which there is no flow of groundwater; therefore, groundwater pressure increases uniformly with depth. When such equilibrium conditions exist, the level of water within the pipe will rise to the groundwater level, independent of the location of the perforations.

Now consider what happens when a layer of fill is placed above the sand shown in Figure 2.5. Fig-

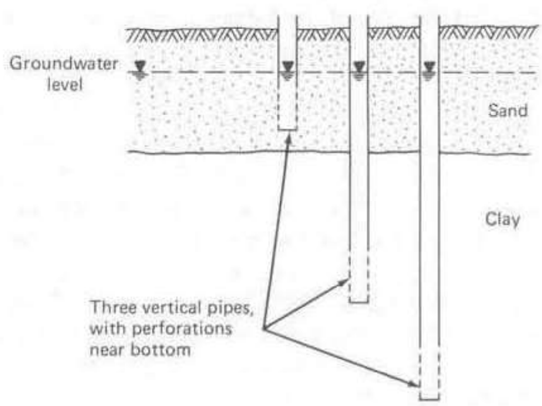


Figure 2.5. Groundwater level when there is no flow of groundwater.

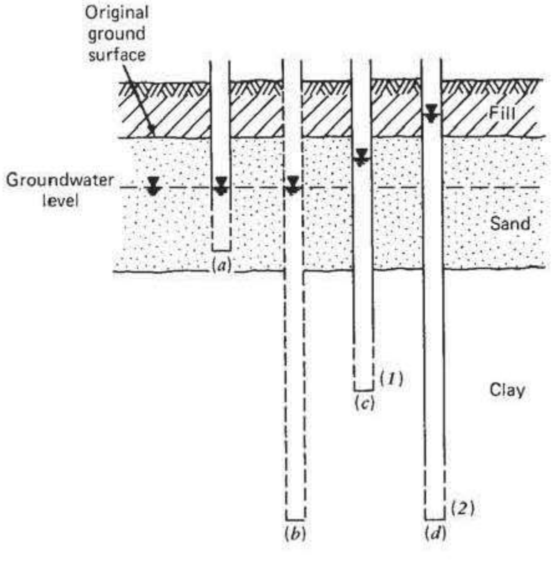


Figure 2.6. Groundwater level and pore water pressure when there is flow of groundwater.

ure 2.6 shows the condition soon after fill placement, when consolidation is not yet complete; therefore, excess pore water pressures exist in the clay and the groundwater is no longer in equilibrium. The four perforated pipes in Figure 2.6 are installed such that soil is in intimate contact with the outsides of the pipes. Pipe (*b*) is perforated throughout its length; the remaining pipes are perforated only near the bottom. Because of the high permeability of sand, excess pore water pressures in the sand dissipate almost immediately and do not exist there. As in Figure 2.5, pipe (*a*) indicates the groundwater level. Pipes (*c*) and (*d*) indicate the pore water pressures in the clay at locations (*1*) and (*2*). The water level in pipe (*c*) is shown lower than in pipe (*d*) because more dissipation of pore water pressure has occurred at level (*1*) than at level (*2*): the drainage path for excess pore water pressure is shorter, and therefore the rate of dissipation is greater. In the case illustrated, pipe (*b*) is likely to indicate the groundwater level because the permeability of the sand is substantially greater than that of the clay: excess pore water pressures in the clay will cause an upward flow of water from the clay to the sand, via the pipe.

In the more general case of a perforated pipe installed through two or more strata, either with perforations throughout or surrounded with sand throughout, an undesirable vertical connection between strata is created, and the water level in the pipe will usually be misleading. This situation is discussed further in Sections 9.1 and 9.12.2, and pipe (*b*) should not be used in practice.

Pipe (*b*) is called an *observation well*. Pipes (*a*), (*c*), and (*d*) indicate pore water pressure and its dissipation within the sand or clay and are called *piezometers*. Details of both types of instrument are given in Chapter 9. As a general rule, piezometers are sealed within the soil so that they respond only to changes of pore water pressure at a local zone, whereas observation wells are **not** sealed within the soil, so that they respond to changes of groundwater pressure throughout their length.

2.1.10. Positive and Negative Pore Water Pressures

All references to pore water pressures in earlier parts of this chapter have been to pressures that are above atmospheric pressure. These are called *positive* pore water pressures. As shown in Figures 2.4a and 2.6, pore water pressure can be increased by applying a compressive force to the soil. The example of placing fill for a highway embankment has been given. Pore water pressure can also increase when a shear force is applied to a soil in which the mineral skeleton is in a loosely packed state. When the array shown in Figure 2.7a is sheared, it decreases in volume. When the pore spaces are filled with water, and water is prevented from leaving, pore water pressure will increase. As a practical example, consider a foundation failure of an embankment on soft ground, with a foundation of loose alluvial material. The material beneath the toe is subjected to lateral shear forces as the embankment is constructed. These shear forces cause deformation, increased pore water pressure, and decreased strength, and therefore increase the tendency toward failure.

Pore water pressure can also be *negative*, defined as pore water pressure that is less than atmospheric pressure. Negative pore water pressure can sometimes be caused by removing a compressive force that has been applied to a soil. For example, when an excavation is made in clay, the soil below the base of the excavation is unloaded, causing an initial decrease of pore water pressure, which may become negative. Pore water pressure can also decrease when a shear force is applied to a soil in which the mineral skeleton is in a densely packed state. When the array shown in Figure 2.7b is sheared, it increases in volume. If the pore spaces

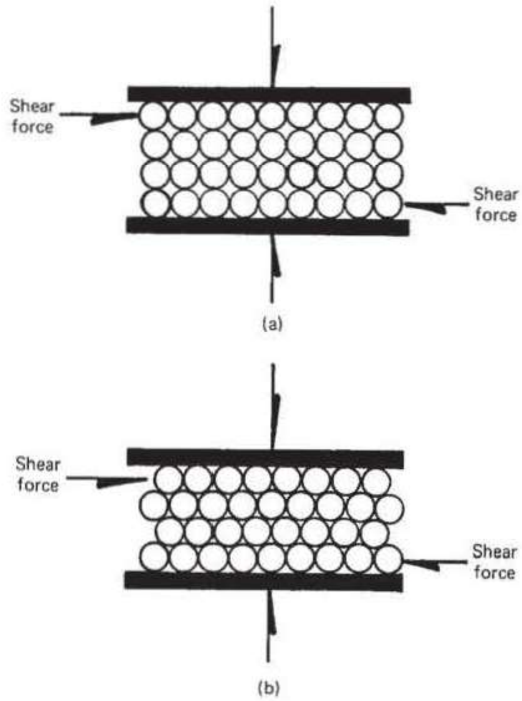


Figure 2.7. (a) Positive and (b) negative pore water pressure caused by application of shear force.

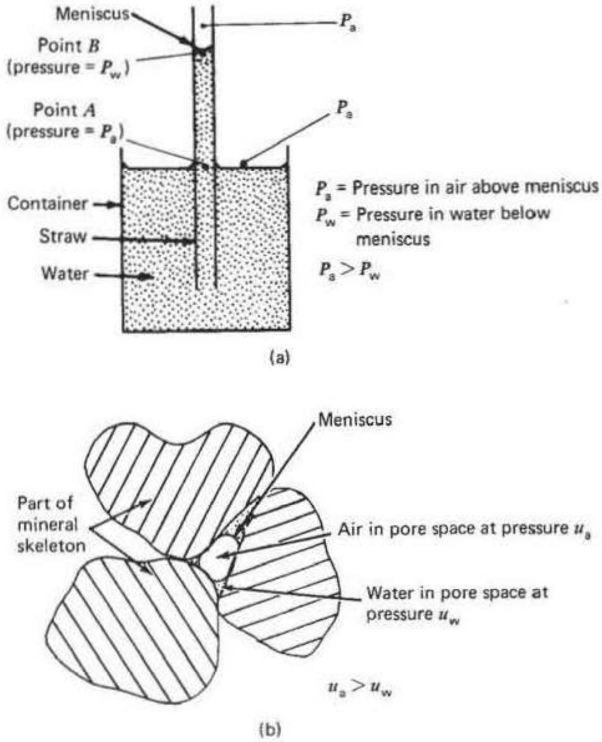


Figure 2.8. Pore gas and pore water pressure: (a) straw in container of water and (b) element of unsaturated soil.

are filled with water, and additional water is prevented from entering, pore water pressure decreases. As a practical example, consider the excavation of a slope in overconsolidated clay. Pore water pressure decreases as a result of unloading, but significant additional decrease can be caused by the development of lateral shear forces. These shear forces cause deformation, a temporary decrease in pore water pressure, and a temporary increase in strength.

2.1.11. Pore Gas Pressure

In an *unsaturated* soil, both gas and water are present in the pore spaces, and the pressure in the gas is called the *pore gas pressure*. As with pore water pressure, pore gas pressure act in all directions with equal intensity. Examples of unsaturated soil include compacted fills for embankment dams and organic soil deposits in which gas is generated as organic material decomposes. When the gas is air, the term *pore air pressure* may be used.

The pore gas pressure is always greater than the pore water pressure. Consider the analogy of a straw placed in a container of water, as shown in Figure 2.8a. The water level in the straw rises to a level higher than in the container and is "held up" by surface tension forces between the straw and water at the meniscus. The pressure in the air is atmospheric pressure P_a; therefore, the pressure at point A must also be P_a: if it were not so, there would be a flow of water to create equality of pressures at the same level. The pressure at point A must be greater than that at point B (P_w), because the pressure in water increases as depth below the surface increases. P_a is therefore greater than P_w, and the pressure at the air side of the meniscus is greater than the pressure at the water side. It is well known that water in a smaller diameter straw rises to a greater height: the pressure difference across the meniscus is therefore greater, and the radius of curvature of the meniscus is smaller.

Now consider a meniscus between air and water in a pore space within soil, as shown in Figure 2.8b. The same rule applies as in the analogy: the pore air pressure u_a is greater than the pore water pressure u_w. The smaller the pore space, the smaller the radius of curvature of the meniscus, and therefore the difference between pore air pressure and pore water pressure is greater.

2.1.12. Other Terms Relating to Behavior of Soil

A *perched groundwater level* is above and not hydraulically connected to the more general groundwater level. For example, groundwater may be trapped above a clay layer at shallow depth, whereas the general groundwater level is in a lower layer of sand.

An *aquifer* is a pervious soil or rock stratum that contains water. An *artesian aquifer* is confined between two relatively impervious layers and capable of carrying groundwater under pressure.

The *piezometric elevation*, or *piezometric level*, is the elevation to which water will rise in a pipe sealed within the soil, as shown for pipes (c) and (d) in Figure 2.6.

2.1.13. Primary Mechanisms that Control Behavior of Soil*

The primary mechanisms that control the engineering behavior of soil may be categorized as hydraulic, stress-deformation, and strength mechanisms.

When a soil is subjected to excess pore water pressure, the water flows through the pore spaces in the soil. These may be fairly large, as are the spaces in openwork gravel, or microscopic, as in the spaces between the finest clay particles. As it flows, water reacts against the particles, causing friction and a resistance to flow. The amount of friction depends on both the velocity of flow and the size of the soil particles. In a very fine-grained soil, there is a larger area of contact between the water and soil particles than in a coarse-grained soil, so that there is more friction. The permeability of the soil is governed by the amount of friction and resistance to flow. Just as the soil acts on the water to retard the flow, so also does the water act on the soil. Water exerts a tractive force on the soil, in the direction of flow, owing to the friction. If the soil is saturated, water acts also with a buoyant force on the soil, whether or not the water is moving.

Stress-deformation characteristics of cohesive soil are governed by the time required for water to flow through the pore spaces in the soil and for consequent volume changes to occur. For cohesionless soils, most of the volume change is caused by rearrangement of the relative positions of grains as shear deformation occurs.

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 stresses increase beyond those that can be sustained by the soil and the strength is exceeded.

Footing Foundations

Figure 2.9 depicts a load applied to a footing foundation located on a soil mass. In the upper figure, the load is substantially less than that required to cause failure. The footing transfers the stress to the soil, causing the soil to compress in the vertical direction, and the footing settles. In the lower figure, a larger load is applied to the footing, stressing the soil and causing a rotation that tends to push the adjacent block of soil out of the ground, as if it were a rigid body. This movement is opposed by the shearing resistance of the soil along the potential failure surface. In a cohesionless soil, this shearing resistance is frictional, and the magnitude of friction depends directly on the normal stresses against the potential failure surface. In a cohesive soil, this shearing resistance is often purely cohesive, independent of the normal stresses during the shearing process but dependent on the history of previous effective stresses.

Deep Foundations

Figure 2.10 shows a loaded pile or drilled shaft, embedded in soil. The pile moves downward in response to the load and, as it moves with respect to the soil, it mobilizes the skin friction or shearing stress, which resists the sliding along the soil/pile interface. This accounts for part of the support that the pile receives from the soil. The rest of the support is from point bearing, the same mechanism that supports a footing on soil.

When soil settles with respect to a pile or drilled shaft, the pile is loaded by frictional forces at the interface, causing an increase in stress within the pile and/or increased settlement. The loading is referred to as *downdrag* or *negative skin friction*. Downdrag loading may be caused by several events. First, when piles are driven through fill that overlies clay, the loading from the fill may cause continuing primary consolidation or secondary time effects. Second, settlements are caused

* Written with the assistance of Norbert O. Schmidt, Professor of Civil Engineering, University of Missouri–Rolla, Rolla, MO.

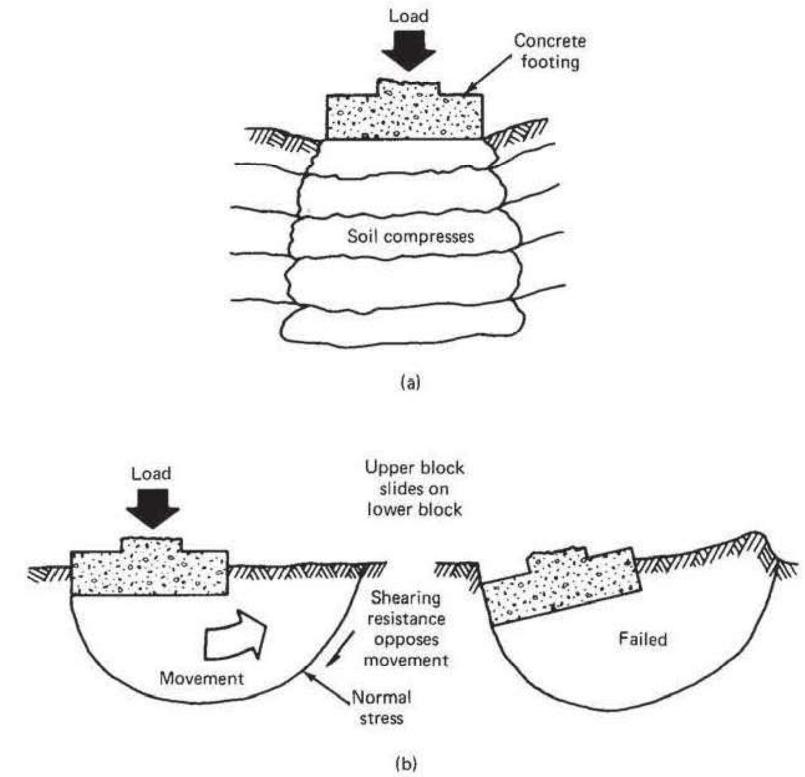


Figure 2.9. Behavior of a footing foundation: (a) settlement of footing and (b) bearing failure.

when ground surface loading is increased after piles are driven, for example, by placing an approach fill alongside a pile-supported bridge abutment. Third, dewatering, site grading, and/or vibration during pile driving may cause settlement and downdrag loading.

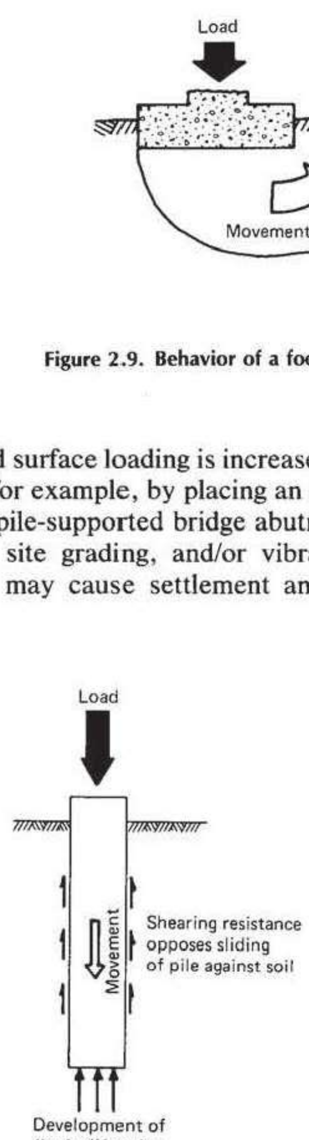


Figure 2.10. Behavior of a driven pile or drilled shaft.

Excavated and Natural Slopes

Excavated and natural slopes often involve layered sediments, which may be parallel to the original surface of the slope. One of these layers is usually weaker than the others, so the potential surface of sliding is noncircular and tends to follow the weakest layer as depicted in Figure 2.11. When the soil is relatively homogeneous, the potential surface of sliding may be more circular. The stability of slopes in soil is controlled by the ratio between available shearing resistance along a potential surface of sliding and the shear stress on that surface. Any increase in pore water pressure along the potential surface of sliding decreases the shearing resistance and the factor of safety against sliding.

Retaining Walls

Soil is only partially capable of supporting itself. Sand requires a retaining structure if it is to stand vertically, but clay may support itself vertically for limited heights for some period of time. Figure 2.12 shows a retaining wall with forces against it. The earth pressure shown pushing the wall towards the

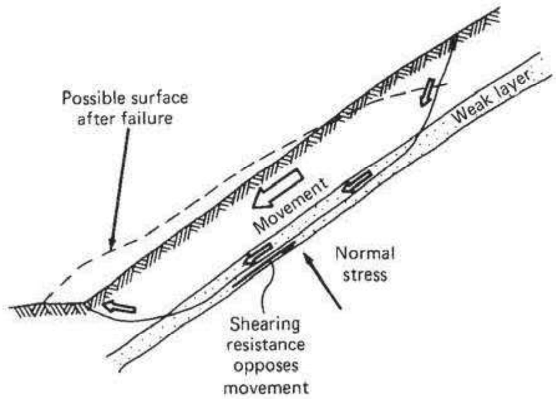


Figure 2.11. Failure of a slope in layered soil.

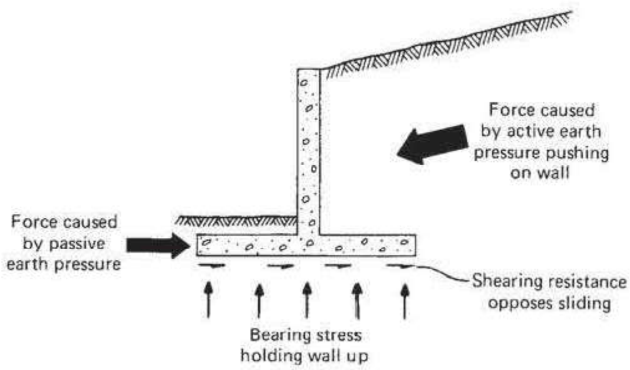


Figure 2.12. Behavior of a retaining wall.

left is that portion of the pressure that remains after the soil tries to support itself. It is known as the *active earth pressure* and is reduced to its minimum value when the wall slides and tilts slightly to the left. The sliding also mobilizes the shearing resistance between the soil and the base of the wall. In front of the wall on the left, the *passive earth pressure* is mobilized as the soil resists sliding.

Braced Excavations

When compared with retaining walls, braced excavations differ in their mobilization of earth resistance because significant sliding or tilting toward the excavation is not permitted. The wall of a braced excavation may be braced against the opposite wall with *cross-lot bracing,* braced against the bottom or the adjacent wall with *rakers,* or held in place by *tieback anchors* that pull against the soil outside the excavation. Stresses against a braced wall are greater than against a retaining wall because the passive pressure is greater. However, if bracing is properly installed, deformation of the soil is small and buildings on adjacent sites may therefore experience only small settlements and little distress. When a deep braced excavation is made in soft soil, soil tends to move into the bottom of the excavation: this is called *bottom heave,* and special construction techniques may be required to control deformation.

Embankments

Embankments of relatively homogeneous soils overlying hard ground tend to fail by rotation along an almost circular arc. This is depicted in Figure 2.13. As with the bearing failure of a footing foundation, shown in Figure 2.9, the soil behaves as if it were a rigid body. Rotation is resisted by mobilization of shearing resistance along the arc, as described for footing foundations.

Embankments on Soft Ground

The behavior of embankments on soft ground tends to be dominated by the properties of the soft ground. A potential circular failure surface may develop, with a large portion of the surface in the weak foundation material as shown in Figure 2.14a. However, the loading of the embankment may cause settlement and lateral bulging of the foundation, as shown in Figure 2.14b, long before the rotational failure occurs. The lateral bulging of the soft ground transfers horizontal tension to the embankment, which may experience tension cracking, since it is less deformable than the soft foundation.

Embankment Dams

Embankment dams may experience distress or failure in a variety of ways.

Overtopping may result from incorrect estima-

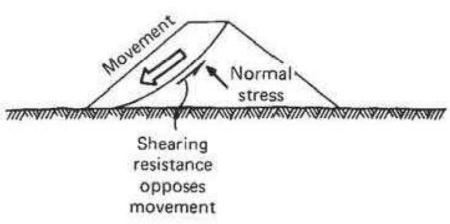


Figure 2.13. Behavior of an embankment of relatively homogeneous soil.

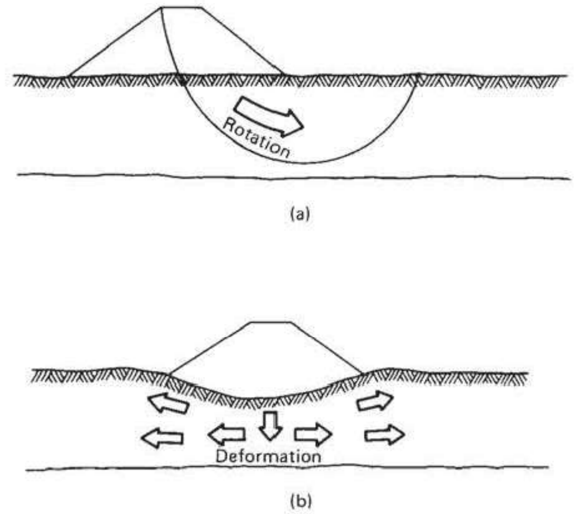


Figure 2.14. Behavior of an embankment on soft ground: (a) rotational slide along arc and (b) settlement and lateral bulging of soft foundation.

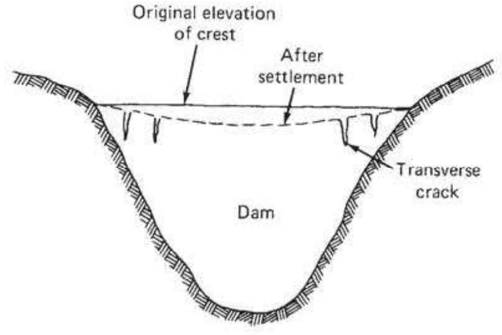


Figure 2.15. Transverse cracking of an embankment dam.

tion of storm water volume or duration. It may also be the result of slope failure on the reservoir rim, causing a large volume of material to slide into the reservoir and induce a wave, as occurred at Viaont Dam in Italy.

Internal erosion, or *piping*, can cause distress to an embankment dam. Erosion occurs where seepage water is flowing at a velocity sufficient to carry soil particles along with the water. If the soil has some measure of cohesion, a *pipe* or small tunnel may form at the downstream exit of the seepage path as the soil is eroded. As the pipe lengthens inside the embankment, there is less resistance to flow, the flow in the pipe increases, and piping accelerates. Silts and fine sands are most prone to piping, because they erode easily, and when moist are sufficiently cohesive to form the walls of a pipe without collapsing. In a well-designed embankment dam, piping is prevented by sizing downstream material such that the pore spaces of that material are just smaller than the larger sizes of the mineral skeleton in the adjacent upstream material, so that migration of particles is blocked. Such a downstream material is known as a *filter*.

When the slopes of a dam are too steep, the dam may fail as described above in the discussion on embankments. Many river sediments consist of *soft ground*, and a dam constructed over these materials may behave as shown in Figure 2.14.

If a dam is built on loose granular material, especially silty sand, an earthquake can cause the foundation to liquify and flow, as with the near failure of the San Fernando Dam in California.

Even if the design of the dam is adequate, the weight of the embankment dam on the underlying soil or rock must be considered. Heavily loaded soil under the dam may settle, and there will be downward and lateral movements of the base of the dam. Moreover, even well-compacted fill material will experience settlements when loaded with overlying material, and poor compaction procedures will result in greater settlements. If the crest of the dam is initially level, with time it will settle, and the center of the dam will settle the most. If the abutments are steep, the settlements may put the crest of the dam in tension, as shown in Figure 2.15, possibly causing cracks transverse to the axis of the dam.

Soft Ground Tunnels

When a tunnel is excavated in soft ground, it may be excavated to a diameter slightly larger than its lining so that the lining may be placed, and the soil may be unsupported for a short time period. Stresses are relieved and soil tends to move inwards toward the tunnel cross section as well as into the face. Although the space between the soil and lining is usually small and may be grouted, the ground surface may settle, with greatest settlements occurring directly over the tunnel as shown in Figure 2.16.

If the groundwater level was previously above the invert of the tunnel, the tunnel may drain the soil. In granular soils, the groundwater may have to be predrained to the level of the invert, so that the tunnel can be constructed. The reduction in groundwater level will increase effective stresses in the soil

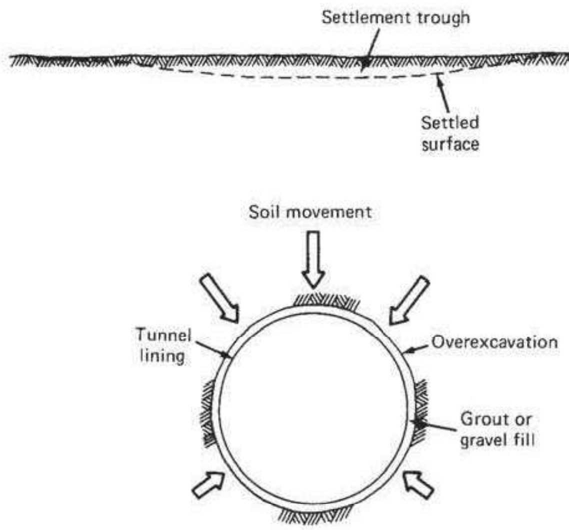


Figure 2.16. Behavior of a soft ground tunnel. Note that soil also tends to move toward the face of the tunnel.

profile below the original water level, and in cohesive soils this will cause the initiation of consolidation settlements. In cohesionless soils, the increased stresses will tend to cause immediate strains in the soil and therefore settlement.

2.2. BEHAVIOR OF ROCK*

2.2.1. Geologists' View of Rock

Rock is by definition a material older than about 1 million years; a material formed before the *Pleistocene* ice age. The oldest rocks, which are more than 2 billion years old, have been welded by geologic processes and so are usually stronger than the more recent rock formations.

Rock types are classified geologically according to their *genesis,* the way in which they were formed. *Igneous rocks,* such as granites and basalts, are those formed by the cooling and solidification of a hot molten magma originating in the earth's core. Although in our life span they are strong and durable, over geologic time periods they dissolve in the groundwater or break down to form soils through heating and cooling, freezing and thawing, and chemical attack. *Sedimentary rocks,* such as sandstones, limestones, and shales, are those formed when soils are welded or cemented together by overburden pressure or by intergranular cements deposited from groundwater solutions. Other sedimentary rocks, termed *evaporites,* such as rock salt, potash, anhydrite, and gypsum, are formed as crystalline residues when a saline lake dries up. The third main category, *metamorphic rocks,* such as slates, marbles, and schists, are those formed from either igneous or sedimentary types as a result of extreme geologic heating or pressure, sufficient to cause recrystallization and the formation of new minerals.

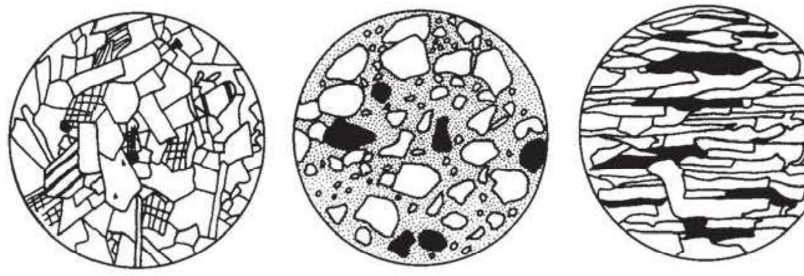
The microtexture of most rocks is characteristically granular, as shown in Figure 2.17. Igneous rocks are composed of grains that are angular and interlocked, with microcracks along the grain boundaries that give a very low level of intergranular porosity. Sedimentary rocks, in contrast, usually have rounded grains with not much interlocking. The intergranular porosity of sedimentary rocks is generally greater than igneous rocks, but depends on the degree to which the pore spaces have been filled by finer-grained fragments or cement. Metamorphic rocks tend to have elongated grains, oriented subparallel to each other as a result of recrystallization, which makes them *fissile,* meaning easily split along the alignment of the grains.

