28

In Situ Testing and Field Instrumentation

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28.1 Introduction

In all geotechnical engineering problems, performance prediction requires determination of the properties of the soil or rock mass under consideration, and their appropriate use employing soil mechanics theories. For the determination of the soil properties to be used in design, geotechnical engineers can follow two, often complementary, approaches: obtain soil samples from the field and subsequently perform laboratory tests on these samples, or make use of ***in situ* tests**.

Laboratory tests are performed under well-defined and controlled boundary and testing conditions (e.g., drainage, stress path, strain rate) and have the benefits of isolating specific engineering properties. However, their use is limited by the variable and often not completely understood effects of sample disturbance and by generally long testing times and high costs. In addition, because testing involves relatively small specimens, extrapolation of the measured properties to the entire site is often challenging.

In contrast, *in situ* tests, which represent the focus of the first part of this chapter, provide the response of a much larger soil mass under natural, *in situ* conditions (e.g., stresses, void ratio, saturation, temperature) often through approximately continuous records. Thus, they not only provide more economical and rapid estimates of some properties, especially when sampling is difficult, but also are excellent means for soil profiling, furnishing information on the stratigraphy of the site and on trends in engineering properties. In this capacity, they are often used in conjunction with laboratory testing to obtain information on the spatial variation of properties measured in the laboratory.

In situ tests also have limitations, namely poorly defined boundary conditions, non-uniform and high strain rates imposed during testing, inability to control drainage conditions, and effects of installation that are hard to quantify (in the case of some tests). For these reasons, most *in situ* tests do not provide a way to measure directly the fundamental properties of the soil. Instead, the measurements must be related to the quantities of interest in most instances by means of empirical correlations.

The second class of field instruments that are discussed in this chapter are those used for monitoring field conditions before, during, and after construction. Deep foundations, braced excavations, mining excavations, natural or excavated slopes, bridges, embankments on compressible ground, and dams are just some of the structures that may be monitored during construction or operation. In this process, quantities (such as pore-water pressures, total stresses, loads or stresses in structural elements, deformation and displacements) whose values were assumed, computed, or specified during design are measured and recorded. The analysis of these data provides the means to modify the design or the construction procedures to reduce costs or avoid catastrophic failure, in accordance with the observational method (Peck, 1969). In addition, some monitoring instruments may also be used before design and construction, such as piezometers, which are routinely used during site investigation to obtain information about the groundwater conditions at a site.

The goal of this chapter is to present the devices most commonly used for *in situ* testing and monitoring, and discuss their use and the interpretation of the measurements.

28.2 *In Situ* Tests

The Role of *In situ* Testing in a Site Investigation Program

Geotechnical design requires an assessment of the properties of the soil or rock at the site where construction activity will take place. Information gathered during this process, referred to as the *site investigation phase*, generally includes:

1. The groundwater regime at the site
2. The nature of soil and rock found at different depths as far down as thought to be of consequence. For soils, key characteristics include particle size distribution, water content, Atterberg limits, and unit weight. For rocks, geologic origin, degree of weathering, frequency, thickness, length and spatial orientation of discontinuities are some of the most relevant parameters.
3. The engineering properties of relevance for the particular problem under investigation (e.g., shear strength, compressibility, hydraulic conductivity)
4. Any particular geologic characteristic, such as an underground cavity or a fault

In the site investigation phase of a project, *in situ* tests play an important role, and at least one form of *in situ* test is always performed. The most common tests in the U.S. are the standard penetration test (SPT) and the cone penetration test (CPT). Other *in situ* tests include the pressuremeter test (PMT), the dilatometer test (DMT), and the field vane test (FVT). Table 28.1 summarizes the properties that can be estimated using these devices.

TABLE 28.1 Capabilities of the Most Common *In Situ* Test

Capability	SPT	CPT/CPTU	PMT	DMT	FV
Soil profiling	•	••/•••	—	•	—
Soil identification	••• from sample	••	—	—	—
Relative density, D_r	••	•••	—	•	—
Horizontal stress, σ_h'	—	•• sands	• sands •• clays	•	—
Friction angle, ϕ' (sands)	••	•••	••	•	—
Undrained strength, s_u (clays)	•	•••	•	•	••
Initial shear modulus, G_{max}	• from correlations	• from q_c ••• w/v_s measurements	•	(•• for oedometric modulus)	—
Coefficient of consolidation, C_h	—	—/•• from dissipation tests	—	—	—
Liquefaction resistance	••	•••	—	—	—

• Provides crude estimate of property.
•• Provides acceptable estimate of property.
••• Provides reliable means of estimating property.

Standard Penetration Test

The SPT is performed by advancing a split spoon sampler into the base of a borehole by blows from a hammer with a standard weight of 140 pounds falling from a height of 30 inches. The number of blows N required to advance the sampler a distance of 1 foot into the soil is recorded and indicates the soil's density and confining stress. In addition, a sample, on which classification tests can be performed, is obtained when the split spoon sampler is extracted. The approach to SPT interpretation is usually based on correlations to the blow count. For example, a number of widely used relationships exist between N and properties such as the relative density and the friction angle of cohesionless soils. In addition, the SPT is used commonly for the evaluation of liquefaction susceptibility of a deposit.