Rocks are composed of minerals. Simple rock types are formed from just one mineral variety, for example, marble is composed of interlocking crystals of calcite only and quartzite from interlocking quartz. Most rocks, however, are *polymineralic,* meaning composed of several mineral types. Granite, for example, is composed of quartz, feldspar, and mica.

Geologic names are assigned to rock materials according to their mineral composition and also their grain size. For example, rocks composed mainly of calcite fragments are called limestones, and rocks composed mainly of quartz fragments are called siltstones, sandstones, or conglomerates, depending on whether the typical grain size is small, medium, or large.

On the larger scale, different *primary structures* have become solidified into rock formations by the very different processes of sedimentary and igneous rock formation. Sedimentary rocks are characteristically *bedded,* being composed of *beds* (layers) of materials such as sandstone and shale, separated by *bedding planes* that run continuously through the

*This section has been coauthored by John A. Franklin, Consultant and Research Professor, University of Waterloo, Ontario, Canada.



Igneous rock: angular, interlocking grains with low porosity

Sedimentary rock: rounded grains in a fine-grained matrix, with high porosity

Metamorphic rock: elongated, subparallel grains imparting fissility to the rock

Figure 2.17. Microtexture of rocks.

deposit and form planes of weakness. *Flow banding* is a characteristic of igneous volcanic rocks such as basalt, in which layers of lava are often separated by volcanic froth (pumice stone) and windborne or water-deposited layers of ash or bentonite clay. *Tension joints* (cracks) have been formed by contraction of igneous rocks during cooling and of sedimentary rocks during the accumulation of overlying material.

Secondary structures have been generated by the subsequent action of metamorphism, heat, and pressure, caused mainly by drifting of rigid continental blocks on the more fluid mantle and core of the earth. Slowly but continuously the continents are being thrust one beneath the other, in a process of *continental drift* that is creating mountain chains and belts of volcanic and earthquake activity along the lines of impact. This has resulted in the folding and sometimes complete overturning of beds that were originally horizontal. The same forces acting on more brittle rocks have created not only further tension joints but also *faults*, defined as surfaces of sliding and shearing. *Fault zones* are common, consisting of several subparallel faults or shears (small faults) with interposed *fault breccia* (broken rock) and *fault gouge* (finely crushed rock and clay).

2.2.2. Engineers' View of Rock

The many hundreds of rock names assigned by geologists often mean little in the context of an engineering project. The engineer is concerned not so much with the history of the rock or its precise mineral composition as with its potential behavior in an excavation or foundation. When classifying rocks for engineering purposes, the engineer must consider properties that often go unreported by the geologist yet are critical to the mechanical character and behavior of the rock mass.

On the small scale, the engineer has to consider how mineral composition and microtexture affect properties such as rock strength and durability. Pores are by far the weakest rock-forming component, and porous rocks are much weaker and more deformable than dense ones. *Porosity* (the ratio of pore volume to total volume) can exceed 50% in some sandstones and highly weathered granites. *Hard rocks (competent rocks)* are usually formed from hard and resistant minerals. *Soft rocks* such as shales are usually composed of clay and similar minerals that are themselves weak and deformable. These rocks often break down when subjected to wetting and drying because their minerals tend to attract a boundary layer of water. Limestones composed of calcite and salt rocks composed of saline minerals, although quite strong and brittle when found in near-surface engineering construction, deform and flow quite readily when subjected to the higher temperature and pressures found in deep underground mines.

Mineral composition has an important influence on how rocks deform in response to stress. Those like granite that are composed mainly of hard minerals are usually *elastic*, because when moderate levels of stress are applied and then removed the rocks return to their original size and shape. If the small deformations that occur are in direct proportion to the magnitude of the applied stresses, the rock is described as *linearly elastic*. At higher stresses and after very little deformation, they fail suddenly in a *brittle* manner. Rocks like potash that contain soft minerals are often *inelastic* and may *creep* (continue to distort) when a high level of stress is maintained. This is termed *viscous* or *vis-*

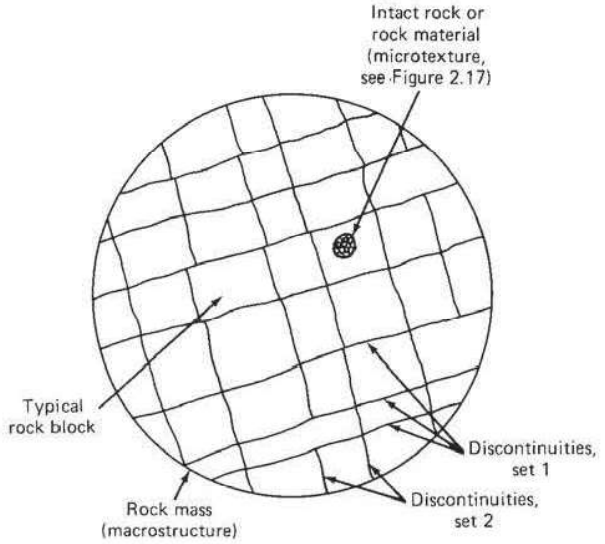


Figure 2.18. Rock mass terminology.

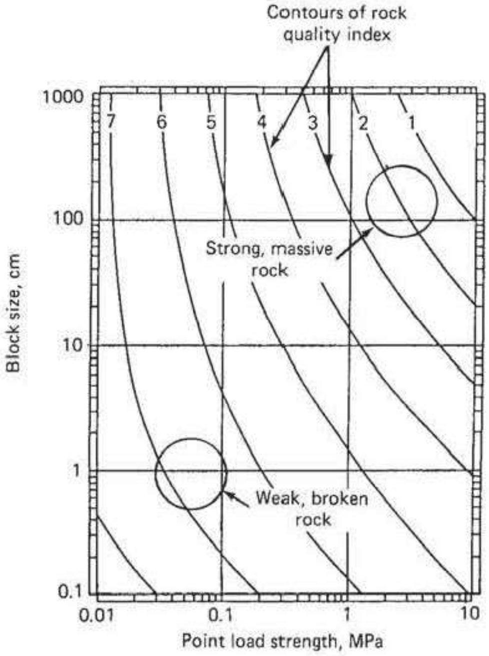


Figure 2.19. Size–strength rock mass classification diagram (after Franklin, 1986).

coelastic behavior. Their failure is *ductile* (gradual and accompanied by large deformations).

Rocks with subparallel platy minerals, as noted earlier, tend to be fissile and are also *anisotropic* (with strengths that vary according to the direction of loading). Slates are characterized by *slaty cleavage* so that they can be split readily into thin plates, and schists and gneisses by *foliation surfaces* along which platy mica minerals are abundant. In general, such rocks are much weaker than those with randomly oriented, equidimensional, and interlocking grains.

Even more important in an engineering context than minerals and microtexture are the features of rock on a larger scale. Rock engineers distinguish between *intact rock* and *rock mass*. The properties of intact rock, otherwise termed *rock material*, are those that can be measured by testing a small specimen of solid rock in the laboratory. The same properties measured on the scale of the rock mass are affected by large-scale structural features and can only be measured directly by large-scale in situ tests. Figure 2.18 shows the difference between intact rock and rock mass. The rock mass is nearly always much weaker, more deformable, and more permeable than the intact material it contains. This is because of the presence of *discontinuities*, a global term used for the various types of fracture and weakness planes discussed earlier: joints, faults, shears, bedding planes, and surfaces of cleavage and foliation. Joints are the most common, and the terms *jointing* and *jointed* (e.g., widely or closely jointed) are often used to apply to discontinuities irrespective of their origin. Nearly all aspects of rock behavior, both at the surface and underground, are controlled much more by the characteristics of such discontinuities than by those of the intact rock blocks within the mass.

Figure 2.19 shows a multipurpose *size–strength* rock mass classification that takes into account the two features of the rock mass that are usually the most important in engineering applications: the *size* of rock blocks and their *strength*, plotted respectively along the vertical and horizontal axes. Zones in the rock mass that plot toward the lower left of the diagram are broken and weak and easy to excavate but difficult to support in excavations. Those toward the upper right are massive and strong and require blasting for excavation but are often self-supporting. The diagram is contoured to give a *rock quality index*, which is a combined measure of block size and strength.

Note must be taken of other discontinuity characteristics that affect rock mass character and behavior, such as the orientation (dip magnitude and direction) of joint sets. In a rock slope, for example, horizontal jointing generally has little effect on stability, whereas joints that dip steeply into the excavation may well be a source of sliding failures. Other characteristics of discontinuities such as roughness, continuity, and the presence or absence of a clay infilling determine the shear strength of the discontinuity surfaces. Rough joints with no infilling are strong compared with smooth, slickensided, and clay-filled fault planes.

2.2.3. Water in Rock

Seepage through rock masses occurs almost exclusively along discontinuities, with little or no flow through the intact rock blocks unless these are extremely porous. Discontinuity characteristics govern water pressures and flow rates through the rock mass, just as they govern mechanical characteristics such as rock mass strength and deformability. Flow and pressures are governed by the *aperture* (openness or tightness) of the discontinuities and by their spacing and continuity.

Joint water pressures within a rock mass can have a most important influence on stability. When there is a need to monitor these pressures, measurements must be made within zones of open jointing. The principle of effective stress discussed for soil in Section 2.1.5 applies equally to the rock mass, except that the pore water and mineral skeleton system are replaced by the joint water and rock block system.

In strong and durable rock masses, high joint water pressures are the main problem related to groundwater, and these can usually be relieved effectively by drainage. In weaker and less durable rock types such as shales, further problems may result from swelling, and rocks containing clay minerals are particularly prone to breakdown. Closely jointed or less durable rock types are also susceptible to internal erosion within the jointing or to external erosion by processes of raveling and slaking. Vertical rock cliffs are often undercut by erosion, and groundwater can be a hazard also in tunnels and underground chambers. Clayey fault gouge acts as a barrier to high-pressure water. Tunnels penetrating such faults can encounter sudden and catastrophic inflows of water and broken rock.

In other respects, the groundwater regime in rocks is similar to that found in soils, so that terms such as groundwater level, perched groundwater level, aquifer, artesian aquifer, and piezometric elevation and level, defined in Section 2.1, apply with the same definitions in a rock engineering context.

2.2.4. Stress in Rock

In contrast to soils, which are usually deformable, rocks are rigid and permit the transfer and storage of high stresses. Stability of a rock mass therefore depends on three principal factors: the characteristic of the intact rock and particularly of the discontinuities, the characteristics of the groundwater regime, and the magnitudes of ground stress in relation to rock strength and brittleness.

The stresses acting vertically at depth can be estimated, as for soils, from the weight of overlying materials. The magnitudes of horizontal stresses cannot be estimated in this way and can be much greater than those acting vertically. At some locations, even close to the surface, horizontal stresses can be ten or more times greater than vertical stresses. High horizontal stresses close to the surface can result in buckling and heaving of shallow excavations and in squeezing and cracking of tunnel linings and buried concrete pipes. When high stresses surround an underground excavation, they can be a stabilizing influence, helping to hold in place the rock arch above a tunnel, a mine stope, or an underground powerhouse cavern. However, if excessive they can cause extensive damage in the form of squeezing or rockbursting.

Rock engineers distinguish between *virgin stresses* (also called *in situ stresses*) created by geologic processes and *induced stresses* caused by excavation. We can speculate that the virgin stresses were first established by continental drift as discussed in Section 2.2.1. They have since been modified by the deposition and erosion of geologic materials. In the past, many locations on the surface of the earth were overlain by several miles of soil, rock, or ice. Geologic weathering and erosion over many millions of years have removed this overburden. However, the horizontal stresses existing in rocks that were once deeply buried may not be entirely relieved by erosion. Rigid rock types, in particular, often contain large virgin horizontal stresses that reflect their geologic history and that have important influences on present-day engineering construction.

When an excavation is made in rock, the stresses originally carried by the excavated material are transferred to the rock that remains in place. Stress levels around tunnels are amplified to several times their virgin values. The rocks may become overstressed and may suffer from squeezing or explosive bursting, depending on whether the materials are comparatively ductile or brittle.

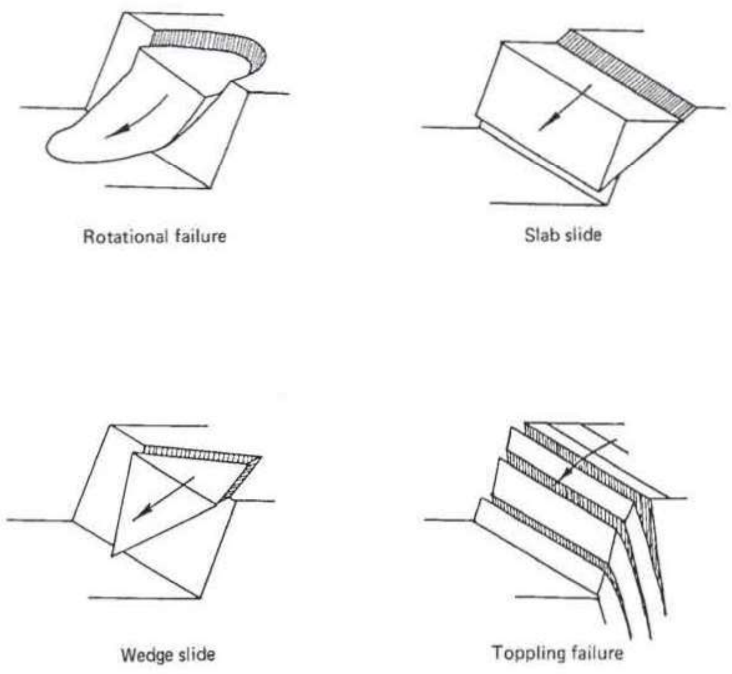


Figure 2.20. Primary mechanisms of rock slope failure (after Hoek and Bray, 1974). By permission of the Institution of Mining and Metallurgy.

2.2.5. Primary Mechanisms that Control Behavior of Rock

The important differences between rocks and soils, and between their respective groundwater and ground stress regimes, result in different patterns of behavior. Whereas soft rocks behave similarly to soils, the stronger, more competent and massive rock types behave quite differently. Examples are given below.

Foundations on Rock

Foundations on rock are rarely subject to *generalized* or *rotational failures* such as outlined in Section 2.1.13 for footing foundations on soil. Generalized failure is a real possibility only in the case of foundations near the crest of a rock cut, which can be considered as a special type of slope stability problem. Slopes in rock are discussed in the next subsection.

Differential settlement, however, remains a potential problem. Settlement magnitudes are again governed by the presence and characteristics of discontinuities. They depend on whether the discontinuities are closely or widely spaced, open or tight, filled or unfilled. Foundation loading may cause open discontinuities to close, unless they have been filled with a suitable grout.

Slopes in Rock

Slopes in rock fail predominantly by sliding along preexisting discontinuities, particularly along those bedding planes or faults that cut extensively through the rock and appear in the face of the slope. The *rotational failures* that are characteristic of soil happen only occasionally in rock because they require rupturing of intact rock blocks, which are much stronger than discontinuities. Rotational failures do occur, however, in very closely jointed and weak rock masses that behave like soils. Groundwater pressures that develop within discontinuities and within tension cracks behind the crest of the slope are often the cause of instability. Depending on the number of discontinuity sets and their relative orientations, failure of a rock slope may occur either as *slab sliding, wedge sliding,* or *toppling* (Figure 2.20). *Undercutting* and *raveling* of steep rock faces may also result from toe erosion, particularly if the rock is closely jointed or of low durability.

Underground Openings in Rock

Yield and failure of rock around underground openings occur by a variety of mechanisms, depending on the stress levels, groundwater conditions and rock characteristics, the shape and size of the open-

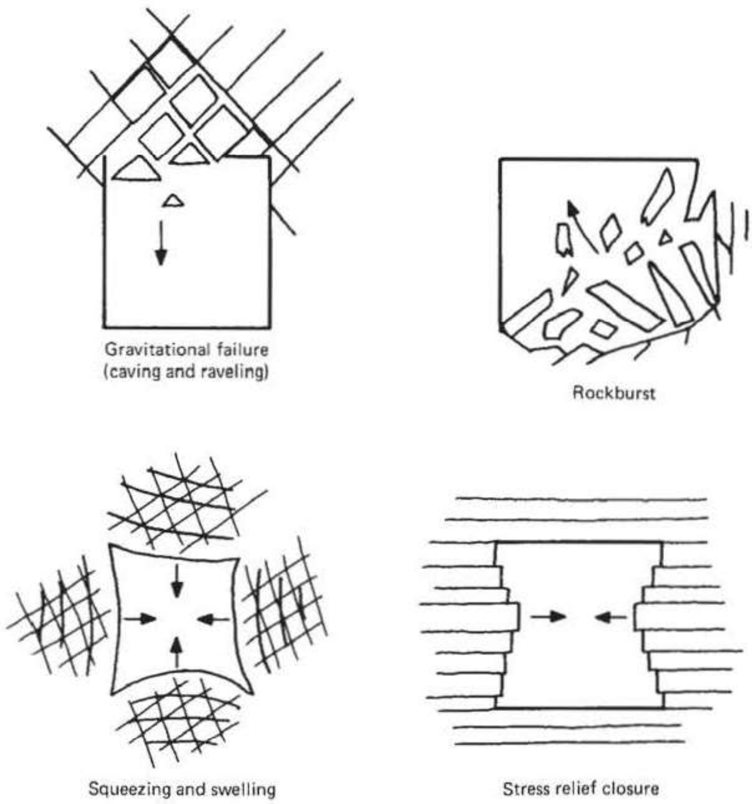


Figure 2.21. Primary mechanisms of yield and failure of underground openings in rock.

ing, the methods used for excavation (e.g., blasting or boring machine), and the type and quality of support installed. Each of these mechanisms, shown in Figure 2.21, is characteristically different and calls for its own individual approach to monitoring and design of instrumentation systems.

Gravitational failures (caving and raveling mechanisms) occur when rock blocks fall from the roof of an underground opening without appreciable breakage of intact rock material. Such failures are governed entirely by discontinuities. They start with the fall of small keystone blocks and progress upward until they either reach the ground surface or are arrested by *bulking* of broken rock within the opening (broken rock occupies a greater volume than undisturbed rock). Uncontrolled caving in a Quebec mine in 1980 migrated upward until it reached the saturated overburden soils, which liquified and flowed into the workings. Miners were killed, and the affected levels of the mine had to be closed.

Rockbursting is the characteristic mode of failure in brittle rock materials where the strength of the intact rock is exceeded by the magnitudes of excavation-induced stresses. Classic examples occur in South African mines at depths approaching 2–3 miles (3–5 km) where even the high-strength rocks are incapable of sustaining the stresses that develop.

Squeezing behavior is characteristic of rock masses that are overstressed but relatively weak or closely jointed. The rock mass yields by shearing along weak discontinuity surfaces or by crushing or distortion of the rock blocks. Tunnel closures in excess of 3 ft (1 m) have been recorded, for example, by convergence monitoring in the Austrian Alps.

Swelling behavior is encountered when the minerals of the rock are themselves of a swelling variety. Clay minerals are the most common in this category. Some shales contain montmorillonite and similar clay minerals that adsorb water, expand, and eventually generate high pressures on tunnel liners and support systems. Swelling problems are also experienced in anhydrite rock types that convert to gypsum when wetted.

Stress relief closure occurs most commonly in openings excavated in horizontally bedded sedimentary rocks. The beds expand as a result of stress relief and slide inward, exerting very high pressures on liners and supports. Some sliding occurs immediately when the rock is blasted, but continuing creep along the bedding planes results in the development of squeeze over much longer time periods, sometimes of years or decades. Hydroelectric turbine pits in Niagara have suffered from stress relief closure. The inward movement in one pit has been monitored monthly since 1905, and total movement has exceeded 4 in. (100 mm), sufficient to cause severe misalignment problems and shattering of a cast iron support strut.

Part 2

Planning Monitoring Programs

Part 2 is addressed primarily to people who make important decisions during the design phase of civil engineering projects: owners, project managers, project engineers, and project geologists.

Chapter 3 enumerates the benefits of using geotechnical instrumentation. Probably the greatest shortcoming in the state of the practice of geotechnical instrumentation is inadequate planning of monitoring programs, and this is the subject of Chapter 4. Chapter 4 is the hub of the book and sets out a logical step-by-step planning process that is vital to success. Chapters 5 and 6 describe the various contractual arrangements that are available for procuring instruments and field instrumentation services. Recommendations are made for contractual arrangements that maximize the quality of instrumentation data.

CHAPTER 3

BENEFITS OF USING GEOTECHNICAL INSTRUMENTATION

The role of geotechnical instrumentation is described in Chapter 1. In the foreword to this book, Ralph Peck states: "every instrument installed on a project should be selected and placed to assist in answering a specific question. Following this simple rule is the key to successful field instrumentation." Unfortunately, many practitioners select and place instrumentation when there is no specific question, perhaps because *everybody is doing it*. Benefits of using geotechnical instrumentation are described in this chapter, and examples of instrumentation applications for various project types are given in Part 5.

3.1. BENEFITS DURING DESIGN

Instrumentation is used to provide input to the initial design of a facility or for the design of remedial treatment.

3.1.1. Definition of Initial Site Conditions

Instrumentation often plays a role in defining site conditions during the design phase of a project. For example, groundwater pressures and fluctuations must often be determined for design purposes, requiring use of piezometers. Knowledge of in situ stress and deformability conditions is sometimes required to permit rational design of a tunnel lining or as input to predictions of movements around a large excavation. Preconstruction conditions surveys are often made to define initial ground elevations and the condition of any structures that may be influenced by future construction.

3.1.2. Proof Testing

Because of uncertainties inherent in a design, specifications for geotechnical construction may require that the contractor conduct one or more proof tests to verify adequacy of design. Ideally, proof tests are performed as part of the design phase so that construction specifications can reflect test results, but time constraints or contractual restrictions often make this impossible.

A proof test will always include observations, which may include instrumentation. For example, specifications for pile-supported foundations usually call for one or more load tests before production pile driving, requiring the use of deformation gages and a load cell. Similar instrumentation is required for proof testing of tiebacks. When ground conditions differ from past experience and construction methods are uncertain, the designer can choose between an ultraconservative design, or an economical design based on results of a full-scale proof test. There are many examples in geotechnical engineering practice of full-scale tests designed to answer specific questions, including test embankments, test excavations, evaluation of vertical drain performance, and evaluation of effectiveness of bitumen coating in reducing downdrag load on driven piles.

3.1.3. Fact-Finding in Crisis Situations

If a crisis situation occurs, its characteristics must be defined so that remedial measures can be planned and put into practice. Instrumentation often plays a role in defining these characteristics. For example, measurements of water table position and fluctuation, together with failure plane depth, are needed to define the nature of a landslide.

3.2. BENEFITS DURING CONSTRUCTION

Instrumentation is used during construction to ensure safety, minimize construction costs, control construction procedures or schedules, provide legal protection, provide data for measurement of quantities, enhance public relations, and advance the state of the art.

Inherent in the use of instrumentation for construction reasons is the absolute necessity for deciding, in advance, a positive means for solving any problem that may be disclosed by the results of the observations (Peck, 1973). If the observations should demonstrate that remedial action is needed, that action must be based on appropriate, previously anticipated plans.

3.2.1. Safety

Safety is an essential consideration in all construction projects. Instrumentation programs can provide the needed safeguards, by indicating behavior with respect to threshold limits and by providing a forewarning of any adverse effects of construction. For example, there is often a need to monitor the effect of construction on adjacent structures, such as the measurement of deformation in and around an excavation as a means of ensuring safety of the lateral support. Use of instrumentation for safety monitoring is routine during excavations for buildings, subway tunnels, and highways in urban areas.

3.2.2. Observational Method

Construction is becoming increasingly expensive, nullifying the justification for overconservative designs, and construction costs can be reduced by the use of the *observational method*. Peck (1969a) lists the following ingredients for complete application of the observational method:

(a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
(b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.
(c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.
(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
(e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
(f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
(g) Measurement of quantities to be observed and evaluation of actual conditions.
(h) Modification of design to suit actual conditions.

Peck cites several examples of the method, two of which will illustrate the application. First, rather than accept the owner's conservative design for support of a braced excavation, the contractor opted to work with a lower factor of safety and ensure adequacy of support by measuring load in every strut. The contractor had additional struts available for immediate insertion if needed and achieved overall economy while providing positive assurance that no strut would become overloaded. Second, Peck describes use of the observational method during construction of a soft ground tunnel. It was feared that tunneling beneath a large building would cause settlement and resultant building damage. Protective work was designed—not included in the tunnel contract but available if the need should develop. The contractor started work several thousand feet from the building and advanced toward it, making extensive deformation measurements to judge the effect of construction on surface facilities. Well before reaching the critical building it became evident that the planned protective work would not be required.

3.2.3. Construction Control

Uncertainties in engineering properties or behavior during the design phase often affect construction procedures or schedules. The designer may therefore specify a program to monitor actual behavior during construction so that procedures or schedules can be modified in accordance with actual behavior. This use of instrumentation is normally referred to as *construction control,* even though it also plays a role in ensuring safety and reducing construction costs. For example, in the construction of an embankment on a soft clay deposit using staged construction procedures, instrumentation will normally be used to determine when the clay can support the next stage of fill. Similarly, instrumentation can be used to monitor contractor performance, thereby ensuring that contract requirements are met. For example, during excavation alongside an existing building, the designer may require that movements are limited to a specified amount to avoid damage to the building.

3.2.4. Providing Legal Protection

Where construction may affect neighboring property, instrumentation is useful in determining if there is a relationship between construction and changing conditions of that property. For example, if an open cut is to be excavated in a city, the designer or a building owner may use instrumentation to provide a bank of data concerning performance of adjacent structures during excavation, for possible use in the event of litigation. Instrumentation to provide legal protection will be used to a greater extent if the construction procedure is relatively new, or if there is a possible direct link between the construction procedure and damage to the property off the right of way, such as dewatering, or if nearby structures are particularly sensitive to ground movements or vibrations.

3.2.5. Measurement of Fill Quantities

When embankments are constructed on soft foundations and payment for fill quantities is based on measurements to the actual bottom of the fill, there is a need to determine the final elevation of the bottom of the fill. Settlement gages can be used for this purpose.

3.2.6. Enhancing Public Relations

Plans for an instrumentation program, indicating that the construction will be watched carefully, can give reassurance to the public and thus can expedite approval of the project. In situations where community or political obstacles threaten delays to approval, it may be appropriate for an owner to specify extensive instrumentation—more than is needed for technical reasons—to reassure the public that safety will be enhanced and that adverse problems will be minimized. Although such an approach will result in higher-than-normal instrumentation costs, it may in fact create an overall cost saving because the effects of inflation and other costs of delays will be reduced.

3.2.7. Advancing the State of the Art

Many advances in geotechnical engineering have resulted from field measurements. Often these measurements have been made for one of the project-specific reasons described above, and the general advance of knowledge has been a by-product. However, several notable practical research tests have been made to check and extend existing theories for soil and rock behavior and thus provide a basis for extending the state of the art for design of geotechnical construction. These research-oriented investigations, which usually require much more extensive field instrumentation than is required for other purposes, include the following:

- Measurement of stress and deformation in embankment dams to advance the state of the art of dam design.
- Measurement of total stress on culverts beneath highway embankments.
- Full-scale tests on individual piles and pile groups to determine load transfer relationships.
- Measurement of tunnel support load and ground deformation as input to improved support design procedures.
- Measurement of the effectiveness of various types of vertical drains.
- Measurement of rock behavior at elevated temperatures during studies relating to the disposal of high-level nuclear waste.

3.3. BENEFITS AFTER CONSTRUCTION IS COMPLETE

Engineers have an obligation to build safe structures, particularly if loss of life would result from lack of safety. Performance monitoring over the life of a structure, using observations and instrumentation, may be the expedient way to ensure long-term safety. Examples are given below:

- Long-term measurements of leakage, pore water pressure, and deformation are made frequently during the operating life of embankment dams.
- If permanent tiebacks are used for support of an excavation, surface and subsurface ground deformations may be measured, and perhaps also load in representative tiebacks.
- Where rockbolts have been used to stabilize a natural or an excavated slope in rock, fixed borehole extensometers may be installed to provide a means of indicating long-term performance of the rockbolts.
- If drainage arrangements have been provided to increase the stability of a slope or retaining wall, piezometers may be installed to check on long-term performance.

3.4. GENERAL CONSIDERATIONS

When the need for instrumentation is properly and correctly established, and when the program is properly planned, cost savings may be a direct result, as indicated by previous examples. However, instrumentation does not have to reduce costs to be justified. In some cases, instrumentation has been valuable in proving that the design is correct. In other cases, instrumentation might show that the design is inadequate, which may result in increased construction costs. However, the value of added safety and the avoidance of failure (and saving the cost of repairs) will make the instrumentation program cost effective.

CHAPTER 4

SYSTEMATIC APPROACH TO PLANNING MONITORING PROGRAMS USING GEOTECHNICAL INSTRUMENTATION

Planning a monitoring program using geotechnical instrumentation is similar to other engineering design efforts. A typical engineering design effort begins with a definition of an objective and proceeds through a series of logical steps to preparation of plans and specifications. Similarly, the task of planning a monitoring program should be a logical and comprehensive engineering process that begins with defining the objective and ends with planning how the measurement data will be implemented.

Unfortunately, there is a tendency among some engineers and geologists to proceed in an illogical manner, often first selecting an instrument, making measurements, and then wondering what to do with the measurement data. Franklin (1977) indicates that a monitoring program is a chain with many potential weak links and breaks down with greater facility and frequency than most other tasks in geotechnical engineering.

Systematic planning requires special effort and dedication on the part of responsible personnel. The planning effort should be undertaken by personnel with specialist expertise in applications of geotechnical instrumentation. Recognizing that instrumentation is merely a tool, rather than an end in itself, these personnel should be capable of working in a *team-player* capacity with the project design team.

Planning should proceed through the steps listed below. The steps are summarized in checklist form in Appendix A. All steps should, if possible, be completed before instrumentation work commences in the field.

4.1. DEFINE THE PROJECT CONDITIONS

If the engineer or geologist responsible for planning a monitoring program is familiar with the project, this step will usually be unnecessary. However, if the program is planned by others, a special effort must be made to become familiar with project conditions. These include project type and layout, subsurface stratigraphy and engineering properties of subsurface materials, groundwater conditions, status of nearby structures or other facilities, environmental conditions, and planned construction method. If the monitoring program has been instigated to assist in finding facts during a crisis situation (Chapter 3), all available knowledge of the situation should also be assimilated.

4.2. PREDICT MECHANISMS THAT CONTROL BEHAVIOR

Prior to developing a program of instrumentation, one or more working hypotheses must be developed for mechanisms that are likely to control behavior. The hypotheses must be based on a comprehensive knowledge of project conditions, as described above. Various mechanisms that control the behavior of soil and rock are described in Chapter 2.

4.3. DEFINE THE GEOTECHNICAL QUESTIONS THAT NEED TO BE ANSWERED

Every instrument on a project should be selected and placed to assist in answering a specific question: if there is no question, there should be no instrumentation. Before addressing measurement methods themselves, a listing should be made of geotechnical questions that are likely to arise during the design, construction, or operation phases. Various potential geotechnical questions are posed in Part 5 of this book.

4.4. DEFINE THE PURPOSE OF THE INSTRUMENTATION

Instrumentation should not be used unless there is a valid reason that can be defended. Benefits of using instrumentation are discussed in Chapter 3. When using this chapter to assist with planning a monitoring program, if engineers or geologists are unable to define a clear purpose for the program, they should cancel the program and proceed no further through this chapter. Peck (1984) states, "The legitimate uses of instrumentation are so many, and the questions that instruments and observation can answer so vital, that we should not risk discrediting their value by using them improperly or unnecessarily."

4.5. SELECT THE PARAMETERS TO BE MONITORED

Parameters include pore water pressure, joint water pressure, total stress, deformation, load and strain in structural members, and temperature. The question *which parameters are most significant?* should be answered.

Variations in parameters can result both from *causes* and *effects*. For example, the primary parameter of interest in a slope stability problem is usually deformation, which can be considered as the *effect* of the problem, but the *cause* is frequently groundwater conditions. By monitoring both cause and effect, a relationship between the two can often be developed, and action can be taken to remedy any undesirable effect by removing the cause.

Most measurements of pressure, stress, load, strain, and temperature are influenced by conditions within a very small zone and are therefore dependent on local characteristics of that zone. They are often essentially *point* measurements, subject to any variability in geologic or other characteristics, and may therefore not represent conditions on a larger scale. When this is the case, a large number of measurement points may be required before confidence can be placed in the data. On the other hand, many deformation measuring devices respond to movements within a large and representative zone. Data provided by a single instrument can therefore be meaningful, and deformation measurements are generally the most reliable and least ambiguous.

4.6. PREDICT MAGNITUDES OF CHANGE

Predictions are necessary so that required instrument ranges and required instrument sensitivities or accuracies can be selected.

An estimate of the maximum possible value, or the maximum value of interest, leads to a selection of instrument range. This estimate often requires substantial engineering judgment, but on occasion it can be made with a straightforward calculation, as is the case with maximum pore water pressure in a clay foundation beneath the centerline of an embankment.

An estimate of the minimum value of interest leads to a selection of instrument sensitivity or accuracy. There is a tendency to seek unnecessarily high accuracy, when in fact high accuracy should often be sacrificed for high reliability if the two are in conflict. High accuracy often goes hand in hand with delicacy and fragility. In some instances, high accuracy may be necessary where small changes in the measured variable have significant meaning, or where only a short time is available for defining trends, for example, when establishing the rate of slide movement from inclinometer data. Parametric studies with the aid of a computer can often be carried out to assist in establishing range, accuracy, and sensitivity.

If measurements are for construction control or safety purposes, a predetermination should be made of numerical values that indicate the need for remedial action. These numerical values will often be in terms of rate of measured change, rather than absolute magnitude. In his ingredients for the observational method, defined in Chapter 3, Peck (1969a) includes the following:

- Selection of quantities to be observed . . . and calculation of their anticipated values on the basis of the working hypothesis.
- Calculation of values of the same quantities under the most unfavourable conditions.

The first of the above steps allows any abnormalities to be recognized. The first and second steps allow the determination of *hazard warning levels*. Hazard warning levels may be based on clearly defined performance criteria—for example, where an acceptable differential settlement has been established for a structural foundation—or may be based on substantial engineering judgment, requiring a general assessment of ground behavior modes and mechanisms of potential problems or failures. When in doubt, several hazard warning levels should be established. As an example, Table 4.1 shows a hypothetical example of hazard warning levels and contingency actions for slope monitoring at an open pit mine.

The concept of green, yellow, and red hazard warning levels is also useful. Green indicates that all is well, yellow indicates the need for cautionary measures including an increase in monitoring frequency, and red indicates the need for timely remedial action. Fellenius et al. (1982) present a case history that illustrates this concept.

Table 4.1. Example of Hazard Warning Levels

Warning Level	Criterion	Action
1	Movement greater than 10 mm at any one survey station	Report to mine management
2	Movement greater than 15 mm at two adjacent stations; or velocity exceeding 15 mm per month at any one station	Verbal report and site meeting followed by written report and recommendations
3	Movement greater than 15 mm plus acceleration at any one station	Immediate site inspection by consulting engineer, site meeting and probable remedial measures (according to contingency plans)

Source: Franklin (1977). Reprinted with permission.

4.7. DEVISE REMEDIAL ACTION

Inherent in the use of instrumentation for construction purposes is the absolute necessity for deciding, in advance, a positive means for solving any problem that may be disclosed by the results of the observations (Peck, 1973). If the observations should demonstrate that remedial action is needed, that action must be based on appropriate, previously anticipated plans.

As described above, several hazard warning levels may be identified, each requiring a different plan. Planning should ensure that required labor and materials will be available so that remedial action can proceed with minimum and acceptable delay and so that personnel responsible for interpretation of instrumentation data will have contractual authority to initiate remedial action. An open communication channel should be maintained between design and construction personnel, so that remedial action can be discussed at any time. A special effort will often be required to keep this channel open, both because the two groups sometimes tend to avoid communication and because the contract for design personnel may have been terminated. Arrangements should be made to determine how all parties will be forewarned of the planned remedial actions.

4.8. ASSIGN TASKS FOR DESIGN, CONSTRUCTION, AND OPERATION PHASES

When assigning tasks for monitoring, the party with the greatest vested interest in the data should be given direct line responsibility for producing it accurately. The various tasks involved in accomplishing a monitoring program, together with alternative choices of the parties available for performing

Table 4.2. Chart Used for Task Assignment

Task	Responsible Party			
	Owner	Design Consultant	Instrumentation Specialist	Construction Contractor
Plan monitoring program				
Procure instruments and make factory calibrations				
Install instruments				
Maintain and calibrate instruments on regular schedule				
Establish and update data collection schedule				
Collect data				
Process and present data				
Interpret and report data				
Decide on implementation of results				

them, are listed in Table 4.2. It is useful to complete this chart during the planning stage by indicating the responsible party for each task.

Several of the tasks involve the participation of more than one party. In cases where the owner is also the designer, there will be no design consultant. Instrumentation specialists may be employees of the owner or the design consultant or may be consultants with special expertise in geotechnical instrumentation. All tasks assigned to instrumentation specialists should be under the supervision of one individual.

Chapters 5 and 6 include guidance on assigning tasks for instrument procurement and field services, and Section 6.6.5 indicates required qualifications of instrumentation specialists.

If construction contractors have economic or professional incentive to contribute toward good data, they should be assigned major responsibilities. If the instrumentation program has been instigated by the contractor, clearly the contractor will have responsibility for all tasks. However, if the instrumentation program has been instigated by the owner, as is usually the case, the construction contractor will often regard it as an interference with normal construction work and the contractor's participation should be minimized. The contractor will usually be responsible for providing support services during installation and access during the data collection phase. Instrument selection and procurement, factory calibration, installation, regular calibration and maintenance, and data collection, processing, and presentation should preferably be under the direct control of the owner or instrumentation specialist selected by the owner. When any of these tasks are performed by the construction contractor, data quality is often in doubt. Data interpretation and reporting should be the direct responsibility of the owner, the design consultant, or instrumentation specialist selected by the owner. Table 4.3 gives an example of task assignments for an owner-instigated monitoring program for which the contractor's cooperation is not assured. It is emphasized that Table 4.3 should not be used as a "cookbook": it is merely an example, and the needs of each project should be considered individually.

While completing Table 4.2, it may become evident that personnel are not available for all tasks, leading either to assignment of additional personnel or to a change in direction of the monitoring program. For example, if personnel available for data collection are insufficient, it may be appropriate to turn toward use of automatic data acquisition systems: this decision will affect instrument selection.

Task assignment should include planning of liaison and reporting channels. Assignments should clearly indicate who has overall responsibility and contractual authority for implementing the results of the observations.

4.9. SELECT INSTRUMENTS

The preceding eight steps should be completed before instruments are selected. Instruments are de-

Table 4.3. Example of Task Assignment for Owner-Instigated Monitoring Program

	Responsible Party			
Task	Owner	Design Consultant	Instrumentation Specialist	Construction Contractor
Plan monitoring program	•	•	•	
Procure instruments and make factory calibrations		•	•	
Install instruments			•	•
Maintain and calibrate instruments on regular schedule			•	•
Establish and update data collection schedule		•	•	
Collect data			•	•
Process and present data			•	
Interpret and report data		•	•	
Decide on implementation of results	•	•		

scribed in Part 3, and commercial sources are listed in Appendix D.

When selecting instruments, the overriding desirable feature is **reliability**. A recipe for reliability is given in Chapter 15. Inherent in reliability is maximum simplicity, and in general transducers can be placed in the following order of decreasing simplicity and reliability:

- Optical
- Mechanical
- Hydraulic
- Pneumatic
- Electrical

Lowest cost of an instrument should never be allowed to dominate the selection, and the least expensive instrument is not likely to result in minimum total cost. In evaluating the economics of alternative instruments, the overall cost of procuring, calibration, installation, maintenance, monitoring, and data processing should be compared.

The state of the art in hardware design is far ahead of the state of the art in user technology. It is the responsibility of users to develop an adequate level of understanding of the instruments that they select, and users will often benefit from discussing their application with geotechnical engineers or geologists on the manufacturer's staff before selecting instruments. They should discuss as much as possible about the application and seek out any limitations of the proposed instruments.

Instruments should have a good past performance record and should always have maximum durability in the installed environment. The environment for geotechnical instruments is harsh, and unfortunately some instruments are not sufficiently well designed for reliable operation in such an environment. Table 4.4 is a list of some of the main features of the instrument environment. Transducer, readout unit, and the communication system between the transducer and readout unit should be considered separately because different criteria may apply to each.

Table 4.4. Instrument Environments

1. Large deformations—often shearing deformations
2. High pressures—both solids and fluids
3. Corrosive—chemical (groundwater, grouts, concrete additives, bacteria) and electrolytic (electrolysis of dissimilar materials, stray electrical currents)
4. Temperature extremes—subfreezing to 100°F+ in the sun (temperature can be higher in certain instances, such as nuclear waste storage)
5. Shock—blasting, construction activities, rough handling during transportation to and from site
6. Vandalism, destruction by construction equipment, fly rock
7. Dust, dirt, mud, rain, chemical precipitates
8. High humidity, flowing or standing water
9. Erratic power supplies (electrical instruments)
10. Loss of accessibility to instruments when covered by rock, soil, shotcrete, and other supports

Source: After Cording et al. (1975).

With certain instruments, if a reading can be obtained, that reading is necessarily correct, while other instruments have a feature whereby calibration can be verified after installation; clearly, either feature is very desirable.

Instrument selection should recognize any limitations in skill or quantity of available personnel, identified while completing Table 4.2, and should consider both construction and long-term needs and conditions. Criteria for the two phases may be different and may entail selection of two different monitoring methods.

Other goals for instrument selection include good conformance (Chapter 7), minimum interference to construction, and minimum access difficulties while installing and reading.

The need for an automatic data acquisition system should be determined, and readouts should be selected in recognition of planned frequency and duration of readings. Unnecessary sophistication and automation should be avoided.

Action should be planned in the event any part of the system malfunctions, and the need for spare parts and standby readout units should be identified. Lead time for delivery and time available for instrument installation may affect instrument selection.

The final question is: *Will the selected instrument achieve the objective?* If an unproven instrument is selected, all parties should recognize the experimental nature of the instrument, and maximum backup should be provided, as described in Section 4.12.

4.10. SELECT INSTRUMENT LOCATIONS

The selection of instrument locations should reflect predicted behavior and should be compatible with the method of analysis that will later be used when interpreting the data. Finite element analyses are often helpful in identifying critical locations and preferred instrument orientations. A practical approach to selecting instrument locations entails three steps.

First, zones of particular concern are identified, such as structurally weak zones, most heavily loaded zones, or zones where highest pore water pressures are anticipated, and appropriate instrumentation is located. If there are no such zones, or if instruments are also to be located elsewhere, a second step is taken. A selection is made of zones, normally cross sections, where predicted behavior is considered representative of behavior as a whole. When considering which zones are representative, variations in both geology and construction procedures should be considered. These cross sections are then regarded as *primary instrumented sections*, and instruments are located to provide comprehensive performance data. There should usually be at least two such primary instrumented sections. Third, because the selection of representative zones may be incorrect, instrumentation should be installed at a number of *secondary instrumented sections*, to serve as indices of comparative behavior. Instruments at these secondary sections should be as simple as possible and should also be installed at the primary sections so that comparisons can be made. For example, instrumentation of a tieback wall might entail selection of two or three primary cross sections for installation of optical survey points, inclinometers, and load cells. Optical survey points would also be installed at a large number of secondary sections and used for monitoring both horizontal and vertical deformation of the wall. If in fact the behavior at a secondary section appears to be significantly different from the behavior at the primary sections, additional instrumentation may be installed at the secondary section as construction progresses.

When selecting locations, survivability of instruments should be considered, and additional quantities should be selected to replace instruments that may become inoperative. For example, Abramson and Green (1985) report on a survey of users, conducted to establish the required number of strain gages and load cells to compensate for losses occurring after installation. The survey indicates an average survivability rate for load cells of 75%, while for strain gages it is 60%.

Locations should generally be selected so that data can be obtained as early as possible during the construction process. Because of the inherent variability of soil and rock, it is usually unwise to rely on a single instrument as an indicator of performance.

Wherever possible, locations should be arranged to provide cross-checks between instrument types. For example, if both subsurface settlement and pore water pressure are to be measured in a clay subject to consolidation, piezometers should be located at mid-depth between settlement points. If both vertical inclinometers and horizontal fixed embankment extensometers are installed near each other and at the same cross section in the ground, an extensometer anchor should be installed near the inclinometer casing. However, care should be taken to avoid creating nonconformance or zones of weakness by excessive concentration of instruments in clusters.

Although instrument locations will usually be shown on the contract plans, flexibility should be maintained so that locations can be changed as new information becomes available during construction; thus, flexible installation specifications are required. Installation specifications are discussed in Chapter 6.

4.11. PLAN RECORDING OF FACTORS THAT MAY INFLUENCE MEASURED DATA

Measurements by themselves are rarely sufficient to provide useful conclusions. The use of instrumentation normally involves relating measurements to causes, and therefore complete records and diaries must be maintained of all factors that might cause changes in the measured parameters. As discussed in Section 4.5, a decision may have been made to monitor various causal parameters, and these should always include construction details and progress. Visual observations of expected and unusual behavior should also be recorded. Records should be kept of geology and other subsurface conditions and of environmental factors that may, in themselves, affect monitored data, for example, temperature, rainfall, snow, sun, and shade.

Details of each instrument installation should be recorded on *installation record sheets,* because local or unusual conditions often influence measured variables. Installation record sheets are discussed further in Chapter 17.

4.12. ESTABLISH PROCEDURES FOR ENSURING READING CORRECTNESS

Personnel responsible for instrumentation must be able to answer the question: *Is the instrument functioning correctly?* The ability to answer depends on availability of good evidence, for which planning is required. The answer can sometimes be provided by visual observations. For example, visual observations of tunnel lining behavior are essential when questioning correctness of apparently large lining strains or ground deformations during tunneling.

In critical situations, duplicate instruments can be used. A backup system is often useful and will often provide an answer to the question even when its accuracy is significantly less than that of the primary system. For example, optical survey can often be used to examine correctness of apparent movements at surface-mounted heads of instruments installed for monitoring subsurface deformation. Convergence measurements across an excavation can sometimes be used in a similar way when fixed borehole extensometers or inclinometers have been installed in adjacent ground.

Data correctness can also be evaluated by examining consistency. For example, in a consolidation situation, dissipation of pore water pressure should be consistent with measured settlement, and increase of pore water pressure should be consistent with added loading. Repeatability can also give a clue to data correctness, and it is often worthwhile to take many readings over a short time span to disclose whether or not lack of normal repeatability indicates suspect data.

Certain instruments have features that allow an in-place check to be made, and these checks should be made on a regular basis. For example, permeability tests can be made in twin-tube hydraulic piezometers to examine correct functioning. Some instruments have dual transducers. Some fixed borehole extensometers can be checked for free-sliding of the wire or rod by moving the instrument head outward and measuring elongation of the wire or rod.

4.13. LIST THE SPECIFIC PURPOSE OF EACH INSTRUMENT

At this point in the planning, it is useful to question whether all planned instruments are justified. Each planned instrument should be numbered and its purpose listed. If no viable specific purpose can be found for a planned instrument, it should be deleted.

4.14. PREPARE BUDGET

Even though the planning task is not complete, a budget should be prepared at this stage for all tasks listed in Table 4.2, to ensure that sufficient funds are indeed available. A frequent error in budget preparation is to underestimate the duration of the project and the real data collection and processing costs. If insufficient funds are available, the instrumentation program may have to be curtailed or more funds sought from the owner on a timely basis. Clearly, an application for more funds must be supported by reasons that can be defended.

4.15. WRITE INSTRUMENT PROCUREMENT SPECIFICATIONS

Attempts by users to design and manufacture instruments generally have not been successful, although joint efforts by user and manufacturer are sometimes undertaken. Instruments should therefore be purchased from established manufacturers, for which procurement specifications are usually needed. Alternative approaches are described in Chapter 5. At this time, the requirements for factory calibration should be determined and acceptance tests planned to ensure correct functioning when instruments are first received by the user. Responsibility for performing acceptance tests should be assigned. Guidelines for factory calibrations and acceptance tests are given in Chapter 16.

4.16. PLAN INSTALLATION

Installation procedures should be planned well in advance of scheduled installation dates, following the guidelines given in Chapter 17.

Written step-by-step procedures should be prepared, making use of the manufacturer's instruction manual and the designer's knowledge of specific site geotechnical 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. The fact that the owner's personnel will install the instruments does not eliminate the need for written procedures. An example of an instrument installation procedure and an installation record sheet is included in Appendix G.

Staff training should be planned. Installation plans should be coordinated with the construction contractor and arrangements made for access and for protection of installed instruments from damage. An installation schedule should be prepared, consistent with the construction schedule.

4.17. PLAN REGULAR CALIBRATION AND MAINTENANCE

Regular calibration and maintenance should be planned, following the guidelines given in Chapter 16.

4.18. PLAN DATA COLLECTION, PROCESSING, PRESENTATION, INTERPRETATION, REPORTING, AND IMPLEMENTATION

Written procedures for data collection, processing, presentation, and interpretation should be prepared, following the guidelines given in Chapter 18.

The effort required for these tasks should not be underestimated. Many consulting engineering firms have files filled with large quantities of partially processed and undigested data because sufficient time or funds were not available for these tasks. The computer is a substantial aid but is no panacea.

Staff training should be planned. At this stage in the planning a verification should be made to ensure that remedial actions have been planned, that personnel responsible for interpretation of instrumentation data have contractual authority to initiate remedial action, that communication channels between design and construction personnel are open, and that arrangements have been made to forewarn all parties of the planned remedial actions.

4.19. WRITE CONTRACTUAL ARRANGEMENTS FOR FIELD INSTRUMENTATION SERVICES

Field services include instrument installation, regular calibration and maintenance, and data collection, processing, presentation, interpretation, and reporting. Contractual arrangements for the selection of personnel to provide these services may govern success or failure of a monitoring program. Alternative approaches are described in Chapter 6.

4.20. UPDATE BUDGET

Planning is now complete, and the budget for all tasks listed in Table 4.2 should be updated in light of all planning steps.

CHAPTER 5

SPECIFICATIONS FOR PROCUREMENT OF INSTRUMENTS*

Watson (1964) defines a specification as follows:

> A statement containing a minute description or enumeration of particulars, as of the terms of a contract or the details of construction not shown in an architect's drawings. A specification is definite, determinate, distinctly and plainly set forth, and stated in full and explicit terms. The reader will note from this definition that specifications are expected to be all-encompassing and exact. We may simply say that specifications should be clear, concise, complete and correct.

The last sentence of this definition should be emphasized. If specifications are **clear, concise, complete, and correct,** there is less chance of misunderstanding, delay, and conflict.

Procurement of other than the most simple geotechnical instruments should not be considered as a routine construction procurement item because, if valid measurements are to be made, extreme attention must be paid to quality and details. However, simple devices such as settlement platforms may be procured as routine construction items.

When planning the monitoring program in accordance with guidelines given in Chapter 4, an assignment of tasks will have been made, including responsibility for instrument procurement and factory calibration. Justification is given in this chapter for the procurement task assignment recommended in Chapter 4.

After the procurement task has been assigned, the next steps in preparation of procurement specifications are selection of specifying method and basis for determining price. In making these selections, the specifier should remember that the primary needs are high quality and reliability. The final step is to write the detailed specifications. These steps are described in turn.

5.1. TASK ASSIGNMENT FOR PROCUREMENT

Instruments can be procured by the construction contractor, by the owner, or by the design consultant. Alternatively, an assigned subcontract approach can be used, as described in Chapter 6, with instrument suppliers acting as assigned subcontractors. Advantages and limitations of the four options are given in Table 5.1. Procurement by the construction contractor is the least desirable option. Selection among the other three options depends on factors specific to each project.

In its manual on instrumentation for concrete structures, the U.S. Army Corps of Engineers (Corps of Engineers, 1980) acknowledges the need

*Written with the assistance of Robert E. Vansant, Black & Veatch, Kansas City, MO.

Table 5.1. Advantages and Limitations of Task Assignments for Procurement[a]

Procurement by	Advantages	Limitations
Construction contractor	Contractor's liability is clear	If *or equal* provision is required, specification covering all salient points is needed to guard against supply of an undesirable substitution Contractor will generally buy lowest-cost instruments, with risk of low quality and invalid measurement data
Owner	Minimum cost (because no markup) Owner has direct control over substitutions, inspection during manufacture, acceptability on receipt, and warranty service Can select between competitive bid method or (if permitted by owner's regulations) negotiation with one or more suppliers Flexible to accommodate changes	Contractor has no liability for nonperformance Owner may purchase lowest price instruments rather than highest quality
Design consultant	Design consultant has direct control over substitutions, inspection during manufacture, acceptability on receipt, and warranty service Can select between competitive bid method or (if permitted by owner's regulations) negotiation with one or more suppliers Flexible to accommodate changes	Contractor has no liability for nonperformance Cost is included in design fee
Instrument suppliers acting as assigned subcontractors	Owner or design consultant has direct control over substitutions, inspection during manufacture, and acceptability on receipt Can select between competitive bid method or (if permitted by owner's regulations) negotiation with one or more suppliers Flexible to accommodate changes	Contractor has no liability for nonperformance

[a] Procurement should preferably be under the direct control of the owner or design consultant; thus, the first option is the least desirable. Selection among the other three options depends on factors specific to each project.

to avoid procurement by the construction contractor:

> The general policy of the Chief of Engineers is to perform all civil works by contract unless it is in the best interest of the United States to accomplish the work by Government forces. However, the specialized nature of instrumentation facilities and the care required in the preparation, calibration, and placement of test apparatus demands that these features of work be retained under close operational control of the Corps of Engineers. In view of these conditions, direct procurement by the Government of embedded meters, cable, tubing, . . . , indicating or recording equipment, and similar items not normally encountered in construction work . . . is recommended.

5.2. SPECIFYING METHOD

There are two general categories of specifications: *descriptive specifications,* in which the details of the required instruments are specified, and *performance specifications,* in which the end result is specified. Descriptive specifications can be divided further into specifications with or without brand name and model number. A definition of each is given next, followed by recommendations.

5.2.1. Descriptive Specification, with Brand Name and Model Number

The specifier selects the method for making a measurement, including one or more preferred instrument models. The selection may be based on the specifier's previous experience, on the experience of others, or on the reputation of a particular manufacturer. When brand names are used in public work contracts, there should be at least two and preferably at least three sources to make sure that there is effective competition. If only one model is considered suitable, the specifier may write a sole source procurement specification, excluding use of a substitution. On public work where there is only a single source, a rigorous sole source procurement justification will generally be required, and it will usually be preferable for the owner to purchase the instruments and furnish them to the construction contractor. Such an approach facilitates the justification of sole source, allows more effective price negotiation, and precludes the sole source manufacturer from "packaging" that instrument with other instruments required for the project.

The owner may require the specifier to add an *or equal* provision to the brand name and model number, in which case great care must be taken to define what is acceptable as a substitution. *Or equal* specifications are discussed in Section 5.4.6.

5.2.2. Descriptive Specification, without Brand Name and Model Number

The specifier selects the method for making a measurement and writes a generic specification to define the required characteristics of the system and components. For example, a specification may call for pneumatic piezometers, with certain size, mechanical, pneumatic, and other requirements. A descriptive specification may be so limiting that the requirements can be satisfied only by one commercial model.

5.2.3. Performance Specification

In this method the end result is specified. For example, the specification might state that water pressure measurement devices shall have a certain range and accuracy and must operate for a certain period in the geotechnical environment described in the specifications. The specification should state how the manufacturer's proposed instrument will be evaluated.

5.2.4. Advantages and Limitations of Specifying Methods

Advantages and limitations of the three methods are given in Table 5.2. The second method requires a thorough generic specification, generally not within the capability of geotechnical engineer specifiers, and therefore it is not often used. The third method assumes that the manufacturer will understand instrument design criteria dictated by the specific geotechnical environment and thus is applicable only if the manufacturer's staff includes geotechnical engineers and if the geotechnical environment is clearly specified. Although the second or third method may on occasion be the method of choice, the first method is the most common and is satisfactory provided that a specification covering all salient features is written to guard against supply of an undesirable substitution.

5.3. BASIS FOR DETERMINING PRICE

If instruments are procured directly by the owner or design consultant, price can be determined either by bidding or by negotiation. If instruments are procured through the construction contract, bid items can be included, or the assigned subcontract approach (Chapter 6) can be used to allow the owner or design consultant to retain control over selection of the equipment and basis for determining price.

Advantages and limitations of negotiation and bidding are given in Table 5.3.

If instruments are procured by the owner or design consultant, negotiation is generally preferable, but public agencies may be required to take bids. However, it was a surprise to the author to read (Perlman, 1985):

> Despite the fact that the general policy of the Government is to acquire goods and services on a competitive basis, most Government procurement dollars are spent on contracts awarded *noncompetitively* (i.e., sole source contracts). Of the $146.9 billion spent by the Federal Government in fiscal year (FY) 1982 for goods, $79.2 billion (54%) was expended noncompetitively.
>
> Questions regarding the use (or overuse) of sole source procurements concern every member of the procurement community. From the Government's standpoint, if a contract is improperly awarded on a sole source basis, the Government may pay higher prices than if competition had been sought. On the other hand, *failure* to permit a sole source award in *appropriate* circumstances may unnecessarily (a) increase the price paid for the item, (b) place a greater administrative burden on Government personnel, since competitive procurements require ap-

Table 5.2. Advantages and Limitations of Various Specifying Methods for Procurement of Instruments[a]

Method	Advantages	Limitations
Descriptive specification, with brand name and model number	Most direct way of defining preferred instrument	If *or equal* provision is required, specification covering all salient features is needed to guard against supply of an undesirable substitution Owner may have to accept responsibility if specified model number does not perform adequately
Descriptive specification, without brand name and model number	No bias toward particular model(s) Can specify general material requirements	Specifier must have necessary knowledge to write specification Specified requirements may limit innovation on part of manufacturer
Performance specification	Allows maximum innovation on part of manufacturer Manufacturer has contractual commitment to furnish a device that performs adequately Permits maximum competition No bias toward particular model(s)	Assumes manufacturer will understand design criteria dictated by the specific geotechnical environment; thus, applicable only if manufacturer's staff includes geotechnical engineers Can be difficult to evaluate whether manufacturer's proposed instrument will perform as needed

[a]The first method is the most common and is satisfactory provided that a specification covering all salient features is written to guard against supply of an undesirable substitution.

> proximately twice as much work as sole source awards, and (c) cause the Government user to receive a product that merely meets the minimum requirements of a solicitation, instead of the one that is *best* for the job.

It is therefore apparent that there is ample precedent for procuring geotechnical instruments on a sole source basis, in order to avoid *receiving a product that merely meets the minimum requirements of a solicitation, instead of the one that is best for the job.*

If instruments are procured through the construction contract, the assigned subcontract approach is preferable, with price negotiation by the owner or design consultant.

Two discussions of a paper by Sherard (1981) reinforce quality concerns inherent in the bid procedure. Green (1982) states:

Table 5.3. Advantages and Limitations of Procedures for Determining Price[a]

Procedure	Advantages	Limitations
Bid	Procurement may be least costly	Requires preparation of comprehensive bid specification Lowest cost runs risk of low quality and invalid measurement data Not flexible to accommodate changes Adequate lead time required
Negotiation	Owner or design consultant has direct control over quality and price Can use preferred sources Flexible to accommodate changes	Often resisted by public agency procurement community

[a]Negotiation is generally preferable. If instruments are procured through the construction contract, negotiation procedure entails use of the assigned subcontract approach.

> On the subject of cost, the writer is in entire agreement with the author [Sherard] that instrumentation hardware cost is so small that it should not be the deciding factor. However, this is not the case in practice. In far too many instances, instrumentation hardware is put out to bid on the basis of a . . . make and model number, or approved equal. Despite specification writers' good intentions, it is possible for manufacturers to use lower quality components, for example, the leads, and the commonly used low bid process encourages this. Until high quality can be adequately specified, instrument procurement on a low bid basis will remain a stumbling block to good field performance.

Mikkelsen (1982) presents a manufacturer's perspective:

> Sales often go to the lowest bidder on materials. Such practices are often unwise since a customer generally gets what he pays for. Also, it is unwise because, as the author [Sherard] also points out, material costs are only a small part of the instrument program cost. This practice also promotes use of marginal and inferior materials. A *manufacturer's dilemma* is created because there is little incentive to make product improvements and use higher quality materials that increase the product cost. A well-designed, high quality product, thoroughly tested, is a total loss to the manufacturer unless it is sold. Unless more informed buyers come forth and a change in the practices of *low bid* procurement occurs, desirable advances in field instrumentation will be slow and unsatisfying.

In his closure, Sherard (1982) agrees:

> The writer agrees completely with Mikkelsen's comments under the heading **Cost,** and similar opinions of Green. Clearly, there is an important problem in the industry created by common *low-bid* procurement and specification of a certain instrument, *or equal*. To combat this problem, the writer suggests that designers should consider to select the instrument (or two) believed to be most suitable, and specify it with no substitution allowed. This practice would allow instrument manufacturers to market products of consistently high quality. The common *or equal* clause, combined with competitive bidding, leads inevitably to excessive emphasis on economy, with the result that high-quality instruments cannot compete. This keeps the quality of the average instrument on the market just above the "acceptable" level, a highly undesirable situation.

5.4. CONTENT OF SPECIFICATIONS FOR PROCUREMENT OF INSTRUMENTS

Depending on the selection of specifying method and basis for determining price, the procurement specification should address some or all of the requirements discussed in this section. Greatest detail is required when the low-bid procedure with an *or equal* provision is used. Some requirements apply to the entire instrumentation system, usually consisting of a transducer, readout unit, and a communication system, and some apply only to one or more of these components.

The specification will usually be written with three main headings. The first heading, **Part 1. General,** will include wording applicable to all instruments, as described in Sections 5.4.1–5.4.10. The second heading, **Part 2. Instrument Details,** will include wording under separate subheadings for each instrument, as described in Sections 5.4.11–5.4.17. The third heading, **Part 3. Measurement and Payment,** will include content described in Section 5.4.18.

The procurement specification is sometimes combined with a specification for field services, following the recommendations given in Chapter 6.

Technical information for the specification should be provided by geotechnical engineers working on the project design, and these same engineers may draft the technical specification, following guidelines given in this chapter. However, the final specification should be reviewed by an experienced specification writer. A review by an instrumentation specialist may also be necessary. If instruments are to be procured as part of a construction contract, the specification should also be reviewed by personnel familiar with the General Conditions and other sections of the technical specifications, to ensure consistency.

Before enumerating the items that should be considered when writing specifications for procurement of instruments, the author will reiterate a key point. The quotations in Section 5.3 will illustrate problems inherent in the low-bid procedure. **Unless you must, don't use the low-bid procedure! The author regrets very much the need to write such a lengthy section as Section 5.4: the length is necessary only because the low-bid procedure continues to be used.** Its use creates lengthy specifications that appear out of proportion to other parts of the specifications, and the author believes that its use is not in the best interests of either manufacturers or users.

5.4.1. Division of Responsibilities

As described in Chapter 4, the division of responsibilities among owner, design consultant, instrumentation specialist, and construction contractor will have been determined during the planning phase. Section 5.1 indicates preferred responsibility for instrument procurement. The procurement specification should contain a clear statement of the work included and should indicate who will be responsible for factory calibration and quality assurance, for review of proposed instruments, and for performing acceptance tests to ensure correct functioning when instruments are first received by the user.

5.4.2. Submittals

The specification will usually include a summary listing of required submittals to the owner or design consultant. Submittals are described in later sections and may include experience lists, requests for review of proposed instruments, calibration certificates, quality assurance checklists, warranties, instruction manuals, shipping documents, and instrument samples. The schedule for all submittals should be specified.

5.4.3. Operating Environment

Instruments are normally required to operate in adverse environments. The specification should provide a general description of the operating environment, including soil or rock type, and all relevant environmental factors listed in Table 4.4. Recognizing that many instrument failures occur as the ground deforms around them, potential deformations should be evaluated and defined, with particular attention given to deformations of buried tubes, cables, and pipes.

5.4.4. Experience

Manufacturers may be required to submit an experience list indicating records of prior instrument use. However, requirements for extensive experience should not be imposed if they may exclude competent new suppliers. Experience lists should include names of firms who have used the instrument, project names, and names and telephone numbers of responsible individuals. When the procurement entails innovation, manufacturers may be required to cite examples of previous successful innovations.

5.4.5. General Material Requirements

Descriptive specifications should include appropriate mechanical, hydraulic, pneumatic, and electrical requirements. The transducer, readout unit, and communication system should each be covered separately. Recommendations for selection of transducers and components are given in Chapter 8.

To assist the manufacturer in selecting materials, desired longevity should be stated, but it is difficult to hold manufacturers to longevity specifications. If an instrument malfunctions after installation, it will generally be unclear whether the problem has been caused by a manufacturing defect or an installation error. When a brand name *or equal* specification is used, good practice dictates that the specification identify all salient characteristics that are considered important for the evaluation of substitutions. Table 5.4 indicates some of the factors to be considered when specifying general material requirements and acceptability of substitutions.

5.4.6. Review of Proposed Instruments

For all cases except sole source procurement, the specification should include requirements for review of proposed instruments, including review of substitutions if brand names and model numbers have been specified.

If instruments are procured by the construction contractor, using the low-bid procedure, the following wording, under a heading **Or Equal** in the General Conditions or in the procurement specification, will minimize the possibility of an unacceptable substitution. Similar wording is applicable when instruments are procured by the owner or design consultant and the low-bid procedure is used.

> The term *or equal* shall be understood to indicate that the *equal* product is the same or better than the product named in the Specifications in function, performance, reliability, quality, and general configuration.
>
> Except for Owner-selected materials and materials where no substitution is clearly specified, whenever any material is indicated or specified by proprietary name, by name of manufacturer, or by catalog number, such specifications shall be deemed to be used for the purpose of establishing a standard of quality and facilitating the description of the material desired. This procedure is not to be con-

Table 5.4. General Material Requirements

Instrument Type	Requirement
All (mechanical, hydraulic, pneumatic, and electrical)	Transducer type Materials specification Environmental factors in Table 4.4, with particular attention to (1) surviving ground deformations, (2) waterproofing needs, (3) chemical corrosion, (4) electrolytic corrosion (dissimilar metals can be separated by inert materials or by passivation methods), (5) temperature sensitivity, and (6) packaging for outdoor operation and rough handling Permanent labeling of all controls and connectors Dust covers on all connectors, anchored to the connector Humidity indicator in readout unit
Hydraulic	Constituents of liquid Dissolved gas content in liquid Liquid freezing point Tubing material Tubing valves and fittings Pressure indicator
Pneumatic	Container for gas Constituents of gas Moisture content in gas Filter for gas Tubing material Tubing valves and fittings Pressure indicator Gas flow rate Gas flow controller Gas flow indicator
Electrical	Battery characteristics Auxillary power supply Fuse Lightning protection Cable Connectors Cable splices Indicator Electrical safety Power consumption

strued as eliminating from competition other materials of equal quality by other manufacturers where fully suitable in design, and shall be deemed to be followed by the words *or equal*. The Contractor may, in such cases, submit complete comparative data to the Engineer for consideration of another material which shall be substantially equal in every respect to that so indicated or specified. Substitute materials shall not be ordered, delivered to the site, or used in the work unless approved by the Engineer in writing. The Engineer will be the sole judge of the substituted article or material.

Requests for review of equivalency will not be accepted from anyone except the Contractor and such request will not be considered until after the bids have been opened. All requests from the Contractor for consideration of a substitution shall clearly state any deviation from the Contract, and differences in cost.

5.4.7. Factory Calibration and Quality Assurance

Instruments should be calibrated, inspected, and tested before shipment to the user, and the procurement specification should indicate required factory calibrations.

Calibrations should be made while the variable parameter is both increasing and decreasing for at least two cycles, to document hysteresis, throughout the maximum range expected to occur in the field. Readings should be taken at about ten equal increments, and the manufacturer should be required to supply a calibration curve with data points clearly indicated, and a tabulation of the data. Each instrument should be marked with a unique identification number. In general, the readout unit that is to be supplied to the user should be used during factory calibrations, and calibrations should be made at several different temperatures to determine the effect of temperature change on the instruments. Calibration specifications should include the following wording:

> Certification shall be provided with each shipment to indicate that the manufacturer's test equipment is calibrated and maintained in accordance with the test equipment manufacturer's calibration requirements, and that all calibrations are traceable to . . .

In the United States, traceability should be to the National Bureau of Standards. However, the practicability of such a requirement should be verified with manufacturers whose products are being considered, since calibration of some commonly used instruments such as inclinometer probes is generally not traceable to standard agencies. Manufacturers, of course, may make an additional charge for calibrations requiring more effort than their standard procedure.

Manufacturers will generally apply their own quality control procedures, but these may not always be adequate, and it is often worthwhile to specify preshipment inspections:

> A final quality assurance inspection shall be made of each instrument prior to shipment. During the inspection, a checklist shall be completed to indicate each inspection and test detail. A completed copy of the checklist shall be supplied with each instrument.

5.4.8. Warranty

Manufacturers will generally warrant their products against defects in material and workmanship for a period ranging from 3 months to 1 year after delivery, and such a requirement should be included in the procurement specification. Standard warranties of the manufacturers whose products are being considered should be studied before specifying warranty terms and duration. However, unless indisputable evidence is provided, most manufacturers will not accept responsibility for malfunction of embedded components after installation, and therefore every effort should be made to specify instruments with proven longevity.

5.4.9. Instruction Manual

The procurement specification should indicate instruction manual requirements. Instruction manuals of the various instrument manufacturers vary greatly in content and quality. Although a comprehensive manual is valuable to the user, it may be impracticable to require a custom-made manual because of time or cost. The requirements should be realistic in light of manufacturers' existing manuals, available time, and the cost of preparing a custom manual.

A comprehensive instruction manual need not and should not be complicated: if it is, it will rarely be read. However, it should contain at least the following:

Purpose of Instrument

- Parameter measured.
- Applications.

Theory of Operation

- Basic measuring principle of instrument with appropriate illustrations, schematics, and circuit diagrams for each component.
- Limitations of system.
- Factors that affect measurement uncertainty.
- Specification sheet.

Calibration Procedure

- Step-by-step acceptance test procedure to ensure correct functioning when instruments are first received by the user. The manual should emphasize the importance of making acceptance tests immediately on receipt.
- Procedure for any possible regular in-place calibration checks on embedded components, including equipment required and recommended frequency.
- Procedure for regular calibration of readout instruments, including equipment required and recommended frequency. If possible, these procedures should be in such a form that check calibrations can be performed by the user or by local calibration houses, thereby avoiding the necessity of returning instruments to the factory for calibration.

Installation Procedure

- Step-by-step procedure for installation, with illustrations of the system and components, showing their correct juxtaposition when installed. Alternative procedures may be required if installation methods are dependent on the application or on field conditions. The procedures should include a listing of materials, tools, and spares required during assembly and installation and any borehole requirements, indicating maximum and minimum borehole diameters and restrictions on wall roughness. Procedures should emphasize the most critical steps and should indicate pitfalls to be avoided. (The user should recognize that, although the manufacturer can suggest installation procedures, those procedures should be planned to suit the specific site geotechnical conditions, well in advance of scheduled installation dates. Planning guidelines are given in Chapter 4.)
- Statement of all factors that should be recorded during installation for later use during data

evaluation. (These factors, as discussed in Chapter 17, will be included on the installation record sheet.)

Maintenance Procedure

- Regular maintenance procedures, with illustrations, including any appropriate disassembly instructions.
- Cleaning, drying, and lubricating instructions.
- Battery service and charging instructions, if required.
- Frequency of required maintenance.
- Recommended spare parts list, including consumables.
- List of part numbers and manufacturers of standard parts to facilitate local procurement by user.
- Troubleshooting guide, with appropriate illustrations, including a list of failure indications and probable cause and corrective action requirements for each listed failure.
- Names, addresses, and telephone numbers of instrument service representatives.

Data Collection Procedure

- Step-by-step procedure for equipment set-up and turn-on.
- Functional explanation of each connector and control.
- Cautions pertaining to personnel and equipment.
- Statement of procedure for obtaining initial reading, with appropriate illustrations.
- Statement of procedure for obtaining readings subsequent to initial reading.
- Statement of construction or environmental factors that might cause changes in the measured data. (Users should recognize that, although the manufacturer can suggest these factors, specific procedures should be planned for recording factors that may influence measured data, well in advance of instrument installation. Planning guidelines are given in Chapter 4.)
- List of equipment and tools required during reading.
- Field data sheet.
- Sample completed field data sheet.

Data Processing, Presentation, and Interpretation Procedures

- Data calculation sheet.
- Step-by-step calculation procedure, including an instruction manual for any computer program supplied by the manufacturer.
- Sample data calculation.
- Alternative methods of plotting data.
- Sample data plots.
- Notes on data interpretation.

5.4.10. Shipment and Delivery

Delivery dates should be specified, or suppliers should be required to state the time for delivery. If lead time is short and installations are to be made at several different times, a schedule of partial shipments and dates should be prepared. The method of shipment can be specified, or manufacturers can be given freedom to ship at their own option to meet the specified delivery dates. Specifications should indicate whether freight charges should be prepaid.

Unless specified otherwise, the manufacturer's responsibility for the instruments ends when they have been delivered to the carrier for shipment. Therefore, the specification should indicate requirements for insurance against loss and damage in transit. Standard transit insurance often requires notice of damage within a relatively short period after delivery; thus, the user should make a careful inspection before this time has expired.

5.4.11. Instrument Operating Principles

This is the first section of the specification under the heading, **Part 2. Instrument Details**, requiring wording under separate subheadings for each instrument.

A general description of each system and its components should be given. The operating principle should be stated, and general characteristics of the transducer, readout unit, and communication system should be defined.

5.4.12. Component Specifications

The general approach to specification of components will depend on the selection of specifying method. With this in mind, the general criteria given in Section 4.9 for selecting instruments should be reviewed. Component specifications should formalize decisions made while systematically planning the monitoring program: instrument range, acceptable uncertainty, conformance requirements, and method of verifying reading correctness. If nonstandard instruments or components are required, detail design may be necessary at this stage.

Manufacturers' price lists are often very helpful when identifying and specifying components that make up an instrumentation system. The product literature may not convey clearly the need for each component, but component listings in price lists will usually do so, and a study of these lists will help to avoid omission of an essential component.

5.4.13. Compatibility with Other Instruments

A newly procured instrument may be used in conjunction with previously procured instruments. For example, a new inclinometer probe may be required for use in existing inclinometer casing, or additional strain gages may be required for use with a previously purchased readout unit. In these cases, care must be taken to specify the features required for mechanical, hydraulic, pneumatic, and/or electrical compatibility.

5.4.14. Physical Size Limitations

Physical size limitations of each component should be defined. Components may have to fit in a certain diameter or length of borehole, or terminal size may be limited by terminal enclosure dimensions. Physical size and weight of readout instruments are often limited to permit easy carrying.

5.4.15. Submittal of Samples

The specification may require submittal of a sample instrument or instruments for testing, in which case the characteristics to be tested and a submittal schedule should be indicated.

5.4.16. Installation Tools and Materials

As described in Chapter 4, written installation procedures should include a listing of required tools and materials. The tools and materials should either be included in the instrument procurement specification or be procured separately.

5.4.17. Spare Parts

Spare parts may be required either to replace components damaged during installation or to replace accessible malfunctioning components during operation. A listing of appropriate spare parts should be made and included in the procurement specification.

Provision should be made for spare or standby readout units, for use in case of malfunction. Options are procurement of a spare unit, arrangement with the manufacturer for rental of a spare unit if needed, and a standby equipment lease. A standby equipment lease entails making arrangements with the manufacturer for a spare unit to be held in readiness at the factory, to be called on if needed. The manufacturer will generally charge either a lump sum or a monthly amount for holding the equipment. If the spare is in fact called on, payment will either be covered by the lease, or an additional payment will be made. However, the standby equipment lease procedure is not available from all instrument manufacturers. Some prefer to rent spare items and allow some or all of the rental cost to apply to a later purchase. A readout unit may also be available at short notice on a temporary basis from another user whose current day-to-day needs are low.

5.4.18. Measurement and Payment

When instruments are procured as part of a construction contract, a measurement and payment specification section is required. Instrument procurement should be measured and paid for on a unit price basis rather than a lump sum, to allow for changes in quantities as work proceeds. The unit price schedule should contain sufficient items so that major component prices are defined. For example, when requiring piezometers with attached tubing, either the length of tubing should be specified for each piezometer, or a separate unit price item should be provided for tubing. When requiring multipoint fixed borehole extensometers, either the distances between each anchor and the head should be specified, or a separate unit price item should be provided for heads, anchors, and connecting linkage.

A special effort should be made to ensure that a unit price pay item is included for every specified requirement. If payment for a specified requirement is deemed to be included in the price bid for a particular item (e.g., if payment for factory calibration is deemed to be included in the unit price for a diaphragm piezometer), this should be stated clearly.

If instruments are to be procured by use of the assigned subcontract approach, clear wording is required to define quantities, payment, and markup. The following wording is suitable:

> Payment for procurement of instruments will be made under allowance item no. ______. The Owner's Representative will determine instrument descriptions, sources, quantities, and prices and will provide this information to the Contractor. The Contractor shall place orders with assigned instrument suppliers within three working days after receipt of instructions from the Owner's Representative. The Contractor shall submit copies of suppliers' invoices and will be reimbursed in accordance with those invoices, plus the specified (or bid) markup. If the actual total cost of instruments is more or less than the allowance, the contract price will be adjusted to the actual approved amount.

Payment for procurement of instruments is often combined with payment for installation by using several *furnish and install* unit price items in the bid. Measurement and payment recommendations for this case are given in Chapter 6.

5.4.19. Checklist for Specification Content

Appendix B contains a checklist for content of specifications for procurement of instruments. Use of the checklist will help ensure completeness. However, each individual specification may require only some of this content.

CHAPTER 6

CONTRACTUAL ARRANGEMENTS FOR FIELD INSTRUMENTATION SERVICES*

Field instrumentation services include installation, regular calibration and maintenance, and data collection, processing, presentation, and interpretation. Selection of personnel responsible for field services may govern the success or failure of a monitoring program. Even if the program has been planned in a complete and systematic way and appropriate instruments have been procured, measured data may not be reliable unless field personnel perform high-quality work. Geotechnical instrumentation field work should not be considered a routine item of construction work, because successful measurements require extreme dedication to detail throughout all phases of the work. Specifications should be clear, concise, complete, and correct (Watson, 1964).

When planning the monitoring program in accordance with guidelines given in Chapter 4, an assignment of tasks will have been made. Contractual arrangements for each field task are discussed in this chapter, and justifications are given for task assignments recommended in Chapter 4.

*Written with the assistance of Robert E. Vansant, Black & Veatch, Kansas City, MO.

6.1. GOALS OF CONTRACTUAL ARRANGEMENTS

The primary goals of contractual arrangements for field instrumentation services are (1) to ensure high-quality work at acceptable cost to the owner, (2) to create a cooperative working relationship between specialty intsrumentation personnel and the construction contractor, and (3) to permit flexibility to accommodate changes during progress of the work. Flexibility is needed because unforeseen factors are often revealed during construction, requiring a change of instrument types and/or locations.

6.2. DEFINITION OF TERMS

Definitions of terms used in the discussion on contractual arrangements are given below.

6.2.1. Support Work

Tasks that are within the capability of the average construction contractor are considered *support work*.

6.2.2. Biddable Support Work

Support work of a production nature, for example, production drilling, protection from damage, and furnishing and installing simple instruments such as settlement platforms, is considered *biddable support work*. Support work that can be bid by the hour, for example, drill rig and crew to assist during instrument installation, is also considered biddable support work.

6.2.3. Nonbiddable Support Work

Support work that will be controlled by the owner's instrumentation schedules or procedures, for example, access for reading; support work that is not defined at the time of bid, for example, revised instrumentation owing to geologic conditions revealed during construction; and contractor's assistance that will be needed on an *as required* basis, for example, assistance of tradespeople, are all considered *nonbiddable support work*.

6.2.4. Specialist Work

All instrumentation tasks outside the capability of the average construction contractor are considered *specialist work*.

6.2.5. Force Account and Contingency Allowance

Force account is a method of payment to the construction contractor for work additional to the specified work, whereby reimbursement is on a time and materials basis. The cost of force account work may be included in the total bid price by adding a *contingency allowance* in the contract. A line item in the bid schedule is identified as a contingency allowance, and the owner's cost estimate is entered in the amount column. Because the work is not specified, a single contingency allowance can be used for many items of work. The cost of force account work is sometimes not included in the total bid price, in which case there must be a separate contingency fund.

The contingency allowance procedure can also be used to pay for nonbiddable support work, in which case the item description in the bid schedule will be *Instrumentation support work* and the specification will indicate the work included and the method of establishing payment rates, which are normally the same as force account rates.

Payment rates for labor are normally based on wage rates actually paid by the contractor, plus direct payroll overhead such as social security, unemployment, and pension funds. Payment rates for plant and equipment are normally based on rental rates accepted by the industry. Payment rates for materials are based on actual cost, supported by receipts. The construction contactor is normally allowed a specified or agreed markup on all payment rates. If force account work is performed by a subcontractor, both the construction contractor and subcontractor are normally allowed a markup.

6.2.6. Assigned Subcontract

For an *assigned subcontract*, the owner negotiates the purchase and assigns the contract to the construction contractor for administration. Payment is made on the basis of actual work done, and the cost is included in the total bid price. A line item in the bid schedule is designated as an *allowance item* and appropriate wording entered in the description column to define the work category. The owner's cost estimate is included in the bid schedule. After contract award, the construction contractor is instructed to enter into a subcontract with the assigned subcontractor, and payment is made to the subcontractor via the construction contractor under the allowance item. The contractor's monthly payment requests to the owner are supported by including copies of subcontractor invoices.

There are two circumstances in which assigned subcontracts are expedient in geotechnical instrumentation specifications:

1. *For Procurement of Instruments.* When instruments are procured through the construction contractor (Chapter 5), the assigned subcontractor approach can be used to allow the owner or design consultant to retain control over selection of equipment and basis for determining price. The item description will be *Furnish instruments*. The owner specifies that, after contract award, the owner's representative will determine instrument descriptions, sources, quantities, and prices and will provide this information to the contractor. The contractor is then required to place orders, within a specified time period, and the instrument suppliers become assigned subcontractors.
2. *For Specialist Field Work.* When specialist field work is to be performed by specialist personnel selected by the owner, the cost can be included in the total bid price by use of the assigned subcontractor approach. The item

description will be *Provide services of specialty field instrumentation personnel.* The owner specifies that, after contract award, the contractor will be instructed to enter into a subcontract with an organization selected by the owner and agreeable to the contractor, and the organization becomes an assigned subcontractor.

Payment to the construction contractor can be at actual cost without markup, but this inhibits the contractor's willingness to cooperate and is not recommended. A markup for overhead and profit can be specified, in which case the cost estimate entered by the owner in the bid schedule will be the marked up amount. Alternatively, bidders can be invited to bid a markup, in which case bidders will enter the percent markup in the bid schedule and extend the marked up estimate to the amount column.

The owner's estimate should not be regarded as a *not to exceed* figure, and the contract price should be increased by change order if needed.

6.3. CONTRACTUAL ARRANGEMENTS FOR INSTRUMENT INSTALLATION

Five basic contractual arrangements for installing instruments are described below. Recommendations are given in Section 6.3.6.

6.3.1. Method 1. Specialist Installation Work by Owner's Personnel

The owner's personnel perform all *specialist work,* sometimes using their own equipment such as drill rigs, and *support work* is performed by the construction contractor. *Biddable support work* is bid, and *nonbiddable support work* is paid for at *force account* rates under a *contingency allowance.*

6.3.2. Method 2. Bid Items in Construction Contract, without Prequalification

All instrument installation work is included in the construction contract, usually specified as *furnish and install,* and bid on a unit price or lump sum basis. No qualification requirements for specialist personnel are included, and no distinction is made between *specialist* and *support work.* If the work is specified as *furnish and install,* the specification should include sections on procurement of instruments, as described in Chapter 5.

6.3.3. Method 3. Bid Items in Construction Contract, with Prequalification

Contractual arrangements are similar to the preceding method, and all instrument installation work is bid. However, the specification includes a requirement that all installation work shall be performed under the direct supervision of suitably qualified personnel. Qualification requirements are discussed in Section 6.6.5.

6.3.4. Method 4. Instrumentation Specialist Selected by and Contracting with Owner

Specialist work is performed by an instrumentation specialist under contract to the owner, the design consultant, or the construction manager. The owner or design consultant determines which tasks are within the capability of the average construction contractor and designates these as *support work.* The remainder of the instrument installation tasks are designated as *specialist work,* and the owner or design consultant selects personnel to perform *specialist work,* in accordance with appropriate parts of the following recommendations given in the proposed new text of *ASCE Manual No. 45* (ASCE, 1987). In this extract, *consulting engineers* refers to instrumentation specialists:

1. By invitation or by public notice, state the general nature of the project and services required and request statements of qualifications and experience from consulting engineers who appear to be capable of meeting the project requirements. . . .
2. Evaluate the statements of qualifications received. Select at least three consulting engineers that appear to be best qualified for the specific project. . . .
3. Write a letter to each consulting engineer, describing the proposed project in as much detail as possible, including a scope of work and outline of services required, and asking for a proposal describing in detail the consulting engineer's plan for managing and performing the required work, the personnel to be assigned, the proposed work schedule, experience in similar work, and other appropriate information such as office location in which work is to be performed, financial standing, present work-

load, and references. Each selected firm should have an opportunity to visit the site, review all pertinent data, and obtain clarification of any items as required.

4. On receipt of proposals, invite the firms to meet individually with the selection committee for interviews and discussions of the desired end results of the project and the engineering services required. During each interview, the selection committee should review the qualifications and experience of each firm, its capability to complete the work within the time allotted, and the specific key personnel to be assigned to the project; and should be satisfied that each firm understands the scope and requirements of the project.
5. Check carefully with recent clients of each firm to determine the quality of their performance. This check should not be limited only to references specified by the consulting engineer.
6. List the firms in the order of preference, again taking into account their reputation, experience, financial standing, size, personnel available, quality of references, workload, location, and any other factors peculiar to the project being considered.
7. Invite the consulting engineer considered to be best qualified to appear for a second interview to discuss the project and agree on a detailed scope of work and work products, the schedule, and negotiate fair compensation for the work and services.
8. The compensation proposed by the consulting engineer should be evaluated on the basis of the client's previous experience, taking account of the range of charges reported by other users of engineering services, . . . giving consideration to the project's special characteristics and the scope of services agreed upon. Fair and reasonable compensation to the consulting engineer is vital to the success of the project to enable the expertise of the consulting engineer to be fully utilized.
9. If satisfactory agreement is not reached with the first consulting engineer, the negotiations should be terminated and the consulting engineer notified in writing to that effect. An interview should then follow with the second firm; and failing an accord, the third should be called in for negotiations. Such a procedure will usually result in development of a satisfactory contract. All such negotiations should be on a strictly confidential basis, and in no case should the compensation discussed with one consulting engineer be disclosed to another.
10. When agreement has been reached on scope of work, schedule and compensation the client and selected consulting engineer should formalize their agreement in a written contract. . . .

Qualification guidelines are given in Section 6.6.5. If the owner has had satisfactory experience with one or more instrumentation specialists in the past, it may not be necessary to follow all the above steps. In fact, as discussed in Chapter 5 for procurement of instruments, a sole source approach may be used, both by private and public agencies. Perlman (1985) indicates that in 1982 more than half of procurement dollars spent by the U.S. government to acquire goods and services were spent on sole source contracts.

The contract will be for specialist work only, and payment provisions will normally be on a time and materials basis. Contracts and charges for engineering services are also discussed in *ASCE Manual No. 45* (ASCE, 1987).

Support work is performed by the construction contractor. As for Method 1, *biddable support work* is bid, and *nonbiddable support work* is paid for at *force account* rates under a *contingency allowance*.

6.3.5. Method 5. Instrumentation Specialist Selected by Owner and Contractor, and Contracting with Contractor as an Assigned Subcontractor

Specialist work is performed by an instrumentation specialist under contract to the construction contractor. As with Method 4, the owner or design consultant determines which tasks are *support work* and which are *specialist work*. After the construction contract is awarded, the owner and contractor mutually select an instrumentation specialist in the following manner. The owner supplies a list of suitable instrumentation specialists to the contractor. From this list the contractor selects and submits the names of three specialists. The owner finally selects an instrumentation specialist from this short list, following the qualification guidelines given in Section 6.6.5 and the selection procedures described in *ASCE Manual No. 45* (ASCE, 1987) and Section 6.3.4. The owner negotiates a time and materials payment method with the selected instrumentation specialist, who then becomes an *assigned subcontractor*.

Support work is performed by the construction contractor and paid for in the same way as Method 4.

6.3.6. Recommended Contractual Arrangements for Installing Instruments

The major advantages and limitations of the five arrangements are given in Table 6.1.

Method 2 can be used for simple installations that can be considered as normal construction items, such as settlement platforms, but should never be used for more complex installations. Method 3 should be used only when owner regulations require use of the low-bid method because even with prequalification requirements, construction contractors will generally shop for the lowest price, with risk of subcontractor cost cutting and possible invalid measurement data. Use of Method 3 entails a very comprehensive specification addressing all issues discussed in Section 6.6.

Methods 1, 4, and 5 are all satisfactory, the selection depending on factors specific to each project.

Methods 1 and 4 sometimes raise concerns about adversary relationships between owner's and construction contractor's personnel, but in practice cooperation can normally be achieved by following the suggestions given in Section 6.6.7.

Use of Method 1 is supported by a major U.S. public agency. In its manual on instrumentation for concrete structures, the U.S. Army Corps of Engineers (Corps of Engineers, 1980) states:

> The general policy of the Chief of Engineers is to perform all civil works by contract unless it is in the best interest of the United States to accomplish the work by Government forces. However, the specialized nature of instrumentation facilities and the care required in the preparation, calibration, and placement of test apparatus demands that these features of work be retained under close operational control of the Corps of Engineers. In view of these conditions . . . , utilization of Government personnel to accomplish certain phases of the fabrication and installation work, such as embedment of instruments and splicing of cables, is recommended.

Method 5 sometimes raises concerns about professionalism on the part of the instrumentation specialist, who has negotiated with the owner but contracted with the construction contractor. However, in practice, again by following the suggestions in Section 6.6.7, this concern is generally unfounded. Guertin and Flanagan (1979) used Method 5 for a major tunnel project in Rochester, New York, and comment that the day-to-day operations during the monitoring program proceeded smoothly with a minimum of conflict between the instrumentation specialist, design consultant, construction contractor, and owner. A spirit of common purpose existed during the project that, the writers believe, would not have developed as readily under a different contractual arrangement. Where space limitations are severe (and they are particularly severe during tunnel construction), the construction contractor and instrumentation specialist **must** have a cooperative working relationship so that instrument installation schedules and access needs can be coordinated with construction needs. In these cases Method 5 is most suitable.

6.4. CONTRACTUAL ARRANGEMENTS FOR REGULAR CALIBRATION AND MAINTENANCE

Contractual arrangements for regular calibration and maintenance should preferably follow Method 1, 4, or 5. If Method 3 is used, procedures, schedules, and personnel qualifications should be defined. Use of Method 2 entails a similar specification, but without personnel qualifications. However, Method 2 should be used only for very simple calibration and maintenance.

6.5. CONTRACTUAL ARRANGEMENTS FOR DATA COLLECTION, PROCESSING, PRESENTATION, INTERPRETATION, AND REPORTING

Contractual arrangements for data collection, processing, and presentation should preferably follow Method 1, 4, or 5. If Method 3 is used, the pay item unit should be *data set* or *man-hour* with clear definition of procedures and personnel qualifications. Use of Method 2 entails a similar specification, but without personnel qualifications. However, Method 2 should be used only for very simple data collection, processing, and presentation.

Data interpretation and reporting must be the direct responsibility of the owner or the owner's representative; therefore, Methods 2 and 3 are not suitable.

Table 6.1. Advantages and Limitations of Various Contractual Arrangements for Instrumentation Installation[a]

Method	Advantages	Limitations
1. Specialist installation work by owner's personnel	Owner has direct control over cost and quality Flexible to accommodate changes	Potential problems with contractor cooperation if instrumentation work interferes with other work, but see Section 6.6.7 Owner must plan for workload well in advance Assumes owner has necessary in-house skills Cannot always be financed by construction funds
2. Bid items in construction contract, without prequalification	Installation costs will usually be low Financed by construction funds	Generally, contractor will shop for lowest price subcontractor, with risk of lowest quality and invalid measurement data Requires strong and experienced supervision by owner's representative Not flexible to accommodate changes
3. Bid items in construction contract, with prequalification	Installation costs will usually be low Excludes inexperienced instrumentation subcontractors Financed by construction funds	Generally, contractor will shop for lowest price "qualified" subcontractor, with risk of subcontractor having inadequate price, cutting corners, and thus invalid measurement data Often difficult to substantiate desire to reject questionably qualified subcontractor Usually requires strong and experienced supervision by owner's representative Not flexible to accommodate changes
4. Instrumentation specialist selected by and contracting with owner	Owner has direct control over cost and quality Flexible to accommodate changes Instrumentation specialist can, if retained early enough, assist with design of monitoring program	Potential problems with contractor cooperation if instrumentation work interferes with other work, but see Section 6.6.7 Cannot always be financed by construction funds Requires some effort by owner to select specialist
5. Instrumentation specialist selected by owner and contractor, and contracting with contractor as an assigned subcontractor	Owner has direct control over cost and, via the owner's representative, quality Facilitates cooperation and scheduling with contractor Flexible to accommodate changes Financed by construction funds	Selection is made after award of construction contract: instrumentation specialist therefore cannot assist with design of monitoring program Assumes "professionalism" on part of instrumentation specialist, who has negotiated with the owner but contracted with the construction contractor, but see Section 6.6.7 Requires some effort by owner to select specialist Not permitted under some public agency regulations

[a] Method 2 should be used only for simple installations that can be considered as normal construction items. Methods 1, 4, and 5 are more likely to result in valid measurement data than Method 3.

6.6. CONTENT OF SPECIFICATIONS FOR FIELD INSTRUMENTATION SERVICES

Depending on selection among the five methods for instrument installation, regular calibration and maintenance, and data collection, processing, presentation, and interpretation, the specification for field instrumentation services should address some or all of the requirements discussed in this section. It is not intended that all specifications should address all these requirements but, if Method 2 or 3 has been selected for any task, extra care must be taken to write a comprehensive specification and all relevant requirements should be specified.

The specification for field instrumentation services will sometimes be combined with a specification for procurement of instruments, following the recommendations given in Chapter 5.

The specification will often be written with four main headings. The first heading, **Part 1. General,** will include wording relating to the overall approach, as described in Sections 6.6.1–6.6.7. The second heading, **Part 2. Products,** will include wording relating to materials, including procured instruments, as described in Section 6.6.8 and part of Section 6.6.9. The third heading, **Part 3. Execution,** will include detailed wording related to the field work, as described in Sections 6.6.9–6.6.18. The fourth heading, **Part 4. Measurement and Payment,** will include content as described in Section 6.6.19.

Technical information for the specification should be provided by geotechnical engineers working on the project design, and these same engineers may draft the technical specification, following guidelines given in this chapter. However, the final specification should be reviewed by an experienced specification writer. A review by an instrumentation specialist may also be necessary. The specification should also be reviewed by personnel familiar with the General Conditions and other sections of the technical specifications, to ensure consistency.

Before enumerating the items that should be considered when writing specifications for field instrumentation services, the author will reiterate a key point. When the low-bid procedure is used, even when prequalification requirements are included, construction contractors will generally shop for the lowest price, with risk of subcontractor cost cutting and possible invalid measurement data. An engineer who has a serious need for valid data cannot afford to take this risk. **Unless you must, don't use the low-bid procedure! The author regrets very much the need to write such a lengthy section as Section 6.6.: the length is necessary only because the low-bid procedure continues to be used.** Its use creates lengthy specifications that appear out of proportion to other parts of the specifications, and the author believes that its use is not in the best interests of the owner.

6.6.1. Purpose of Instrumentation Program

Many construction contractors view instrumentation as an interference with their normal construction work. However, if contractors are aware of a clear purpose for an instrumentation program, their willingness to cooperate is likely to be increased. Therefore, specifications should include a brief statement of purpose, of the parameters monitored by each instrument, and of how the data will be used. More detailed statements on use of data should be included under the heading **Implementation of Data** (see Section 6.6.15).

6.6.2. Division of Responsibilities

As described in Chapter 4, the division of responsibilities among owner, design consultant, instrumentation specialist, and construction contractor will have been determined during the planning phase. Specifications should include a clear statement of the work items for which the construction contractor is responsible and the work items to be undertaken by others.

6.6.3. Specification Method

The specification should indicate which of the five contractual arrangements has been selected for each field task. Table 6.2 summarizes the recommendations made earlier in this chapter. For Methods 1, 4, and 5, a clear definition should also be made of which tasks are *specialist work* and which are *support work*.

If a contingency allowance or an assigned subcontract procedure is being used, a brief definition should be given, based on appropriate parts of Sections 6.2.5 and 6.2.6, and the relevant work items should be listed. A more detailed specification should be included under the heading **Measurement and Payment** (see Section 6.6.19).

Table 6.2. Summary of Recommendations for Specifying Field Instrumentation Services

Task	Method				
	1	2	3	4	5
Installation, regular calibration and maintenance, and data collection, processing, and presentation	Satisfactory	Only very simple instrumentation	Less satisfactory than Methods 1, 4, and 5	Satisfactory	Satisfactory
Data interpretation and reporting	Satisfactory	Unsatisfactory	Unsatisfactory	Satisfactory	Satisfactory

6.6.4. Related Work Specified Elsewhere

A listing should be made of related work that is specified elsewhere, for example, dewatering, support of excavation, and other work items that are affected by implementation of instrumentation data. Section numbers of related parts of the specification should be given.

6.6.5. Qualifications of Specialist Field Instrumentation Personnel

Successful operation of an instrumentation program requires a special effort. Reliability and patience, perseverance, a background in the fundamentals of geotechnical engineering, mechanical and electrical ability, attention to detail, and a high degree of motivation are the basic requirements for qualities needed in instrumentation personnel.

If the safety of the project depends on the measurements, then the requirements for reliable personnel are doubly important. Personnel must also be flexible and ingenious to adapt to constantly changing situations. In selecting personnel to perform or supervise field work, consulting firms with special expertise in geotechnical instrumentation should be considered. Geotechnical consulting firms are listed in various professional magazines, in the directory of the American Consulting Engineers Council,* and in the membership list of the Association of Soil and Foundation Engineers.† Some instrumentation manufacturers do not maintain a staff of experienced geotechnical engineers and field technicians; therefore, caution should be exercised in specifying that *installation of the instruments shall be supervised by a representative of the manufacturer*. If instrumentation field work requires combining a knowledge of an instrument with a knowledge of appropriate geotechnical conditions, it will usually be necessary to involve a **geotechnical engineer** having comprehensive experience with the selected instrument.

Qualification wording should address requirements for the firm responsible for field instrumentation services and also for the individuals who will be directly performing the field work. The specification will usually require the demonstration of certain specific previous experience. All specialist field instrumentation personnel should be subject to the owner's approval.

When specification Method 3 is used, if instrumentation work is the primary part of the construction contract, qualifications will usually be required with the bid, and attention will normally be drawn to this requirement both in the invitation to bid and at the prebid conference when one is held. If instrumentation work is not the primary part of the construction contract, qualifications will be required within a certain period after award. For example, the following wording may be appropriate for an instrumentation program of substantial size, but which is not the primary part of the construction contract:

> Installation of piezometers and inclinometers shall be under the full-time supervision of a geotechnical engineering consulting firm with previous experience in installing similar instruments. The two senior individuals who will actually be performing the supervision shall be a qualified Geotechnical Instrumentation Engineer and a qualified Field Supervisor. The Geotechnical Instrumentation Engineer

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†8811 Colesville Road, Suite G106, Silver Spring, MD 20910.

shall be a registered professional engineer with a minimum of a Master of Science degree in geotechnical engineering. The Geotechnical Instrumentation Engineer shall have at least 4 years experience in geotechnical engineering and geotechnical instrumentation and shall have direct field experience in the installation of geotechnical instruments including piezometers and inclinometers. The Geotechnical Instrumentation Engineer shall prepare detailed written procedures for installation of each type of instrument, shall personally supervise the installation of at least the first two instruments of each type, shall review and sign all submittals, shall instruct the installation crews regarding installation procedures, and shall be available for consultation with the crews at all times. All geotechnical instruments shall be installed under the full-time field supervision of the Field Supervisor, who shall have a minimum of a Bachelor of Science degree in civil engineering or geology, and at least 2 years field experience in the drilling and logging of soil and rock borings. The firm, the Geotechnical Instrumentation Engineer, and the Field Supervisor shall be subject to the approval of the Authority. The firm's name and individuals' names shall be submitted to the Authority for approval no later than 120 days prior to installing the first piezometer or inclinometer. The submission shall include a statement of past similar experience of the firm and the individuals.

6.6.6. Submittals During Construction

If details of any work items are to be determined by the construction contractor or subcontractor, drawings and procedures should be submitted to the owner for approval, a specified time period prior to commencing that work in the field. Sufficient time should be allowed for suppliers' lead times and for one or more resubmittals in the event that the first submittal is not approved. Such a requirement creates a contractual commitment to plan the work well in advance and gives the owner an opportunity for timely review. Submittals may include detailed step-by-step installation procedures with a listing of materials and equipment, logs of installation activities, and procedures for any other tasks assigned to the construction contractor (Table 4.2).

6.6.7. Cooperation Between Construction Contractor and Owner's Specialist Field Instrumentation Personnel

When Method 1 or 4 is used, a cooperative working relationship between the construction contractor and the owner's field personnel is essential. The specification should convey that extreme attention to detail is necessary and should include a general requirement for the contractor's cooperation. However, if the contractor has no economic incentive to cooperate, it can be difficult to enforce such requirements, and the owner's field personnel should make a special effort to establish a cooperative relationship. The best way of establishing such a relationship is for instrumentation personnel to initiate thorough communication with all levels of the contractor's personnel several weeks or months before anything has to be accomplished physically in the field. The instrumentation personnel should meet with the contractor's engineers and supervisors to explain what will be done, why it must be done, and what will be required of the contractor. They should prepare sketches to forewarn the contractor of the impact on normal construction work, provide lists of materials that will be required for support work, and be willing to adjust their own plans to create minimum interference to the contractor's work. In short, mutual respect can usually be established by thorough communication, dispelling the adversary relationship that sometimes arises between architect-engineers and construction contractors. Having established this respect, instrumentation personnel should maintain the contractor's respect by performing top-quality work, be responsive to the effects of the program on the contractor, and work **with** the contractor to minimize any adverse effects.

When Method 5 is used, the specification should also include a general requirement for the contractor's cooperation. Concerns related to professionalism on the part of the instrumentation specialist, who has negotiated with the owner but contracted with the construction contractor, can usually be nullified by establishing mutual respect as suggested above.

6.6.8. Procurement of Instruments

This is the first section of the specification under the heading, **Part 2. Products.**

If instruments are to be procured under a separate contract and provided to the construction contractor for installation, the specification for field instrumentation services should include a full listing of all instruments, spare parts, tools, and associated materials that will be provided. The construction contractor's understanding and therefore cooperation will be increased by including a brief description of instrument operating principles and physical sizes. Information should be included on factory calibration and quality assurance, checking and testing by the owner on first receipt (acceptance tests), warranties, shipment and delivery arrangements, schedules and insurances, and procedures for handing over to and checking by the construction contractor. These last procedures must ensure that the contractor accepts responsibility for the condition of the instruments at the time of handing over.

If instrument procurement is included in the same specification as field instrumentation services, the Chapter 5 guidelines should be followed. In this case a special effort should be made to include in the plans and specifications the required quantities of instruments, communication systems, readout units, and terminals. All too often this information is unclear, and a tabular listing would resolve the difficulty.

The specification will normally require the construction contractor to provide clean, dry, secure storage space for instruments, including requirements for size, windows, doors, benches, furniture, tools, power outlets, lighting, heating, air conditioning, locks, completion date, and ownership at the end of the construction period.

6.6.9. Support Work

Typical support work items are listed in Table 6.3. The first two items relate to products and will be included under the heading **Part 2. Products.** The remaining items relate to execution and will be included under the heading **Part 3. Execution.**

Each biddable support work item should be specified in sufficient detail, either in this section or in later sections, so that bidders can understand requirements and bid an appropriate amount. Use of the term *as directed by the Owner's Representative* is strongly discouraged: if the owner is unable to specify a work item, how can bidders be expected to prepare a bid for the item? Support work specified as *incidental* (i.e., when no separate pay item is provided) should also be specified in detail. Nonbiddable support work that is to be paid for under a contingency allowance should be described but need not be specified in detail.

If the owner will be responsible for specialist work (specification Method 1 or 4), scheduling of support work should be under the control of the owner, and the following wording is appropriate:

> The Contractor's instrument-related support work shall be scheduled with the Owner. These work items shall not be conducted or paid for unless the Owner's Representative is present.

6.6.10. Locations of Instruments

The exact location of instruments should usually be determined in the field, when geologic details and construction procedures are defined more closely than during the design phase. The specification should state that the owner's representative will indicate the final locations, orientations, depths, and number of instruments in the field and will confer with the contractor as to the suitability of all locations. The approximate locations of instruments, communication systems, and terminals should be shown on the contract plans, but a note should be added to indicate that they are approximate and subject to change. The contractor should be required to perform a record survey of all instrument locations to define the vertical and lateral positions of the exposed parts, and the required measurement accuracy should be specified.

6.6.11. Installation of Instruments

The five basic contractual arrangements for installing instruments are described in Section 6.3. Installation will normally require both specialist and support work.

If Method 2 or 3 has been selected, comprehensive step-by-step installation procedures should be specified, and details should be included on the contract plans. The procedures will be abbreviated versions of the procedures described in Chapter 17, retaining key items for enforcement by the owner's representative. The wording *installation procedures shall be in accordance with the manufacturer's recommendations* is applicable **only** if the manufacturer's procedures are first reviewed, in order to ensure that they are complete and applicable

Table 6.3. Typical Support Work Items

Item	Usual Category		Usual Bid Unit
	Nonbiddable	Biddable	
Take delivery of instruments procured under a separate contract		•	Lump sum
Furnish simple components and instruments such as settlement platforms		•	Each
Check instruments procured under a separate contract		•	Lump sum (usually combined with the first item in this table)
Install simple instruments such as settlement platforms		•	Each (usually combined with the second item in this table)
Provide storage space for instruments		•	Month or lump sum
Obtain permits for drilling	•		None: incidental work item
Production drilling		•	Linear foot
Drilling or grouting as directed by the owner		•	Hour
Drill rig and crew to assist during instrument installation		•	Hour
Standby of drill rig and crew		•	Hour
Excavation of trenches, backfilling and compaction for instrument tubes		•	Linear foot or cubic yard
Tradespeople to assist owner on *as needed* basis, e.g., cutting, welding, fabrication services	•		None: force account or contingency allowance
Use of air, water, and electrical power supplies	•		None: incidental work item
Hoisting and transportation equipment to move instruments	•		None: incidental work item, force account, or contingency allowance
Protection from damage	•		None: incidental work item
Optical survey work to lay out instruments and to record location	•		None: incidental work item
Access for installation or reading by owner	•		None: incidental work item, force account, or contingency allowance
Make initial instrument readings jointly with the owner's representative	•		None: incidental work item
Optical survey work to read instruments[a]		•	Each, data set, hour, or lump sum
Provide information to owner on construction events and progress that may influence measured data	•		None: incidental work item
Revised instrumentation due to geologic conditions revealed during construction	•		None: force account or contingency allowance
Remove or salvage instruments or restore surface or subsurface	•		None: incidental work item

[a] But data are usually more reliable if optical survey measurements are made as specialist work.

to the specific site geotechnical conditions. The contractor should be required to submit detailed step-by-step installation procedures to the owner for review, a specified time period prior to commencing field installation work. The contractor should also be required to submit logs of installation activities for inclusion on installation record sheets. A listing of items to be recorded is given in Section 17.10. Installation schedules should be specified, including a deadline for instruments to be operational, normally in relation to a construction activity. If instruments are to be installed as geologic or construction conditions indicate, the contractor should be required to complete installations within a certain fixed time after being notified by the owner's representative. Any work restrictions, such as disposal of surplus grout, should also be specified.

If Method 1, 4, or 5 has been selected, installation procedures should also be specified, but in less detail.

If instrument installation requires drilling in soil or rock, drilling requirements will usually be specified in a separate section. However, when using site investigation drilling specifications as a basis for wording, care should be taken to tailor the wording, recognizing that the primary purpose is instrument installation rather than sampling and definition of stratigraphy. The separate drilling section will usually include requirements for drilling equipment, soil boring and sampling methods, rock drilling and coring methods, drilling fluid, drilling records, sample containers, sample storage and submittal. The following wording is often applicable in the general drilling section:

> Whenever withdrawing drill casing during instrument installation, care shall be taken to minimize the increments and rate of casing withdrawal so that collapse of the borehole does not occur and to ensure that backfill material does not build up inside the casing such that the instrument is lifted as the casing is withdrawn. The casing shall be withdrawn without rotation. The casing may be omitted only where permitted in accordance with specifications herein describing installation of each instrument, and where it can be shown to the satisfaction of the Engineer that instrument installation without the casing will not cause collapse of the borehole or in any way adversely affect instrument installation.

The sections describing installation of each instrument will usually include maximum and minimum borehole or casing diameter, tolerance on borehole alignment, and sampling frequency. Specifications for soil borings will include acceptability of drilling without casing and acceptability of using hollow-stem augers or drilling mud. Where grout is to be used, the mix for each instrument should be specified.

If practicable, acceptance tests should be specified to verify that installations have been completed satisfactorily. For example, falling and rising head tests can be made in open standpipe and twin-tube hydraulic piezometers, groove tracking tests and spiral survey measurements can be made in inclinometer casings, and rod sliding tests can be made in fixed borehole extensometers equipped with a disconnect between rod and anchor. Repeatability should be examined by taking several instrument readings.

6.6.12. Regular Calibration and Maintenance

Recommendations for specifying regular calibration and maintenance are given in Section 6.4.

Use of Method 3 requires specifying personnel qualifications, as well as procedures and schedules following the guidelines in Chapter 16. Method 2 requires a similar specification, but without personnel qualifications. If Method 5 has been selected, a similar specification is required, but in less detail, since detailed requirements will be addressed in the subcontract. No specification is necessary if Method 1 or 4 is used.

6.6.13. Data Collection, Processing, and Presentation

Recommendations for specifying data collection, processing, and presentation are given in Section 6.5.

Use of Method 3 requires specifying personnel qualifications and procedures following the guidelines in Chapter 18, including the format and schedule for submission of data to the owner's representative. If the construction contractor is responsible for any data collection, for example, optical survey work, the required accuracy should be specified. Reading frequency should preferably be as directed by the owner's representative—thus necessitating a *data set* or *man-hour* pay item unit. If reading frequency must be specified, the start, termination, and frequency should be defined. For example, *daily* may or may not include nonworking days and will normally terminate in relation to construction activity. However, such specifications do not allow flexibility to collect data when it is most beneficial to do so and should therefore be avoided wherever possible.

Use of Method 2 requires a specification similar to Method 3, but without personnel qualifications. Method 5 also requires a specification similar to Method 3, but in less detail, since detailed requirements will be addressed in the subcontract. No specification for regular data collection, processing, and presentation is necessary if Method 1 or 4 is used.

To avoid the possibility of disputed measurements of change, the contractor and owner's representative should jointly make initial readings and agree on appropriate values. The method and schedule should be specified for each instrument.

6.6.14. Availability of Data

If the owner is responsible for reading instruments, the data should be made available to the construction contractor. The specification should state whether raw or interpreted data will be made available and on what schedule. Care should be taken to ensure that construction contractors are not relieved of their responsibility to ensure safety. The following wording is usually appropriate:

> Raw data will be made available to the Contrator within one working day of reading. The Contractor may observe the readings at any time or take supplementary readings at no additional cost to the Owner. The Owner's Representative will interpret the data and make interpretations available to the Contractor as soon as practicable. The Contractor is expected to make his own interpretations of the data for his own purposes. Furthermore, the Contractor shall install, monitor, and interpret data from additional instrumentation that the Contractor deems necessary to ensure the safety of the work. Raw data collected by the Contractor, whether from specified instruments or from additional instruments of the same type, shall be taken in the same manner as adopted by the Engineer. All raw data collected by the Contractor shall be made available to the Engineer within one working day of reading. The Owner is not responsible for guaranteeing the safety of the work based on the instrumentation data. The Contractor shall not disclose instrumentation data to third parties and shall not publish data without prior approval of the Owner.

6.6.15. Implementation of Data

Data interpretation and reporting must be the direct responsibility of the owner or the owner's representative; therefore, Method 1, 4, or 5 must be used.

If instrumentation is used to provide benefits during construction (Chapter 3), the specification should include clear statements defining how the data will be used and what action will be taken. If observations are to be used to control construction schedules or quality of work, these requirements should also be clearly specified. If remedial action has been devised to solve problems that may be disclosed by observations (Chapter 4), the construction contractor should be forewarned of the actions. If hazard warning levels have been assigned, the action for each level should be indicated. Contractual responsibility for initiating remedial action and the method of forewarning all parties should be stated.

Great care should be taken to ensure that this section of the specifications is consistent with all other sections of the specifications.

6.6.16. Delay to Construction

If Method 1 or 4 is used for any task and if the owner's instrumentation work is likely to delay construction progress, the specification should provide for appropriate payment. The following wording can be used:

> The Owner will schedule ______ to minimize interference with the Contractor's operations. Delays of up to ______ hours per ______ for a total of ______ hours should be anticipated. No additional payment will be made to the Contractor for such delays.

Delay estimates should be conservative, because field instrumentation work often takes longer than expected. Alternatively, delay compensation can be paid in accordance with actual delay. An hourly bid item can be included for *delay to construction*, or an hourly rate can be stipulated in the contract. However, this is not applicable where a delay can upset an entire construction cycle, as is often the case with tunnel construction, and in such cases the problem should be avoided by using Method 5.

6.6.17. Damage to Instrumentation

Installed instruments are usually prone to damage by construction activities. The specification should include requirements for protection and should indicate the responsibility of the construction contractor in the event of damage.

If the contractor installs and damages instruments, repair or replacement should be required at no additional cost to the owner, and timeliness should be specified. The owner's representative should be the sole judge of whether repair or replacement is required. If data are vital, a work stoppage within a specified distance of the damaged instruments may be appropriate, until instruments are operational. If repair or replacement is not possible, payment for that installation can be negated. Increased incentive to avoid damage can be created by imposing an additional financial penalty. However, the owner will normally lose needed data and therefore should make every effort during the planning phase to select measurement methods with minimum damage potential. If the construction contractor damages instruments installed by the owner, some of the same specification provisions can be included, and the owner's costs can be deducted from payments to the contractor. However, development of mutual respect and cooperation (Section 6.6.7) is usually more productive than penalty clauses.

In general, the owner's representative must exercise good judgment in deciding whether damage was avoidable by the contractor or was due to conditions beyond the contractor's control.

6.6.18. Disposition of Instruments

The specification should define who will own portable or recoverable components at the end of the construction period. If not required for long-term monitoring, instruments such as inclinometer casing, borehole extensometers, and piezometers are usually abandoned in place, and the specification should require the construction contractor to cut off and dispose of protruding parts below the finished surface, grout the open casing or tubing and restore the surface. Sometimes instruments such as load cells and vibrating wire strain gages can be salvaged, overhauled, recalibrated, and reused. Portable instruments and readout units will often be reusable. If the instruments are to be used for long-term measurements, the specification should require them to be overhauled to first class condition and to have permanent protection and access provisions.

6.6.19. Measurement and Payment

Measurement and payment should be specified, in accordance with recommendations given earlier in this chapter. The work should be measured and paid for on a unit price basis rather than a lump sum basis, to allow for changes in quantities as work proceeds. Great care should be taken to ensure that, for every work item specified for the construction contractor, there is either a pay item or a statement that the item will be considered incidental for payment purposes.

There should be no ambiguity in the method of measurement: for example, if an instrument is to be installed near the end of a borehole, and measurement of drilling and installation is by the linear foot, the specification should indicate whether measurement will be made to the specified instrument location or to the actual end of the borehole.

When payment for procurement of instruments is combined with payment for installation, by using several *furnish and install* unit price items in the bid, special care must be taken to satisfy the requirements of Section 5.4.18 for definition of major component prices. For example, a single expensive readout unit should be included in a separate bid item, so that a change in the quantity of installed instruments can be accommodated under the *furnish and install* item.

Each pay item should be clarified by using a clear statement to define the work included. For example, the introductory part of the measurement and payment section might include the following wording:

> The contract prices for furnishing and installing each instrument shall be full compensation for all materials, labor, tools, and equipment necessary for submittals, furnishing all materials for installation, drilling, sampling, withdrawing casing, installation, acceptance test-

ing, protection, replacement or repair of any instruments damaged as a result of the Contractor's operation and/or vandalism, initial readings, restoration of surface and subsurface, providing access to the Engineer for reading, and all other specified items of work for which no separate bid item is provided, all to the satisfaction of the Engineer.

For a bid item per linear foot for *Furnish and Install Piezometers,* the specification might state:

> Measurement will be based on the total number of linear feet of drilling. Payment will be based on the unit price per linear foot for furnish and install piezometers as stated in the Bid.

If a *data-set* unit is used for any instrument readings, the unit must be defined.

If nonbiddable support work is to be paid for under a contingency allowance, the specification should indicate which are the applicable work items and how payment rates for labor, plant, equipment, and materials will be determined, including provisions for a markup.

If an assigned subcontract procedure has been used for specialist work, the specification should indicate which are the applicable work items and how payment will be made, including provisions for a markup. The following wording is suitable:

> Payment for specialist geotechnical instrumentation work will be made under allowance item no. ______. After contract award the Owner's Representative will select a specialist organization, acceptable to the Contractor, to perform specialist work, and will instruct the Contractor to enter into a subcontract with that organization, which will then become an assigned subcontractor. The Contractor shall submit copies of the subcontractor's invoices and will be reimbursed in accordance with those invoices plus the specified (or bid) markup. Measurement will be in accordance with the units included in the subcontract. If the actual total cost of the work is more or less than the allowance, the contract price will be adjusted to the actual approved amount.

6.6.20. Checklist for Specification Content

Appendix C contains a checklist for content of specifications for field instrumentation services. Use of the checklist will help ensure completeness. However, each individual specification may require only some of this content.

Part 3

Monitoring Methods

Part 3 is addressed to people who are involved in the details of instrumentation use. The primary emphasis is on a presentation of various monitoring methods, including comparative information and recommendations for selection among the methods.

The first two chapters are applicable to all monitoring methods. Chapter 7 defines the meaning of terms associated with measurement uncertainty, examines the various types of error that can affect a measurement, and suggests how they may be eliminated. Chapter 8 provides a description of various mechanical, hydraulic, pneumatic, and electrical transducers and communication and data acquisition systems that are used with geotechnical instrumentation.

Chapters 9–14 describe instruments for monitoring six parameters: groundwater pressure, total stress in soil, stress change in rock, deformation, load and strain in structural members, and temperature. Each chapter includes a categorization of available instruments and a brief indication of applications. Monitoring methods are described and compared, and guidelines are given for selection and use. In many cases the comparisons are summarized by listing advantages and limitations in tabular form. The comparative data in each of these tables are with respect to other entries in the same table and are generally qualitative rather than quantitative. Significant emphasis is given in Chapters 9–14 to installation of instruments and to appropriate aspects of calibration and data collection and processing.

CHAPTER 7

MEASUREMENT UNCERTAINTY*

Instrumentation is used for making measurements, and every measurement involves error and uncertainty. The purpose of this chapter is to define the meaning of terms associated with uncertainty, to examine the various types of error that can affect a measurement, and to suggest how they may be minimized.

7.1. CONFORMANCE

Ideally, the presence of a measuring instrument should not alter the value of the parameter being measured. If in fact the instrument alters the value, it is said to have poor *conformance*. For example, fixed borehole extensometers and any surrounding grout should be sufficiently deformable so that deformation of the soil or rock is not inhibited, and embedment earth pressure cells should ideally have the same deformability characteristics as the soil in which they are placed. In addition, the act of drilling a borehole or compacting fill around an instrument should not result in a significantly different condition within the geologic material. Thus, piezometers should not create drainage paths that would reduce the measured pore water pressure below the value elsewhere. Conformance is a desirable ingredient of high accuracy.

*Written with the assistance of Ralph S. Carson, Professor of Electrical Engineering, University of Missouri–Rolla, MO, and J. Barrie Sellers, President, Geokon, Inc., Lebanon, NH.

7.2. ACCURACY

Accuracy is the closeness of approach of a measurement to the true value of the quantity measured. Accuracy is synonymous with *degree of correctness*. Accuracy of an instrument is evaluated during calibration, when the true value is the value indicated by an instrument whose accuracy is verified and traceable to an accepted standard. In the United States, traceability should be, wherever possible, to the National Bureau of Standards. It is customary to express accuracy as a ± number. An accuracy of ±1 mm means that the measured value is within 1 mm of the true value, and an accuracy of ±1% means that the measured value is within 1% of the true value. However, an accuracy of ±1% full scale (FS) indicates a lesser accuracy, because the percentage applies to the full scale of the indicator rather than the measured value.

When selecting an instrument with appropriate accuracy, the entire system must be considered, including accuracy of each component and each source of error. Errors are discussed in Section 7.9.

7.3. PRECISION

Precision is the closeness of approach of each of a number of similar measurements to the arithmetic mean. Precision is synonymous with *reproducibility* and *repeatability*. It is customary to express precision as a ± number. The number of significant figures quoted for a measurement reflects the preci-

Figure 7.1. Accuracy and precision.

sion of the measurement; thus, ±1.00 indicates a higher precision than ±1.0. Conversely, a recorded measurement should reflect the precision of the instrument used. The fact that an instrument yields a measurement to three significant figures is no assurance that it is accurate to ±0.1, and it is pointless to attempt to obtain a reading to three significant figures from an instrument known to be accurate to only ±10%.

The difference between accuracy and precision is illustrated in Figure 7.1. The bull's eye represents the true value. In the first case the measurements are precise but not accurate, as would occur when using a survey tape with a bad kink or a pressure gage with a zero shift. Such errors are *systematic*. In the second case the measurements lack precision but, if sufficient readings are taken, the average will be accurate. Such errors are *random*. In the third case the measurements are both precise and accurate.

7.4. RESOLUTION

Resolution is the smallest division on the instrument readout scale. In some cases it may be possible and convenient to interpolate between divisions on the readout scale, but interpolation is subjective and does not increase the resolution of the instrument. The resolution for a digital display is one digit of change in the last digit.

7.5. SENSITIVITY

Sensitivity refers to the amount of output response that an instrument or transducer produces when an input quantity is applied to it. For example, the sensitivity of a linear variable differential transformer (LVDT) used to monitor displacement across a rock joint might be given as 1000 millivolts per inch (mV/in.). When the same amount of input is applied to several instruments or transducers, the one whose sensitivity is the highest produces the most output. High sensitivity does not imply high accuracy or precision.

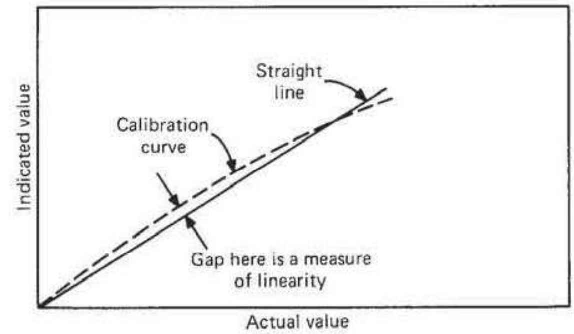


Figure 7.2. Linearity.

7.6. LINEARITY

An instrument is said to be linear when its indicated measured values are directly proportional to the quantity being measured. As illustrated in Figure 7.2, the graphic relationship between indicated and actual value is often slightly curved, owing to instrument limitations. If a straight line is drawn on this plot such that the widest gap between straight line and curve is a minimum, the gap is a measure of *linearity*. Thus, a linearity of 1% FS means that the maximum error incurred by assuming a linear calibration factor will be 1% of the full-scale reading.

7.7. HYSTERESIS

When the quantity being measured is subjected to cyclic change, the indicated measured value sometimes depends on whether the measurement is increasing or decreasing. If the two relationships are plotted as shown in Figure 7.3, the separation between the two curves is a measure of *hysteresis*. Hysteresis is commonly caused by friction or backlash and occurs, for example, in hydraulic jacks as

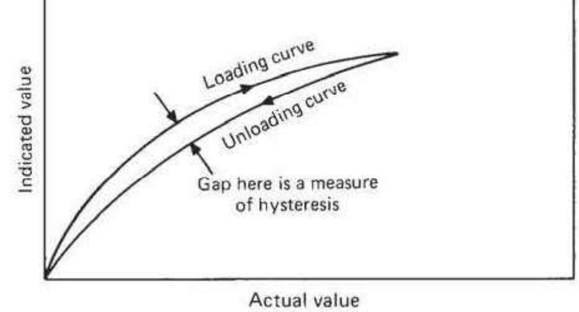


Figure 7.3. Hysteresis.

load is increased and decreased while proof testing tieback anchors. Instruments with large hysteresis are not suitable for measurement of rapidly changing parameters.

7.8. NOISE

Noise is a term used to cover random measurement variations caused by external factors, creating lack of precision and accuracy. Excessive noise in a system may mask small real changes. Radio frequency (RF) interference from high-voltage sources and TV or radio transmitters is an example of an external factor that creates noise.

7.9. ERROR

Error is the deviation between the measured value and the true value; thus, it is mathematically equal to accuracy. Errors arise from many causes, described below and summarized in Table 7.1.

Gross errors are caused by carelessness, fatigue, and inexperience. They include misreading, misrecording, computational errors, failure to operate the readout instrument correctly, incorrect installation, improper electrical connections, and wrong switch positions. Gross errors are avoidable and can be minimized by taking duplicate readings, using more than one observer, checking present readings against previous readings, and insisting on proper care and training.

Systematic errors are caused by improper calibration, by alteration of calibration with time such that readings are consistently high or low, and also by hysteresis and nonlinearity. The first data set in Figure 7.1 shows systematic error. These errors can be minimized by periodic recalibration and by checking readings against "standards" and "no-load" gages kept in the laboratory or in the field. If readings on standards or no-load gages change, cor-

Table 7.1. Causes and Remedies of Measurement Error

Type of Error	Causes	Remedies
Gross error	Inexperience Misreading Misrecording Computational error	Care Training Duplicate readings Dual observers Checking against previous readings
Systematic error	Improper calibration Loss of calibration Hysteresis Nonlinearity	Use of correct calibration Recalibration Use of standards Use of consistent reading procedures
Conformance error	Inappropriate installation details Instrument design limitations	Select appropriate instrument Modify installation procedure Improve instrument design
Environmental error	Weather Temperature Vibration Corrosion	Record environmental changes and apply corrections Make correct choice of instrument materials
Observational error	Variation between observers	Training Use of automatic data acquisition systems
Sampling error	Variability in the measured parameter Incorrect sampling techniques	Install a sufficient number of instruments at representative locations
Random error	Noise Friction Environmental effects	Correct choice of instrument Temporary elimination of noise Multiple readings Statistical analysis
Murphy's law	If something can go wrong, it will	None—any attempt to remedy the situation will only make things worse

rection factors can be applied. Errors caused by hysteresis can sometimes be minimized by operating an indicator such that a measurement is always decreasing or always increasing. Linearity errors can be minimized by using the correct calibration.

Conformance errors are caused by poor selection of installation procedures and by limitations in the instrument design. They can be avoided by use of correct installation procedures and by ensuring that the instrument design is appropriate for the application.

Environmental errors arise because of the influence of heat, humidity, vibration, shock waves, moisture, pressure, corrosion, and so on. Two approaches are possible for minimizing environmental errors: first, by measuring the extent of the influence, such as temperature, and applying suitable correction factors; and second, by choosing an instrument that is not adversely affected by the environment. Environmental conditions should always be recorded when data are collected, because they may correlate with real changes in measured quantities.

Observational errors arise when different observers use different observation techniques. They are minimized by regular training sessions and periodic refresher courses on readout procedures. Use of automatic data acquisition systems will prevent observational errors.

Sampling errors are common when making measurements of geotechnical parameters, because of inherent variability in the geologic materials. Correct measurements made at one location may not be representative of overall behavior. Sampling errors are minimized by installing a sufficient number of instruments at representative locations.

Even when errors are recognized and remedied, readings will still show variation due to *random error*. The second data set in Figure 7.1 shows random error. These errors are caused by noise, internal friction, hysteresis, and environmental effects. They can be minimized by correct choice of instrument and by multiple readings and can be treated mathematically using statistical analyses, so that measurements are presented as average values with a standard deviation and confidence limits. However, average values should be used with caution, because extreme values may in fact be true and may indicate a critical situation. As an example, a person standing with one foot in boiling water and one foot in ice water might, on the basis of the average water temperature, be said to be comfortable.

CHAPTER 8

INSTRUMENTATION TRANSDUCERS AND DATA ACQUISITION SYSTEMS

Most geotechnical instruments consist of a transducer, a data acquisition system, and a communication system between the two. A transducer is a device that converts a physical change into a corresponding output signal. Data acquisition systems range from simple portable readout units to complex automatic systems. This chapter provides a description of various mechanical, hydraulic, pneumatic, and electrical transducers and communication and data acquisition systems that are used with geotechnical instrumentation.

Many geotechnical instruments are not required to survive longer than the construction period. However, many are required to survive as long as practicable, for example, for monitoring long-term performance of embankment dams. Factors that influence the selection of transducer and communication and data acquisition systems, when they are required to survive as long as practicable, are discussed in this chapter.

8.1. MECHANICAL INSTRUMENTS

The two mechanical devices used most frequently in geotechnical instrumentation are *dial indicators* and *micrometers*. Although dial indicators are more common, both can be used in mechanical crack gages, convergence gages, mechanical tiltmeters, fixed borehole extensometers, mechanical strain gages, and mechanical load cells.

8.1.1. Dial Indicator

A dial indicator is used to convert the linear movement of a spring-loaded plunger to larger and more visible movement of a pointer that rotates above a dial. Mechanical parts include a rack and pinion and gear train.

Accuracies are generally ± 0.001 in. (± 0.025 mm) or ± 0.0001 in. (± 0.0025 mm), with typical ranges up to 2 in. (50 mm). Special long-range dial indicators can be obtained, with ranges up to 12 in. (300 mm). Dial indicators are somewhat fragile and susceptible to the effect of dirt entering the gear train but, because they are mass produced for many industrial purposes, they are inexpensive and can often be considered expendable. Sealed and waterproof versions are available, with rubber bellows around the plunger where it exits from the indicator body. Others are oil-filled, also with rubber bellows, and are preferable for long-term applications and for use in adverse environments.

8.1.2. Micrometer

Rotation of a finely threaded plunger causes the plunger to travel in or out of a housing. Longitudinal movement of the plunger is measured, using a scale on the housing, to indicate the number of revolutions of the plunger. Fractional revolutions are determined using graduations marked around the plunger and a vernier on the housing.

Accuracies are limited to about ±0.001 in. (±0.025 mm), because the reading is sensitive to the force applied to the plunger as it is rotated to touch the reference point. Good quality micrometers incorporate a simple clutch to minimize this effect. By changing the length of the plunger, the range of a micrometer can readily be extended to 6 in. (150 mm). Verniers can be difficult to read, and micrometers are now available with digital counters that greatly ease the reading task. Micrometers are more robust than dial indicators and thus are often favored for portable use when they are not built into a protective housing, for example, when used to read fixed borehole extensometers.

8.2. HYDRAULIC INSTRUMENTS

The two hydraulic devices used most frequently in geotechnical instrumentation to measure liquid pressure are *Bourdon tube pressure gages* and *manometers*. Bourdon tube pressure gages are more common and are used with hydraulic piezometers, hydraulic load cells, borehole pressure cells, and in some readout units for pneumatic transducers. Manometers are sometimes used with twin-tube hydraulic piezometers and liquid level settlement gages.

8.2.1. Bourdon Tube Pressure Gage

A Bourdon tube is made by flattening a metal tube and coiling it into a C-shaped configuration. When the tube is pressurized internally, the flattened cross section expands, causing the tube to straighten. The uncoiling motion is transmitted via a mechanical linkage to a pointer that rotates over a circular scale, as shown in Figure 8.1.

Typical accuracy is ±0.5% full scale (FS) for commonly used gages with 4 or 6 in. (100 or 150 mm) dial sizes, but ±0.1% FS "test quality" gages are available. Caution should be used in relying on the accuracy of ±0.5% FS gages, because when checked with a dead-weight tester these gages sometimes do not meet specification. The author recommends use of ±0.25% FS gages when ±0.5% FS accuracy is required. It should be noted that

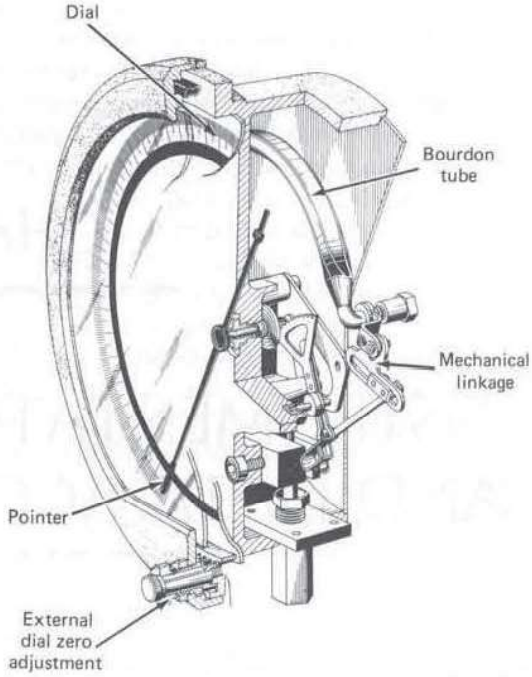


Figure 8.1. Bourdon tube pressure gage (courtesy of Dresser Industries, Newtown, CT).

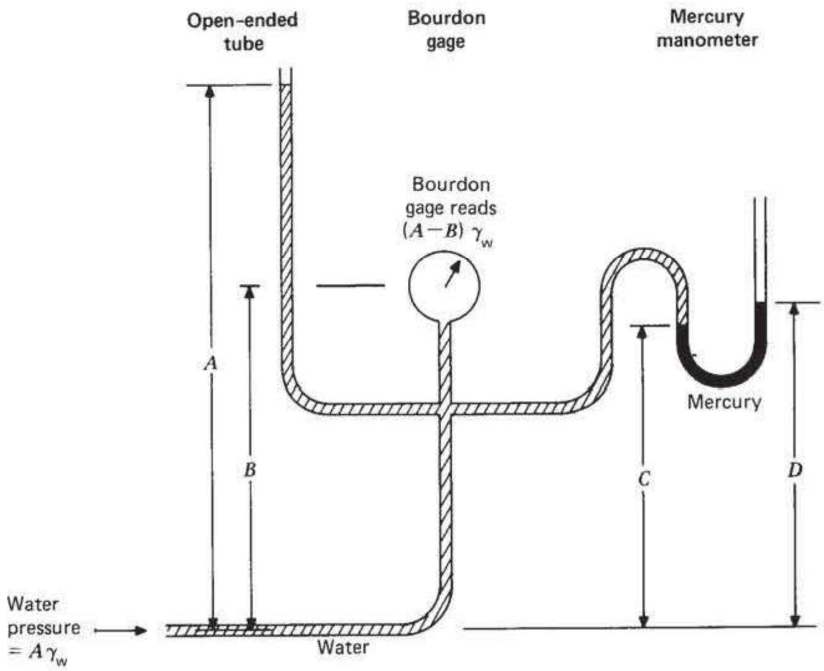
accuracy is usually expressed as percentage of full-scale reading, not as percentage of gage reading. Thus, in selecting an appropriate range for a Bourdon gage, an unnecessarily high range should be avoided.

For long-term permanent installations, Bourdon gages must be of high quality, without risk of galvanic corrosion. The primary long-term application is in terminal enclosures for twin-tube hydraulic piezometers, and recommendations for gage selection are given in Appendix E.

8.2.2. Manometer

A manometer is formed by a liquid-filled U-tube. A pressure on one side of the U-tube is balanced by an equal pressure on the other side.

Figure 8.2 shows pressure readings using an open-ended tube, a Bourdon tube pressure gage, and a mercury manometer. Manometers have been used extensively for long-term monitoring of pore water pressure in embankment dams with twin-tube hydraulic piezometers where adequate headroom is available in the terminal enclosure. They are also useful for measuring very small positive or negative pressures and are easily calibrated. Manometers



γ_w = density of water
γ_{Hg} = density of mercury
When using Bourdon gage, water pressure = gage reading + $B\gamma_w$
When using mercury manometer, water pressure = $(D-C)\gamma_{Hg} + C\gamma_w$

Figure 8.2. Schematic of hydraulic measuring devices.

have greater longevity than most Bourdon tube pressure gages.

8.2.3. Liquid-Filled Tubes for Hydraulic Instruments

Twin-tube hydraulic piezometers and liquid level settlement gages incorporate liquid-filled tubes as an essential part of the pressure measuring system. In these systems the pressure difference between the liquid surfaces at opposite ends of a tube is assumed to bear a known relationship to the elevation difference, via an assumed or measured density of liquid. The three primary causes of error that have long plagued this measurement method appear to be discontinuity in the liquid, liquid density changes caused by temperature variation, and surface tension effects. Each is discussed in turn, after which recommendations are given for tubing material and diameter, tubing fittings, liquid, and routing of liquid-filled tubes.

Discontinuity in Liquid

The source of greatest potential error is discontinuity of liquid in supposedly liquid-filled tubes. A 2 in. (50 mm) long gas bubble in the vertical segment of a tube will cause a reading error equivalent to 2 in. (50 mm) of liquid head. A single large gas bubble in the horizontal segment of a tube is of no consequence, but in practice it may migrate to a nonhorizontal part of the tube and cause an error.

Penman (1978) reports on findings by Jamin that a small tube can effectively be blocked if it contains a sufficient number of gas/water interfaces. At each gas/water meniscus, surface tension causes the gas bubbles to be at a slightly higher pressure than the water, as in unsaturated soil (Figure 2.8). When pressure is applied at one end of the tube to cause flow, the gas/water menisci yield to the attempted direction of flow, thereby opposing the flow. To achieve flow, the applied pressure must be increased sufficiently. As an example of this effect, about 1000 gas bubbles in an otherwise liquid-filled tube (or 1000 water drops in an otherwise gas-filled tube) of 0.11 in. (3 mm) inside diameter will resist an applied pressure of 15 lb/in.^{2} (100 kPa). Dissolved gas is also a major source of corrosion to metallic components. There is therefore ample evidence that all possible sources of gas should be eliminated from liquid-filled tubes. Gas can enter the system and form bubbles from three sources: dissolved gas in the liquid, diffusion through the tubing itself, and through the ends of the tubing.

When water is exposed to the atmosphere for an adequate length of time, it becomes saturated with air gases and thereafter acts somewhat as a sponge. Nitrogen and oxygen are absorbed when temperature decreases and are expelled when the temperature rises. When fully saturated with air, at room temperature and sea level, water contains approximately 10 parts per million of dissolved oxygen (ppm DO) by weight, equivalent to approximately 2% of air gases (oxygen and nitrogen) by volume. DO terminology is generally accepted as a method of specifying dissolved gas levels in water. Unless water is specifically indicated as de-aired (the word "de-aired" is used in this book to describe a liquid from which dissolved gases have been removed), it should be assumed to be saturated with gas. Commercially available bottled distilled and drinking waters are generally saturated with gas.

Many soil mechanics laboratories have "homemade" de-airing systems for use in preparing water for permeability and triaxial testing. These systems generally operate either by boiling water under a vacuum or by spraying water through a column to which a vacuum is applied and usually reduce the dissolved air gas content to between 2 and 5 ppm DO (0.4 and 1% air). The effectiveness of de-airing systems can be tested with a DO test kit, but measurements will be misleading if the liquid was initially saturated with gases other than oxygen. If a DO kit is to be used, air should be bubbled through the liquid for about half an hour before de-airing, to ensure initial saturation with air rather than with other gases.

For liquids in twin-tube hydraulic piezometers and liquid level settlement gages, dissolved gas content should preferably be reduced to less than 1 ppm DO (0.2% air); otherwise, frequent flushing may be required to ensure continuity of liquid. Two types of equipment are commercially available for preparing suitable liquid.

First, gas and electric boilers are supplied by several manufacturers of geotechnical instrumentation (e.g., Figure 8.3). The boiler is normally operated for about 4 hours and the liquid allowed to cool overnight. Dyer (1986) made tests to determine the effectiveness of this method on water that had initially been saturated by bubbling air for 2 hours, with a result of 0.5 ppm DO (0.1% air). The method may not be suitable for liquids other than water if their properties are affected by boiling.

Figure 8.3. Boilers for preparation of de-aired water (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

Second, the *Nold DeAerator*™ can be used. The apparatus, shown in Figure 8.4, consists of a sealed tank, electric motor, impeller, and electric vacuum pump or water-powered aspirator for obtaining the necessary vacuum, which is applied to the space above the liquid. The phenomena of cavitation and nucleation generate an ultrahigh vacuum that vaporizes dissolved gases and volatile liquids. Centrifugal force directs the released vapors outward, where they bubble up to the partially evacuated space above the liquid surface. From there the gases are withdrawn through the aspirator or vacuum pump to the atmosphere. Six liters of water can be reduced from air saturation to less than 0.5 ppm DO (0.1% air) in 4 minutes running time without use of heat and to less than 0.05 ppm DO (0.01% air) in 15 minutes. This apparatus is suitable for de-airing antifreeze liquids as well as water. An automatic version is available for continuous preparation of de-aired liquid.

When transferring de-aired liquid from either a boiler or the DeAerator to the instrument tubes or to other vessels, agitation must be avoided to pre-

Figure 8.4. Nold DeAerator™ (courtesy of Walter Nold Company, Inc., Natick, MA).

vent reintroduction of air, and careless decanting can easily increase the DO content by 1 ppm or more. Transfer of de-aired liquid from one vessel to another is best done by evacuating the receiving vessel. De-aired liquid can be stored and transported either in a steel boiler (Figure 8.3) or in glass (**not** plastic) bottles with rubber stoppers; the container must be full. A convenient *Pressurized De-Aired Water Containment System* is available from the manufacturer of the DeAerator for transporting de-aired liquid, at up to 70 lb/in.^{2} (480 kPa), to instrument terminals in the field without reabsorbing air. The system is described in Appendix E.

Reabsorption of air must be minimized after the tubes are filled with liquid. This may be accomplished by appropriate selection of tubing and by inhibiting air entry at tubing ends. Recommendations for selection of tubing are given later in this section. Inhibition of gas entry at tubing ends depends on the type of instrument. When twin-tube hydraulic piezometers are installed in unsaturated fills, they must incorporate high air entry filters (Section 9.11). The ends of twin-tube hydraulic piezometer tubes will be connected in the terminal enclosure either to Bourdon gages or manometers, and gas-tight tubing fittings and valves should be used. Liquid level settlement gages are usually sealed at one end but open to the atmosphere at the readout end, and arrangements must be made to close this end when readings are not being taken, to avoid reabsorbing air.

Liquid Density Changes Caused by Temperature Variation

When the temperature of a liquid is increased, it expands and its density is reduced. Therefore, a temperature change in a nonhorizontal part of tubing will cause a reading error if the density variation is not taken into account. The error is unlikely to be significant for twin-tube hydraulic piezometer readings, but it is of great concern for liquid level settlement gages, which depend on the accurate measurement of small pressure changes. One solution is to measure temperature at various points along the tubing and apply a correction, but this is normally impracticable. Thus, a goal is selection of a liquid with the least coefficient of thermal expansion, but this may be in conflict with the need for a low freezing point, desirable density, and chemical compatibility with tubing.

As can be seen from Figure 8.5, of the aqueous solutions typically used in liquid level settlement gages, water has the least coefficient of thermal expansion and therefore introduces the least thermal error. The coefficient of thermal expansion increases with increasing ethylene glycol content; thus, unnecessarily high concentrations should be avoided. As an example of the error magnitude, if the temperature of a 50% ethylene glycol and water mix rises from $-10°C$ to $+20°C$ over a 4 ft (1.2 m) vertical height of liquid, an error of about 0.7 in. (18 mm) will be introduced into a settlement measurement. The error increases with increase in height of the liquid column affected by the temperature change. Attention is drawn to the unusual freezing point curve, shown in Figure 8.5, for high concentrations of ethylene glycol.

Surface Tension Effects

A decrease in surface tension will decrease the time required for equilibrium in a liquid-filled tube and

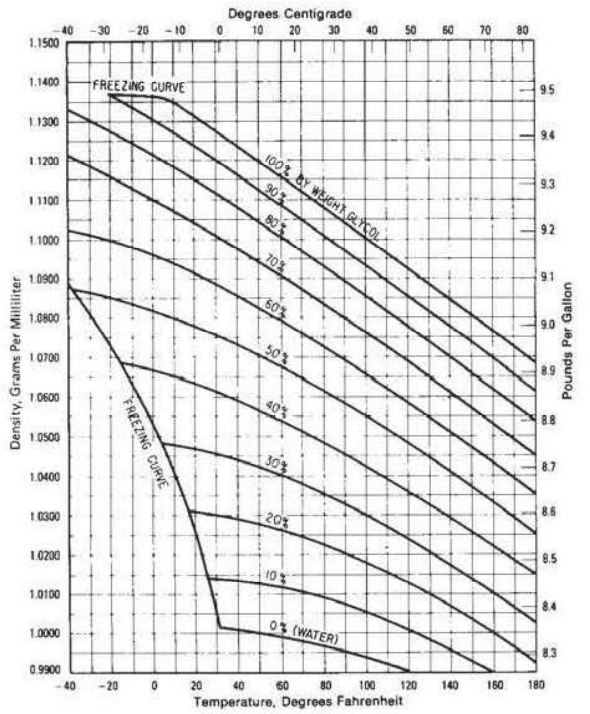


Figure 8.5. Densities of aqueous solutions of ethylene glycol at various temperatures (after Dow, 1981).

thus will tend to increase measurement accuracy. Water has a higher surface tension than typically used antifreeze mixes, but surface tension can be reduced to an acceptable level by adding a wetting agent, as discussed later in this section.

Recommendations for Tubing Material

Certain plastics are permeable to liquids but impermeable to gas; others exhibit the converse.

Tests reported by Penman (1960) indicate that polyethylene is permeable to air and that nylon absorbs water, thereby causing loss of water by evaporation. When filled with de-aired liquid under pressure and exposed to the atmosphere or to gas in unsaturated soil, the permeability of tubing to both liquid and gas must be minimized.

Unplasticized nylon 11 with a polyethylene (polythene) sheath is generally accepted as the tubing of choice for use with twin-tube hydraulic piezometer systems when making long-term measurements in embankment dams and is a good choice in most other cases. There is more than one type of nylon 11, and a specification for the appropriate type is given in Appendix E. Unplasticized nylon 11 with a polyurethane sheath also appears to be a good choice. Polyethylene with a polyvinylcholoride (PVC) sheath appears to be satisfactory from the standpoint of minimizing permeability to liquid and gas, but there is evidence that when compression fittings are attached to polyethylene tubing, the polyethylene creeps at the compression sleeve and long-term sealing is uncertain. The inner tube should therefore be unplasticized nylon 11. Nylon 66 (trade name *type H*) is not a suitable choice because of its water absorption characteristics. Saran tubing deteriorates with time and with exposure to sunlight and should never be used.

Because nylon tends to absorb water and also to leach gas until it becomes saturated with water, one or two flushes are usually required before the liquid-filled tubes can be fully commissioned.

Recommendations for Tubing Diameter

All tubing diameters referred to in this section are **inside** diameters, because the **inside** diameter impacts on the behavior of fluid within the tubing. The reader is cautioned about the possible confusion: industry standards use the **outside** diameter when referring to tubing sizes. The inside diameter of liquid-filled tubes depends on the application, but guidelines on upper and lower limits can be given.

When using water and aqueous solutions, 0.25 in. (6 mm) appears to be the largest **inside** diameter from which gas bubbles can readily be displaced during flushing. A lower limit results both from the need to avoid the Jamin effect described earlier in this section and the need to reach equilibrium within an acceptable time. Penman et al. (1975) indicate that, when using the overflow type of liquid level gage (Section 12.10) in dams, a 0.1 in. (2.5 mm) **inside** diameter water-filled tube could require more than half an hour to reach acceptable equilibrium. Poiseuille's equation for laminar flow in pipes shows that the time required for a given degree of equalization varies inversely as the fourth power of the pipe diameter. By using a tube of 0.25 in. (6 mm) **inside** diameter, the 99.9% equilibrium time was reduced to under 1 minute.

For liquid level settlement gages with aqueous solutions, 0.25 in. (6 mm) **inside** diameter appears to be a good choice for the liquid-filled tubes. This diameter is strongly recommended if any movement of the liquid column occurs at the time of reading, caused, for example, by deformation of a bladder or diaphragm. If no such movement occurs, 0.17 in.

(4.3 mm) **inside** diameter appears to be suitable. When using mercury in liquid level settlement gages, an **inside** diameter between 0.07 and 0.2 in. (2–5 mm) appears to be satisfactory. However, a general caution about use of mercury is appropriate. In the United States, mercury is considered to be a hazardous material, and environmental restrictions prevent its use in many applications. In addition, if mercury remains in plastic tubing in the long term, there is evidence that it can leach gas from the tubing and create discontinuities in the mercury. Also, oxidation can cause contamination and blockage of the tubing.

For twin-tube hydraulic piezometers, the need for rapid equilibrium is less critical, and an **inside** diameter between 0.1 and 0.2 in. (2.5–5 mm) appears to be the best choice.

Recommendations for Tubing Fittings

Compression fittings should be of the type that ensures positive alignment of the compression sleeve, by contact with either a shoulder in the body of the fitting or the nut. The type with a single *olive* compression sleeve that is aligned only by the tubing itself should not be used. Brass compression fittings are suitable for short-term measurements, for example, measurements made during a typical construction period, but nylon fittings are too weak and are not a good choice. For long-term measurements the possibility of corrosion should be recognized. Brass is subject to corrosion by dissolved gases in the liquid within the tubing and in any water surrounding the fittings and, although there is no specific evidence that excessive corrosion of inaccessible fittings has occurred, it appears worthwhile to use stainless steel fittings at all inaccessible locations when long-term measurements are required. Stainless steel should be type 316: this is a nonmagnetic stainless steel that is corrosion-resistant, and compression fittings of this type are readily available. When sheathed tubing is used, compression fittings should fit over the inner tubing, not the sheath. The sheath must therefore be pared back, using a cutting tool made for the purpose, and the protruding nylon tube inspected carefully to ensure that it has not been cut.

Recommendations for Liquid

Despite extensive research and trial use of a variety of liquids, no single liquid appears to be suitable for all purposes.

For twin-tube hydraulic piezometers, antifreeze solutions should not be used since they tend to plug piezometer filters and appear to have generated osmotic pressures. Tubes should be installed below the frost line and terminal enclosure temperatures should be maintained above freezing. Tap or well water may be polluted and should not be used. In the author's view the preferred liquid is filtered distilled water, produced by steam distillation. The water should be de-aired to reduce the dissolved gas content to less than 1 ppm DO. A wetting agent should be added and, for long-term applications, a bacterial inhibitor should also be added to minimize organic growth—two practices are in common use. First, quaternary ammonium compound (QAC)* is used (e.g., Houlsby, 1982; USBR, 1974) both as a wetting agent and bacterial inhibitor. Some users have argued that the chloride ions in QAC are corrosive to brass and copper, but this does not appear to be a realistic concern when the recommended concentration is used. The more likely cause of any observed corrosion is dissolved gases in the liquid. Second, copper sulfate† is used as a bacterial inhibitor and Aerosol OT‡ as a wetting agent (e.g., Corps of Engineers, 1971). Either practice appears to be satisfactory, with a preference for QAC, as this appears to be more effective as a bacterial inhibitor than copper sulfate. Houlsby (1982) reports that tubes for twin-tube hydraulic piezometers developed constrictions over a period of 10 or 15 years of regular flushing with uninhibited water. When QAC was added to the water, tubes were freed from constrictions, and regular usage of QAC was then able to keep tubes clean and free of organically caused bubbles.

For liquid level settlement gages not subjected to freezing temperatures, thermal errors are minimized by using de-aired distilled water as described above for twin-tube hydraulic piezometers. For short-term (construction period) applications, a wetting agent should be added. For long-term applications, QAC should be added, and inaccessible metal components should be type 316 stainless steel. Accessible components for long-term applications should, wherever possible, be selected for

* For example, Hyamine 1622 or 3500, available from Lonza AG. See Appendix D. Use a 60 parts per million solution.

† Use two approximately 0.25 in. (6 mm) size crystals per 10 U.S. gallons (40 liters) of liquid.

‡ Available from American Cyanamid Company. See Appendix D. Use a 50 parts per million solution.

their resistance to corrosion (e.g., plastics or type 316 stainless steel), but if brass components are used they can be replaced if corrosion occurs. Recognition of deterioration assumes vigilance on the part of reading personnel, and it is better practice to design for a maintenance-free system. If tubes are subjected to freezing, the minimum required antifreeze should be added prior to de-airing. Antifreeze mixtures given in Figure 8.5 are suitable, but the commercial types that include a plugging antileak additive should not be used. A wetting agent is not necessary with ethylene glycol mixes. Specific gravity must be known in most cases (Section 12.10). If in doubt about specific gravity and its variation with temperature and dissolved gas content, the user should make laboratory determinations using a volumetric flask and an accurate balance having about $\pm 0.1\%$ accuracy. Some manufacturers of liquid level settlement gages recommend use of methanol/ethylene glycol/water mixes to create a specific gravity of 1.0 so that standard pressure indicator scales graduated in water head can be used. However, distillation occurs while de-airing this mixture, thus changing the specific gravity, and methanol can damage the plastic components of the de-airing system and liquid level gage. It is preferable to avoid use of methanol and to apply a calibration constant to correct for specific gravity.

There is some evidence that aqueous solutions of technical grade ethylene glycol may not remain uniformly mixed after filling tubes in liquid-filled settlement gages. However, it appears that if duplicate liquid-filled tubes are used and the liquid freely connects between both ends of the tube so that flow can occur throughout, the molecules of the mixture will remain in motion and specific gravity will remain uniform.

Some users have added a coloring agent (e.g., ink or food coloring) to liquid in full-profile liquid level settlement gages to facilitate regular inspection for gas bubbles. However, the coloring agent eventually stains the tubing and makes it harder to see bubbles. The author knows of no suitable coloring agent and recommends against its use.

Experience has shown that, despite all precautions discussed above, liquid in supposedly liquid-filled tubes is likely to become discontinuous after a period of months or perhaps years, requiring periodic flushing with fresh de-aired liquid. For twin-tube hydraulic piezometers with appropriate tubing and high air entry filters, flushing frequency is likely to be once every few years. Liquid level settlement gages require more frequent flushing, because highly accurate measurements of small pressure changes are required. For these gages, the author recommends developing a history of the need to flush, by periodic flushing, noting resulting reading change and adopting a job-specific standard procedure based on the data. Liquid-filled tubes in full-profile liquid level settlement gages should be inspected for continuity of liquid prior to each use and flushed when there is evidence of discontinuity.

Routing of Liquid-Filled Tubes

De-aired liquid can withstand significant subatmospheric pressure without breaking its continuity. When the dissolved gas content has been reduced to below 1 ppm DO (0.2% air), a practical limit of subatmospheric pressure appears to be about 20 ft (6 m), and liquid-filled tubes should be routed so that no part is above the internal pressure head level by more than this amount. Even within this limit there is a tendency for the liquid to become discontinuous with time, and if possible tubes should be routed so that a positive pressure exists at all times.

Closed Hydraulic Systems

All closed hydraulic systems unfortunately act as excellent thermometers, because changes in temperature cause the enclosed liquid to expand and contract, which in turn causes the internal pressure to rise and fall. For example, liquid-filled earth pressure cells are sensitive to temperature and may require temperature measurements and appropriate corrections. Liquid level settlement gages generally have valves on the open ends of liquid-filled tubes that are closed on completion of readings to avoid re-airation of the liquid, and thus they become closed systems. If any part of the gage could be damaged by significant rise in internal pressure owing to temperature or pressure surges during handling and transportation, precautions must be taken, for example, by including a cylinder with a spring-loaded piston in the liquid-filled tube.

8.2.4. Data Acquisition Systems for Hydraulic Instruments

Use of Bourdon tube pressure gages and manometers requires visual access to the readout location. Where remote reading is required, an electrical pressure transducer can replace the pressure gage or manometer.

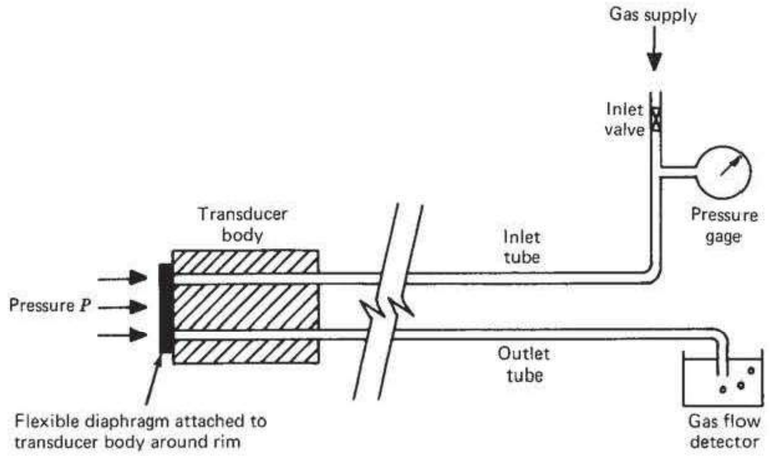


Figure 8.6. Schematic of *normally closed* transducer, read under a condition of no gas flow.

Automatic data acquisition systems for double-fluid full-profile settlement gages and twin-tube hydraulic piezometers are described in Chapter 12 and Appendix E respectively.

8.3. PNEUMATIC INSTRUMENTS*

Pneumatic transducers and data acquisition systems are used for pneumatic piezometers, earth pressure cells, load cells, and liquid level settlement gages.

8.3.1. Basic Types of Pneumatic Transducer

There are two basic types of pneumatic transducer, depending on whether a pneumatic circuit is normally closed or normally open when external pressure is applied to the transducer. Most modern transducers are of the first type.

8.3.2. Normally Closed Transducers

The *normally closed* type of transducer is also called *venting type*. The type can be subdivided according to whether the reading is made under a condition of no gas flow or as gas is flowing.

Normally Closed Transducers, Read Under a Condition of No Gas Flow

Figure 8.6 shows the basic arrangement. 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.

This type of transducer has a variety of diaphragm types, depending on the manufacturer, including flat, hat-shaped, or convoluted (rolling) diaphragms of synthetic rubber or metal.

Normally Closed Transducers, Read as Gas is Flowing

The basic arrangement is the same as in Figure 8.6, but with a gas flow controller and sometimes also a gas flow meter in the inlet tube, and the outlet tube vents directly to the atmosphere. A schematic of the arrangement is shown in Figure 8.7. Gas pressure is increased, under a constant very small flow, causing a rise in pressure gage reading. When the gas pressure exceeds P, the diaphragm moves outward, allowing gas to circulate through the outlet tube, such that the maximum indicated pressure gage reading is equal to P.

As will be seen later, the readings of all types of pneumatic transducer are affected by the rate of gas flow. The version shown in Figure 8.8 incorporates a third tube, such that no gas flow occurs in the tube

*Written with the assistance of the manufacturers listed in Table 8.1.

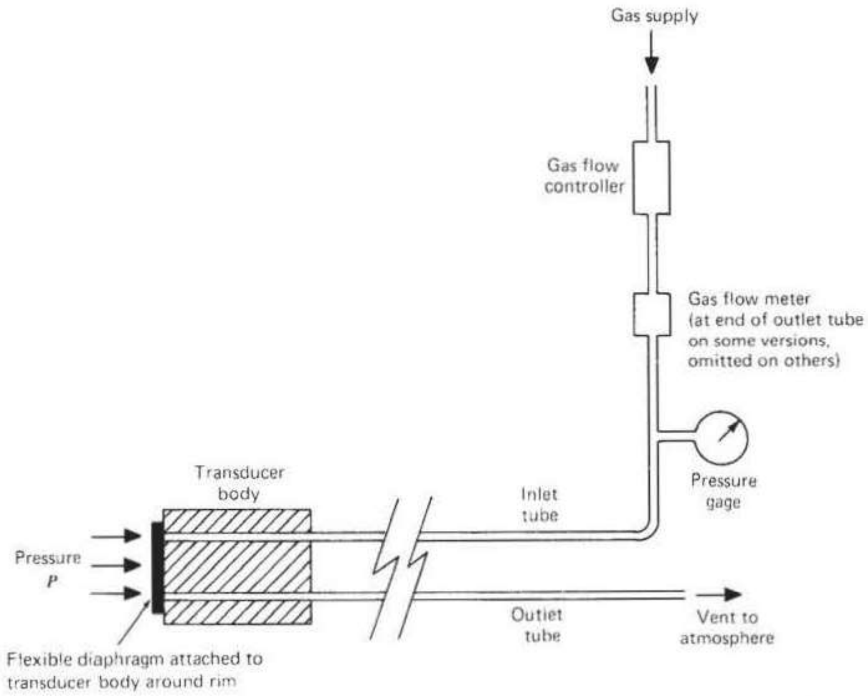


Figure 8.7. Schematic of *normally closed* transducer, with two tubes, read as gas is flowing.

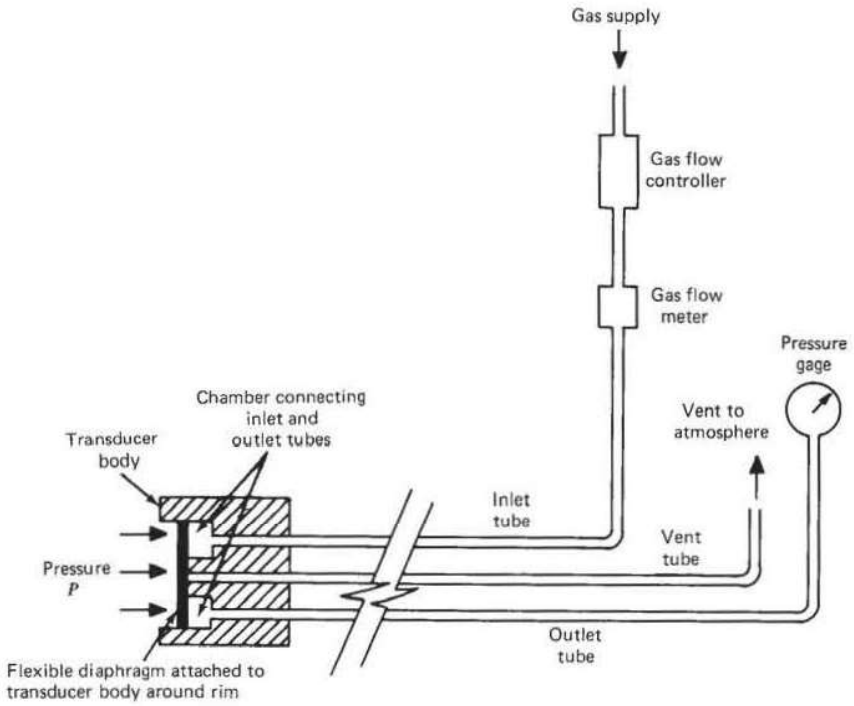


Figure 8.8. Schematic of *normally closed* transducer, with three tubes, read as gas is flowing.

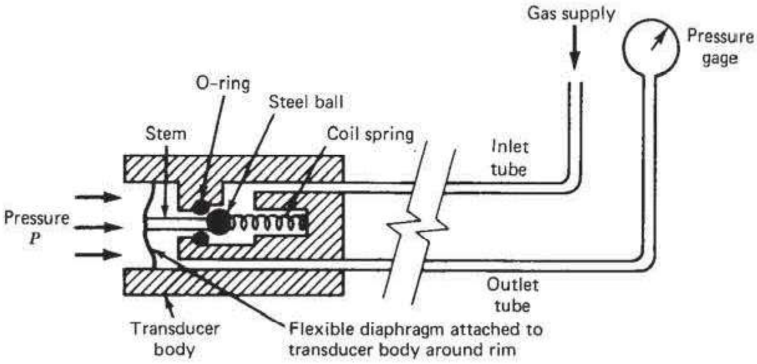


Figure 8.9. Schematic of *normally open* transducer.

to which the pressure gage is attached, thereby reducing errors caused by any variations in the rate of gas flow.

8.3.3. Normally Open Transducers

The *normally open* type of transducer is also called *check valve type*. The version shown in Figure 8.9 has a steel ball/coil spring/O-ring arrangement that serves as a check valve. Other versions have a different type of check valve. The diaphragm may be of synthetic rubber or may be metal bellows. The check valve remains open until the gas pressure first exceeds P, at which point the diaphragm moves outward, the check valve closes, and pressurized gas is locked in the outlet tube. The pressure gage is presumed to indicate P but, as discussed later, the reading is affected by the rate of gas flow. Reading errors caused by an excessive rate of gas flow can be minimized by including a flow controller and flow meter in the inlet tube, so that gas flows at a slow constant rate and gas pressure is reasonably uniform throughout the inlet and outlet tubes.

There is a potential problem with these transducers if water accidentally enters the tubes. If the transducer is at a lower elevation than the pressure gage, and if the pressure P is less than the head of water in the tubes, the check valve will close, and the water cannot be purged through the tubes. Water can sometimes be removed by connecting a vacuum pump, fitted to a water trap, but this is possible only if the head of water in the tube is less than about 25 ft (8 m).

8.3.4. Features of Commercially Available Systems

Table 8.1 indicates commercially available systems. Readers are cautioned that, although the text has been submitted to the listed manufacturers for review, new developments and product line changes are likely to occur on a regular basis; thus, readers are advised to contact manufacturers for a current status. Manufacturers' addresses are given in Appendix D.

Reading Mode

The reading mode, shown in Table 8.1, indicates whether the reading is made under a condition of no gas flow or as gas is flowing.

Sensitivity to Diaphragm Displacement

If a pneumatic transducer is to provide an accurate indication of the actual pressure P, it is important that diaphragm displacement should not cause a change of P at the moment when the transducer is being read. For example, when used in a piezometer installed in clayey soils, diaphragm displacement may in fact cause a change of P because outward diaphragm displacement causes a decrease in the volume of pore water on the outer side of the diaphragm. This volume decrease causes a pressure increase. All pneumatic transducers are sensitive to diaphragm displacement.

For the transducer shown in Figure 8.6, a rapid rise of gas pressure in the inlet tube "hammers" the diaphragm, and this shock causes an immediate pressure increase on the outer side of the diaphragm. When used in a piezometer, water is forced into the ground rapidly, owing to the high pressure differential existing across the diaphragm at that time. However, during diaphragm resetting as gas pressure falls, differential water/gas pressures are smaller and there is little driving force to encourage the diaphragm to return to its original position. Gas

Table 8.1. Commercially Available Pneumatic Transducers and Data Acquisition Systems

Basic Type of Transducer	Brand[a]	Figure Number	Normal Reading Mode
Normally closed (venting type)	Apparatus Specialties Co.	8.6	No flow
	Earl B. Hall, Inc.	8.7[b]	Flow
	Geotechnical Instruments (U.K.) Ltd.	8.6	No flow
	Geosistemas	8.6	No flow
	Glötzl GmbH	8.7	Flow
	Slope Indicator Co. (Model #514177, 514178)	8.7[c]	Flow
	Slope Indicator Co. (Model #51481)	8.8[d]	Flow
	Soil Instruments Ltd.	8.6	No flow
	Thor International, Inc.	8.7	Flow
Normally open (check valve type)	Slope Indicator Co. (Model #51401, 51471)	8.9[d]	No flow
	Terra Technology Corp.	8.9[e]	No flow

[a] Manufacturers' addresses are given in Appendix D.
[b] Gas flow meter is on outlet tube.
[c] Also available with three tubes as in Figure 8.8.
[d] No longer manufactured; included here for completeness.
[e] Also available, when used in a piezometer, with one or two additional tubes connecting to the space outside the diaphragm. Strongly **not** recommended. See Chapter 9.

pressure may therefore fall to a value significantly lower than the water pressure before the diaphragm reseats to seal the pressure in the inlet tube, and the resulting reading will be too low. The error described above is minimized by using a low-volume displacement diaphragm and by very careful control of gas pressure. Some commercially available systems have a reading sequence that is manually instigated but automatically conducted, thus permitting complete control of gas pressure and removing the variable quality of human input from the critical stages. Geotechnical Instruments (U.K.) Ltd. incorporates a "softening" arrangement on the outer side of the diaphragm, consisting of an air-filled rubber tube, such that sensitivity to diaphragm displacement is minimized.

The transducers shown in Figures 8.7 and 8.8 are sensitive to diaphragm displacement for the reasons given above. Errors are minimized by using a diaphragm with minimum volumetric displacement, and commercial versions with displacements of 0.01 cm^3 (0.0006 $in.^3$) or less are preferred. The effect of diaphragm displacement will be reduced if the operator waits until the reading stabilizes under a constant gas flow rate.

The transducer shown in Figure 8.9 is sensitive to diaphragm displacement because the volumetric displacement is large, and readings are made after the diaphragm has moved to a new position.

Sensitivity to Gas Flow Rate and Length of Tubing

Pressure loss (loss of velocity head) occurs as gas flows through tubing. For a given pressure at one end of a tube, the pressure at the other end will be affected by a change in the flow rate. The magnitude of pressure loss is also affected by the length of tubing. All pneumatic transducers are sensitive to pressure loss.

The above discussion on sensitivity to diaphragm displacement, for the transducer shown in Figure 8.6, concluded that the error is minimized by very careful control of gas pressure. This careful control also minimizes errors caused by sensitivity to gas flow rate and length of tubing. It is important to recognize that this type of transducer **must** be totally free from gas leaks in the inlet tube and at the diaphragm closure arrangement: this can sometimes be difficult to achieve when quick-connect fittings are used between inlet tube and readout unit, because the slightest dirt or damage to the O-ring seal in the fitting may create a leak.

The transducers shown in Figures 8.7 and 8.8 are read as gas is flowing, therefore they are sensitive to the gas flow rate and length of tubing. Addition of the third tube reduces errors caused by pressure loss, because no gas is flowing in the tube to which the pressure gage is attached. However, the addition does not eliminate these errors, because pressure is lost as the gas flow passes from the inlet to the vent tube. Tests by Slope Indicator Company (Mikkelsen, 1986a) to compare their two- and three-tube systems show that the sensitivity to gas flow rate and length of tubing is approximately halved by adding the third tube. For these transducers, a constant gas flow rate is therefore essential. The need is particularly critical for liquid level settlement gages, when required repeatability of liquid head measurement is usually a fraction of an inch. The purpose of the gas flow controller is to maintain a constant gas flow. Some manufacturers assume that the flow remains constant once the controller is set, and others provide a gas flow meter in the circuit so that the flow rate can be monitored. Recent experience has shown that gas flow controllers provided in some commercially available readout units do not maintain a gas flow that is adequately constant for use with liquid level settlement gages and that the position of the indicator ball in some gas flow meters is affected by static electrical charge on the ball. The charge builds up with time as gas passes by, the ball falls even when the gas flow remains constant, and the operator is likely to increase the flow to compensate. Improved flow controllers and flow meters are now available for use with liquid level settlement gages. For this application the flow meter should be provided with a bypass valve so that gas flows through it only momentarily when the operator turns the valve to check the flow.

The transducer shown in Figure 8.9 is sensitive to gas flow rate and length of tubing. The check valve will close when the gas pressure against the diaphragm first exceeds P. If significant pressure loss is occurring along the outlet tube as the check valve closes, subsequent pressure equalization along the outlet tube will cause the pressure gage to read less than P.

8.3.5. Readout Units

Gas pressure is measured by using either a Bourdon tube pressure gage or an electrical pressure transducer with a digital indicator. When an electrical pressure transducer is used, a keyboard selection can usually be made of the desired pressure measurement unit (e.g., lb/in.^{2}, kg/cm^2, or ft head). Indicators can be connected to a large gas tank and continuously energized, and the systems can be programmed to scan multiple transducers and display measurements sequentially on the digital display and on a printed paper tape. These systems can be provided with outputs for connection to a variety of automatic data acquisition and processing equipment.

8.3.6. Recommendations for System Selection

Normally closed transducers have largely superseded the *normally open* type, and use of the latter type is not recommended. They are more sensitive than *normally closed* transducers to diaphragm displacement, gas flow rate, and length of tubing, and water that may enter the tubing accidentally cannot always be removed.

All the commercially available *normally closed* transducers are suitable choices. When selecting a system from among those listed in Table 8.1, users should consider the general guidelines given in Section 4.9. Their own familiarity and previous experience with one or more brands will weigh heavily in the selection. The overriding need is very close adherence to the instrumentation manufacturer's recommendations for operation of the selected system.

8.3.7. Recommendations for Various System Components

Several general recommendations can be made for system components.

Components Within a Transducer

Transducer materials should not be subject to corrosion or electrolytic breakdown. Some stainless steels are not corrosion-free under geotechnical field conditions and some plastics are inadequately stable. The diaphragm should be resilient so that a permanent distortion will not be created if the tubes are accidentally overpressured, and nitrile rubber is preferable to steel if overpressurization is possible. Preferably, a positive stop should be provided to protect against overpressurization.

Gas

Most manufacturers of pneumatic instruments agree that a dry gas (carbon dioxide or dry nitrogen) should be used rather than air to avoid condensation of water in the tubing. Carbon dioxide can readily be obtained from companies that service fire extinguishers, and dry nitrogen is available from welding supply companies (*water pumped,* **not** *oil* *pumped* nitrogen). Portable indicators contain a small rechargeable gas cylinder, and an auxiliary larger cylinder can be used where tubes are long or where a large number of transducers are to be read.

Economy can be achieved by using a tank of compressed air and a desiccant canister. Use of a hand air pump and no desiccant runs the risk of water entering the tubing and, if the water is not blown out by flowing air, large reading errors may result from the summation of surface tension forces at gas/water menisci (Section 8.2.3).

Tubing

Section 8.2.3 describes requirements for liquid-filled tubes. Gas-filled tubes are not subject to concerns about discontinuity of liquid, temperature variation, surface tension, freezing, bacterial growth, or routing limitations, but nevertheless certain precautions are necessary. Materials for gas-filled tubes should be impermeable to water so that, when submerged below water or embedded in soil, moisture does not migrate through the walls of the tube. The following tubings appear to have appropriate properties: unplasticized nylon 11 with a polyethylene (polythene) sheath, unplasticized nylon 11 with a polyurethane sheath, and polyamide. Polyethylene with a polyvinylcholoride (PVC) or polyethylene sheath is not a good choice: it is less robust than the above three types; nylon creates a better seal than polyethylene at the entry point to the transducer; and there is evidence that when compression fittings are attached to polyethylene tubing, the polyethylene creeps at the compression sleeve and long-term sealing is uncertain. Saran tubing deteriorates with time and with exposure to sunlight and should never be used.

A 3⁄16 in. (5 mm) diameter tubing is suitable for all applications. A 1⁄8 in. (3 mm) tubing is sometimes used when lengths are less than about 250 ft (75 m), and 1⁄4 in. (6 mm) tubing is also used on occasion. It should be noted that these tubing dimensions are the **outside** diameters of the individual tubes, **not** the sheath.

The maximum length of tubing depends on the length of time considered tolerable for reading. A rule of thumb for reading time is 0.5–1 minute per 100 ft (30 m) of tubing, the longer time being necessary when requiring maximum accuracy. The tubing can be brought up to pressure with an initial high gas flow, but these reading times are required after such initial pressurization. Tubings of 3000 ft (900 m) length are in use, but 2000 ft (600 m) is considered to be a reasonable maximum length.

Tubing Fittings

Recommendations for tubing fittings for liquid-filled tubes are given in Section 8.2.3. The same recommendations apply to fittings for gas-filled tubes.

8.4. ELECTRICAL INSTRUMENTS*

Electrical transducers and data acquisition systems are used in numerous geotechnical instruments. Comprehensive references describing electrical transducers include Arthur (1970), Cerni and Foster (1965), Considine (1971), Herceg (1972), Lion (1959), Norton (1969), Perry and Lissner (1962), Prensky (1963), Spitzer and Howarth (1972), Stein (1964), and Wolf (1973).

Electrical transducers and associated manual data acquisition systems are described in turn below. Automatic data acquisition systems, power supplies, and communication systems are described in Sections 8.4.15 and 8.4.16. General guidelines on the use of electrical transducers and data acquisition systems, including selection of electrical cable, are given in Section 8.4.17.

8.4.1. Basic Types of Electrical Resistance Strain Gage

Electrical resistance strain gages are used in many geotechnical instruments. 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

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

The gage factor for bonded foil and bonded wire gages is usually close to 2. Semiconductor strain

*Sections 8.4.1–8.4.14 have been written with the assistance of Ralph S. Carson, Professor of Electrical Engineering, University of Missouri–Rolla, Rolla, MO, and J. Barrie Sellers, President, Geokon, Inc., Lebanon, NH. Leon J. Weymouth, Principal Engineer, Teledyne Engineering Services, Waltham, MA, assisted with writing Sections 8.4.1–8.4.4 on electrical resistance strain gages.

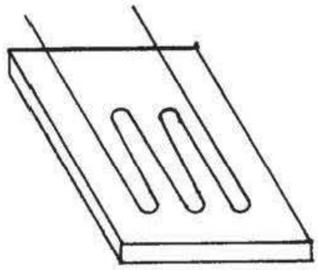


Figure 8.10. Schematic of uniaxial bonded wire resistance strain gage.

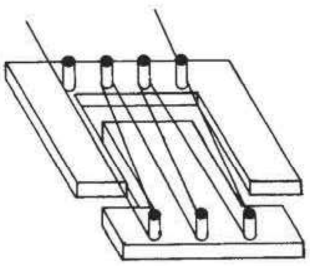


Figure 8.11. Schematic of unbonded wire resistance strain gage.

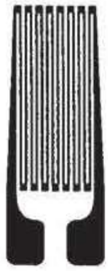


Figure 8.12. Uniaxial bonded foil resistance strain gage.

gages have a much larger gage factor, between 50 and 200.

The five basic types of electrical resistance strain gage—bonded wire, unbonded wire, bonded foil, semiconductor, and weldable—are described in turn below. Guidelines on the use of resistance strain gages for measurement of strain in structural members are given in Chapter 13.

Bonded Wire Resistance Strain Gage

A bonded wire strain gage is fabricated with fine copper–nickel or nickel–chromium wire, looped back and forth, and bonded to a thin elastic mounting of paper or plastic, which in turn is bonded to the structure being monitored. Figure 8.10 shows a uniaxial gage. They are commonly used where long gages are needed for testing rock or concrete specimens, enabling strains to be measured over a representative sample, but for short gage lengths the bonded foil gage is usually preferred.

Unbonded Wire Resistance Strain Gage

In the unbonded wire strain gage (Figure 8.11), a fine wire is looped around two sets of electrically insulated posts that are attached to the structure being monitored. The device is less robust than the bonded gage and was developed at a time when bonding techniques were unreliable. With the advent of improved bonding cements, unbonded wire strain gages have become less common. However, the Carlson unbonded wire strain gage transducer, referred to as an *elastic wire strainmeter,* is frequently used in embedment strain gages and concrete stress cells and has proven reliability and longevity. The Carlson transducer contains two similar coils of highly elastic carbon-steel wire each looped around two posts, arranged such that one increases in length and electrical resistance when strain occurs while the other decreases. The ratio of the two resistances is independent of temperature and therefore the change in resistance ratio is a measure of strain. The total resistance is independent of strain since the resistance change in one coil is equal and opposite to the resistance change in the other coil, and therefore total resistance is a measure of temperature. Wiring diagrams are given by the Corps of Engineers (1980).

Bonded Foil Resistance Strain Gage

A bonded foil strain gage is composed of a thin foil of resistance alloy, such as constantan or nichrome, bonded to a thin plastic film, which in turn is bonded to the structure being monitored. The foil is usually photofabricated and etched or die-cut during manufacture to produce grid patterns of varying designs. A uniaxial gage is shown in Figure 8.12. Temperature compensation is provided by matching the temperature characteristics of the foil to those of the material being studied and, if necessary, by adding additional resistors in the Wheatstone bridge circuit. Most strain gages have a nominal resistance of 120 or 350 ohms. The higher resistance varieties are generally favored for transducer applications because they permit the use of higher voltage inputs, with correspondingly higher outputs, thus minimizing effects of extraneous resistance changes.

Semiconductor Resistance Strain Gage

This gage uses highly doped semiconductor crystals of silicon or germanium. The doping is necessary to give the crystals specific gage factors and thermal coefficients. When strain is applied to the crystal, it undergoes a change in resistance proportional to the strain. Gage factors of 50–200 make this type of gage much more sensitive than other types. Its main

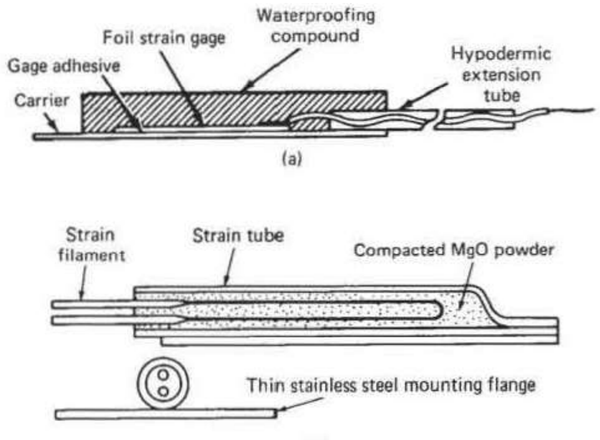


Figure 8.13. Weldable strain gages: (a) bonded foil transducer (courtesy of HITEC Products, Inc., Ayer, MA) and (b) strain filament encased in small tube (courtesy of Eaton Corporation, Los Angeles, CA).

disadvantage is the relatively complicated techniques required for correction of errors induced by temperature change. The effect can be minimized by choosing the correct gage type and by using temperature matched gages, but the gage is not suitable for environments with large temperature gradients or rapid fluctuations. The output of semiconductor gages is nonlinear, and their use is normally limited to monitoring strains of 100 microstrain or less.

Weldable Resistance Strain Gage

During manufacture of the weldable gage, a resistance element is permanently attached to a thin stainless steel mounting flange. The resistance element may be a conventional bonded foil gage (Figure 8.13a; Wnuk, 1981) or a strain filament encased in a small tube (Figure 8.13b). The mounting flange is later welded to the steel structure being monitored, using a small portable capacitive discharge spot welder. Weldable gages with integral leads are more suitable for field attachment than bonded gages.

Longevity of Resistance Strain Gages

Longevity of resistance strain gages is dependent primarily on methods of gage installation, sealing, and protection, rather than on inherent properties of the gages themselves. Bonded wire, unbonded wire, bonded foil, semiconductor, and weldable resistance strain gages can all be used for long-term performance measurements, provided that personnel responsible for gage selection, installation, sealing, and protection are specialists with wide experience in field application of resistance strain gages. Strain gages installed by inexperienced users normally have a short life. Recommendations for gage installation, sealing, and protection are given in Chapter 13.

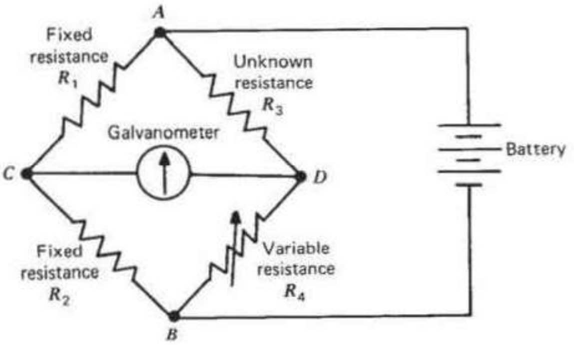


Figure 8.14. Wheatstone bridge circuit.

8.4.2. Wheatstone Bridge Circuits for Use with Electrical Resistance Strain Gages

Output from electrical resistance strain gages is normally measured using a Wheatstone bridge circuit, shown in Figure 8.14. The circuit has four "arms" formed by resistances, R_1, R_2, R_3, and R_4. A voltage is applied between A and B and the resistance R_4 is altered until no current flows between C and D. At this point the needle of the galvanometer is not deflected and the bridge is balanced. Under these conditions,

$$\frac{R_1}{R_2} = \frac{R_3}{R_4},$$

and since R_1, R_2, and R_4 are known, R_3 can be calculated. Bridge networks are described below, and advantages and limitations are summarized in Table 8.2.

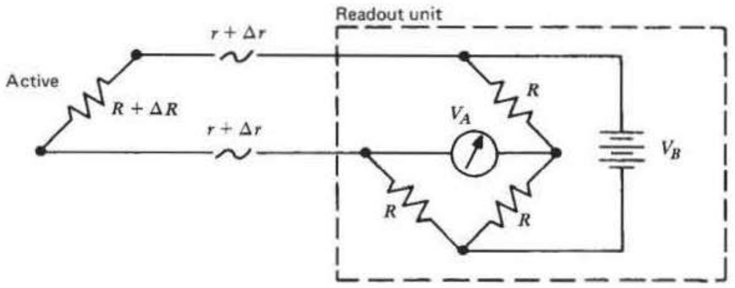
Quarter Bridge Networks

The simplest network is the quarter bridge with two lead wires, shown in Figure 8.15a. However, the resistance of the lead wires in series with the active strain gage desensitizes the bridge and any change in lead wire resistance with temperature change cannot be differentiated from strain. The effect can be substantial if temperature changes and/or lead wire lengths are large but can be eliminated by using

Table 8.2. Wheatstone Bridge Networks

Type	Advantages	Limitations	Bridge Factor[a]	Usage
Quarter, two-wire system; Figure 8.15a	Least expensive Easiest to use	Sensitive to temperature change at gage and leads Nonlinear at high strain levels	1.0	Use only in laboratory environment at constant temperature Never use in geotechnical field applications
Quarter, three-wire system; Figure 8.15b	Eliminates error caused by temperature changes at leads	Sensitive to temperature change at gage Nonlinear at high strain levels	1.0	Most popular network for stress/strain analysis on structures
Half, with dummy gage; Figure 8.16a	No temperature effects	Dummy must be unstressed and bonded to same material and at same temperature as active gage	1.0	Long-term tests on structures where temperature variations are great and increased accuracy is required
Half, with both gages active, at 90° to each other (Poisson effect); Figure 8.16b	No temperature effects	Not suitable for biaxial stress fields	1.3	May be used on long columns or tendons subject to uniaxial loads
Half, with both gages fully active, equal tensile and compressive strains; Figure 8.16c	No temperature effects	Bridge network not always possible to achieve	2.0	Measurement of bending of beams Cantilever type transducers Torsional transducers
Full, with dummy gages; Figure 8.17a	No temperature effects	Most expensive	2.0	Rare
Full, with all gages active, two at 90° to other two (Poisson effect); Figure 8.17b	No temperature effects	Most expensive Not suitable for biaxial stress fields	2.6	Tension links or compression columns, for example, load cells
Full, with all gages fully active, two tensile, two compressive, equal strains; Figure 8.17c	No temperature effects Maximum output	Most expensive	4.0	Bending beams

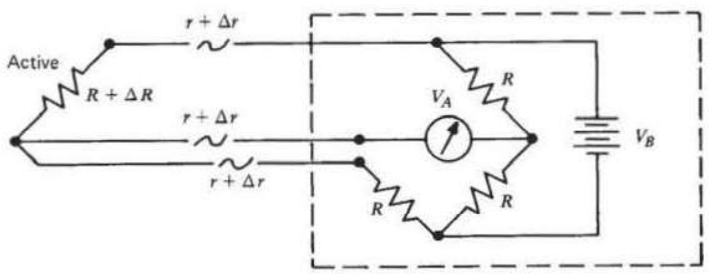
[a] Output relative to quarter bridge network. See Figures 8.15–8.17. Assumes $\Delta r = 0$, $\mu = 0.3$, ΔR is small compared with R, uniaxial stress field, and all gages at same temperature.



$R + \Delta R$ = gage resistance plus gage resistance change
$r + \Delta r$ = lead wire resistance plus lead wire resistance change
R = resistance of bridge completion resistors

$$\frac{V_A}{V_B} = \frac{\Delta R + 2\Delta r}{4[(R + 2r) + \frac{1}{2}(\Delta R + 2\Delta r)]}$$

(a)



$$\frac{V_A}{V_B} = \frac{\Delta R}{4\,[(R + 2r) + \frac{1}{2}\,\Delta R]}$$

(b)

Figure 8.15. Wheatstone bridge quarter bridge networks: (a) two-wire system and (b) three-wire system.

a quarter bridge with three lead wires. As shown in Figure 8.15b, a third wire is connected to one end of the active strain gage and wired into the bridge network. This cancels the thermally induced error caused by lead wire resistance changes. However, the circuit remains sensitive to temperature change at the gage.

In practice, lead wire resistance is minimized and gage resistance is maximized, often by using 350 ohm gages instead of the originally standard 120 ohm type. Thus, because r may be small compared with R, the equations in Figure 8.15 can be rewritten:

$$\text{(a)} \quad \frac{V_A}{V_B} = \frac{\Delta R + 2\Delta r}{4\,[R + \frac{1}{2}(\Delta R + 2\Delta r)]}$$

and

$$\text{(b)} \quad \frac{V_A}{V_B} = \frac{\Delta R}{4\,(R + \frac{1}{2}\Delta R)}.$$

Note that because Δr may be significant with respect to ΔR, the term Δr remains in the equation for a two-wire system, indicating the effect of changing lead wire resistance caused by temperature change.

Half Bridge Networks

Temperature effects that plague a quarter bridge network can almost be eliminated by using a half bridge circuit. A second strain gage is connected to the bridge at the measuring location rather than in the readout unit, either as an active gage or a "dummy" gage. Two arrangements are possible for the active gage; thus, there are three possible configurations, as shown in Figure 8.16. Lead wire

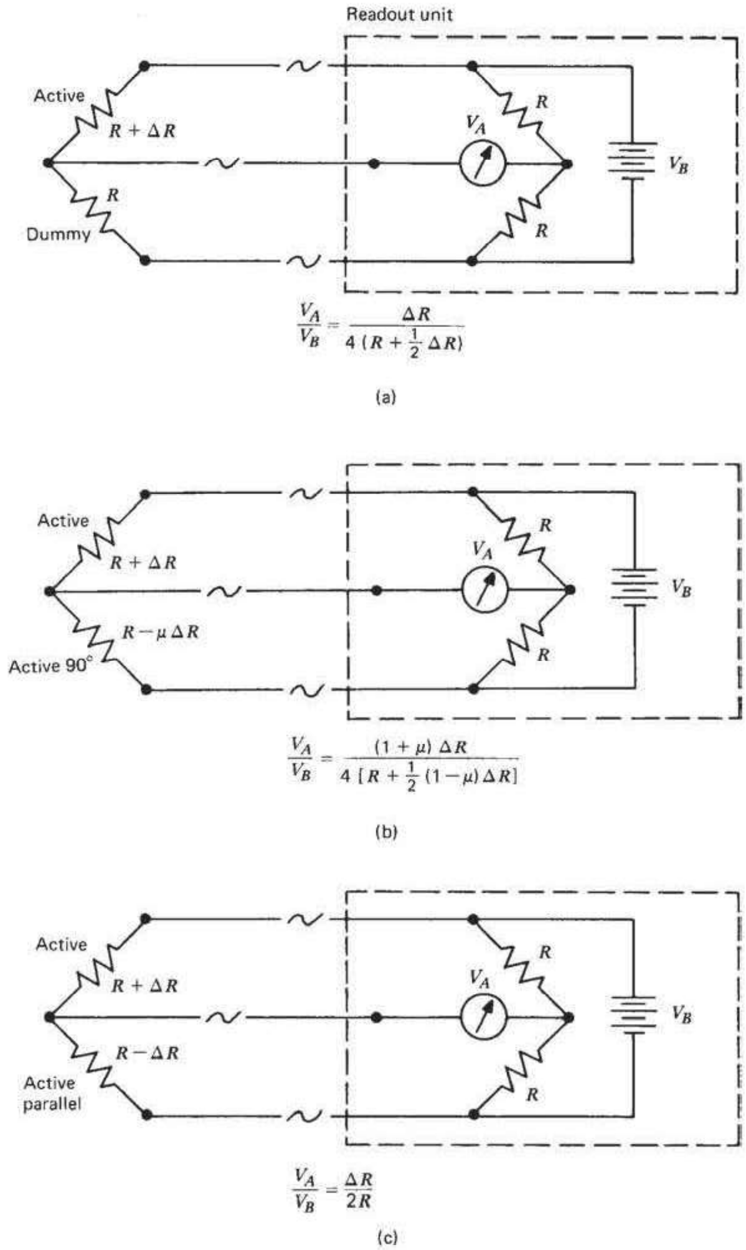


Figure 8.16. Wheatstone bridge half bridge networks: (a) dummy gage, (b) both gages active, at 90 degrees to each other (Poisson effect), and (c) both gages fully active, equal tensile and compressive strains.

resistance r and resistance change Δr have been omitted from the figure because Δr cancels in the bridge circuit and, if r is small compared with R, lead wire effects become negligible.

In the first configuration, Figure 8.16a, the dummy gage, also termed *inactive* or *compensating* gage, is mounted on a piece of the same material as the active gage but isolated from the stress field so that it undergoes no stress caused by temperature change. It is placed adjacent to the active gage so that both experience the same temperature change or gradient, thereby providing temperature compensation.

When the second gage is an active gage, it must be located on the structure in a position that will cause it to be in tension if the first gage is in compression, or vice versa. This can often be arranged by aligning the second gage at 90 degrees adjacent to the first gage, as in Figure 8.16b, thereby measuring the Poisson effect. This increases the output of the network by a factor of 1.3. If the second gage is positioned so that it experiences an equal and opposite strain to that at the first gage, as in Figure 8.16c, the output is doubled. Strain gages positioned on opposite sides of the neutral axis of a flexing beam fulfill this condition. Note that two gages experiencing the same strain in both magnitude and sign would cancel each other out if connected in a half bridge network. Such an arrangement allows use of a half bridge to isolate for bending measurements, because axial load has no effect on the measurements.

Full Bridge Networks

A full bridge network, shown in Figure 8.17, provides a maximum output and almost full compensation for temperature change at the gage and along the leads; thus, this is the optimum arrangement. Three networks are possible, corresponding to the half bridge networks. As for the half bridge networks, lead wire resistance r and resistance change Δr have been omitted from the figures.

Lead Wire Effects

The problem of changing lead wire temperature has been discussed previously and can be solved by avoiding use of two-wire quarter bridge networks. However, two additional errors remain, caused by *thermocouple* and *desensitization* effects. Thermocouple effects are discussed in Section 8.4.4 and can be overcome by use of an AC excitation voltage. Desensitization error can become significant if long runs of cable are used. Since the parasitic lead resistance appears as a larger gage resistance, with no equivalent change in resistance due to strain, the effective gage factor is reduced. This can be calculated by

$$GF_d = \frac{R_g}{R_g + r} GF_n,$$

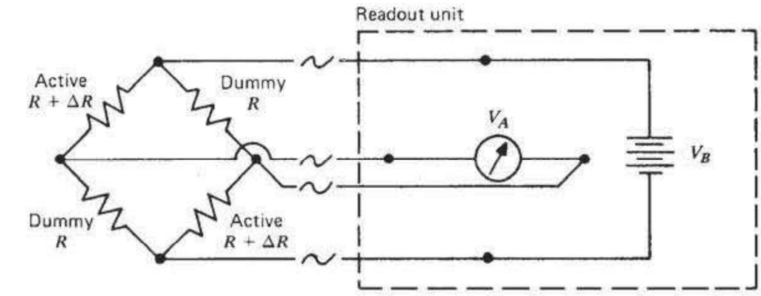
where GF_d = desensitized gage factor,
R_g = basic gage resistance,
r = cable resistance per lead,
GF_n = natural gage factor as reported by the manufacturer.

8.4.3. Use of a Circuit Tester to Check Integrity of Electrical Resistance Strain Gages and Cables

A circuit tester should be used after strain gage installation, and on a regular schedule thereafter, to check integrity of electrical resistance strain gages and cables by measuring gage and insulation resistance. The circuit tester should apply 2 volts or less for gage resistance testing and 15 volts or less for insulation testing.* The following tests should be made (the term *ground* refers to the structural member to which gages are attached):

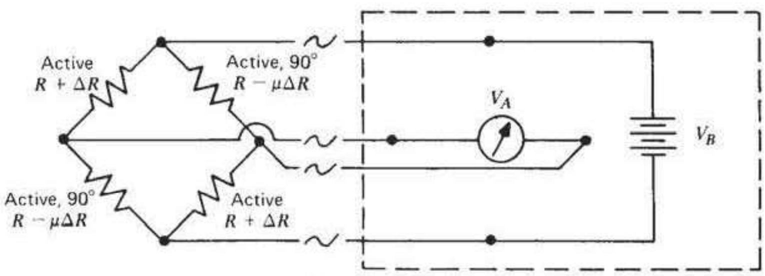
- *Leakage, Bridge to Ground.* A connection is made between ground and any one (or all) of the bridge lead wires. Resistance should be a minimum of 1000 megohms, and preferably 10–20 gigohms.
- *Leakage, Shield to Ground.* A connection is made between shield and ground (shield isolated from structural member to which gage is attached). Resistance should be a minimum of 5 megohms.
- *Leakage, Bridge to Shield.* A connection is made between the shield and any one (or all) of the bridge lead wires. Resistance should be a minimum of 1000 megohms.
- *Gage Resistance.* If an individual gage can be isolated from the bridge, a connection is made between the pair of lead wires attached directly to that gage. If the gages are connected as a Wheatstone bridge and cannot be isolated, the readout unit should be disconnected and the bridge resistance measured across the input corners and output corners. The individual gage resistance, input bridge resistance, and output bridge resistance should not vary by more than $\pm 2\%$ from the nominal 120 or 350 ohm resistance plus any lead wire resistance in series. Lead wire resistance is determined from standard tables. However, commercial strain gage transducers may include auxiliary resistances in the bridge circuit for balancing, thermal correction, or calibration, and in these cases the transducer manufacturer should be contacted for gage resistance testing specifications.

*For example, Model 1300 gage installation tester, Measurements Group, Inc. (see Appendix D).



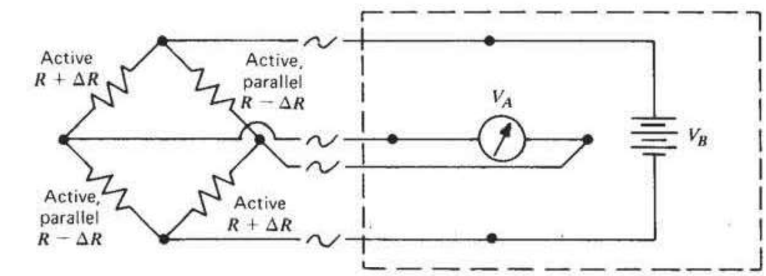
$$\frac{V_A}{V_B} = \frac{\Delta R}{2\,(R + \frac{1}{2}\,\Delta R)}$$

(a)



$$\frac{V_A}{V_B} = \frac{(1 + \mu)\,\Delta R}{2\,[R + \frac{1}{2}\,(1 - \mu)\,\Delta R]}$$

(b)



$$\frac{V_A}{V_B} = \frac{\Delta R}{R}$$

(c)

Figure 8.17. Wheatstone bridge full bridge networks: (a) dummy gages, (b) all gages active, two at 90 degrees to the other two (Poisson effect), and (c) all gages fully active, two in compression, two in tension, equal strains.

Low bridge resistance to ground or shield usually indicates failure of the waterproofing or other environmental protection over the gage or bridge, or breakdown of the insulation cover over the shield and individual lead conductors. It is sometimes possible to locate the damaged area, dry out the moisture causing the partial grounding condition, and repair the waterproofing or insulation. Soap bubble or helium leak detection techniques can sometimes be used to locate the damaged area. The soap bubble technique entails covering the gages and connections with liquid soap and applying light air pressure to the ends of the lead wires, but this procedure is very crude. A much more effective procedure is to apply a vacuum to the ends of the lead wires, connect the vacuum to a mass spectrometer, and spray helium around the gages and connections, using a fine nozzle. In this way, the exact location of minute leaks can be detected rapidly.

Low shield to ground resistance usually indicates moisture in the cable. Excessively high or low gage or bridge resistances usually indicate damage to one or more gages during installation, and gage performance and bridge balance will be affected adversely.

8.4.4. Manual Data Acquisition Systems for Electrical Resistance Strain Gages

A portable strain indicator is used for manual data acquisition. The indicator uses a second set of resistors to null the output voltage of the gage network and provides a measurement of the resistance required to null the circuit. Most portable indicators provide the excitation voltage to the gage. For geotechnical field applications, an AC excitation voltage is recommended and is available in most commercial strain indicators.* When a DC power supply is used, all conductors in the lead wire must be of the same material, otherwise a thermocouple junction is formed, and a signal error may be introduced if a thermal gradient is present between junctions of dissimilar materials.

Particular attention should be paid to keeping portable strain indicators clean and dry, because small current leakage to ground can influence readings. Also, some portable indicators may be influenced by temperature changes, and batteries used with these instruments have a much shorter life when subjected to below freezing temperatures.

*For example, Model P-350A or P-3500, Measurements Group, Inc., or Model HW1-D, Strainsert Company (see Appendix D).

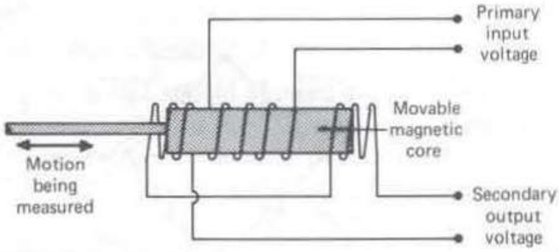


Figure 8.18. Schematic of linear variable differential transformer (LVDT).

8.4.5. Linear Variable Differential Transformer (LVDT)

LVDTs are used in fixed borehole extensometers and in other instruments for measurement of deformation.

An LVDT (Figure 8.18) consists of a movable magnetic core passing through one primary and two secondary coils. An AC voltage, called the *excitation voltage*, is applied to the primary coil, thereby inducing an AC voltage in each secondary coil, with a magnitude that depends on the proximity between the magnetic core and each secondary coil. The secondary voltages are connected in series opposition, so that the net output of the LVDT is the difference between these two voltages. When the core is at its midposition, the net output voltage is zero. When the core moves off center, the net output voltage increases linearly in magnitude with a polarity depending on the direction of core displacement.

A manual data acquisition system for an LVDT includes a means of generating the excitation voltage, a demodulator/amplifier, and a meter display. The meter display can be either analog or digital.

Since the core of an LVDT does not contact the coils, friction is avoided. There is no hysteresis and LVDTs are particularly suitable for measuring dynamic motions and very small displacements. Many types of LVDT have excellent resistance to humidity and corrosion and good long-term stability, and they can be protected within oil-filled housings to maximize longevity. However, the transmission of alternating currents through long lead wires introduces unwanted cable effects, which can seriously degrade the output signal.