Unfortunately, SPT blow counts also depend on the equipment and procedure used to perform the test. The following have all been found to affect the test results: procedure used to raise and drop the hammer, hammer type, string length, presence of a liner inside the sampler, sampler condition, borehole condition, and drilling method. Attempts to standardize the test have been made (Seed et al., 1985; Skempton, 1986). These authors recommend how to correct N for a variety of factors, so that the N value becomes more representative of the soil density and stress state and less representative of equipment and procedural factors. Although these corrections are not perfect, they make it possible to use the test with some effectiveness. That, associated with the familiarity engineers have with the test, is responsible for the continuing importance and wide use of the SPT in geotechnical field testing.

The following are references on the interpretation of SPT results: estimation of friction angle in sands (Skempton, 1986); estimation of undrained shear strength in clays (Stroud, 1975); estimation of liquefaction resistance in sands (Seed et al., 1985; Seed and Harder, 1990); estimation of the settlement of shallow foundations in sand (Burland and Burbidge, 1985); estimation of pile capacity in all soils (Bandini and Salgado, 1998).

Cone Penetration Test

In the CPT (ASTM D3441 and D5778), a cylindrical penetrometer (Fig. 28.1) with a conical tip (10 cm^2 in cross section, with apex angle of 60 degrees) is pushed vertically down into the soil at a rate of 2 cm/sec while the vertical force acting on the tip during penetration is measured. The ratio of this force to the projected area of the tip provides the cone penetration resistance, q_c, which is the most important parameter through which estimates of engineering properties are determined. The frictional resistance, f_s, along a lateral sleeve located immediately behind the cone is also routinely measured.

The most important use of cone resistance values is the estimation of shear strength in both clays and sands. In sands, this is done by first estimating relative density and lateral effective stress using charts of

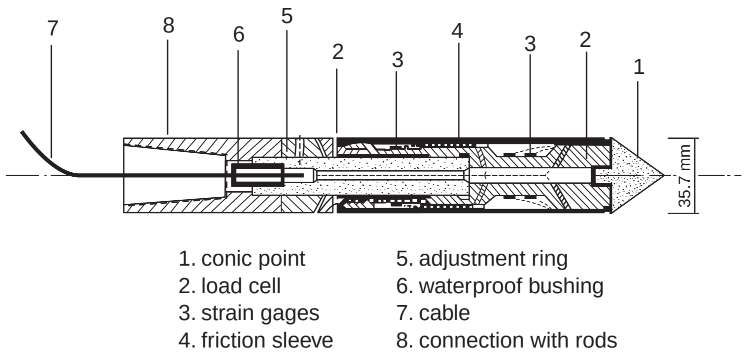

FIGURE 28.1 The standard electrical cone penetrometer. (From De Ruiter, J. 1971. Electric penetrometer for site investigation, *J. Soil Mech. Found. Div. ASCE*, vol. 97, no. SM2, February. With permission.)

cone resistance as a function of these two quantities, such as those presented by Salgado et al. (1997a). The most common procedure is to first calculate the vertical effective stress at the point of interest from the known soil profile. Then an estimate of K_0 is made. This often is possible based on knowledge of the site geology. If the sand is known to be normally consolidated, K_0 ranges from 0.4 for dense to 0.5 for loose sand. Finally, one enters a suitable chart with the value of K_0 and the measured value of q_c to obtain the relative density.

In clays, the undrained shear strength, s_u, is obtained directly from the cone resistance q_c through

$$s_u = \frac{q_c - \sigma_v}{N_k} \tag{28.1}$$

where σ_v = vertical total stress
N_k = cone factor, which is approximately equal to 10 for fully undrained penetration (e.g., see Yu et al. 2000).

Penetration is fully undrained when vd_c/C_v is less than approximately 1, where v = penetration rate, d_c = cone diameter, and C_v = coefficient of consolidation (Bandini and Salgado, 2002). If the clay contains large percentages of either silt or sand, C_v becomes too small and the ratio vd_c/C_v, larger than 1. In these cases, penetration is not fully undrained for the standard penetration rate of 2 cm/sec. Consequently, either the penetration rate must be increased or a higher value of N_k must be used in Eq. (28.1).

Another important use of the CPT is in the assessment of the liquefaction potential of cohesionless soils. Correlations have been developed between the tip resistance (appropriately corrected and normalized) and the cyclic resistance ratio (Robertson and Campanella, 1985), and today the CPT is the preferred tool for determining liquefaction resistance.

One important and widely used variation of the CPT is the piezocone (CPTU – e.g., Baligh et al., 1981), which contains a pressure transducer for measurement of the pore pressure generated during penetration in a porous element located at the face of the conical tip or immediately behind it. The CPTU represents an excellent means for soil profiling, allowing accurate detection of thin lenses of different soils and delineation of drainage boundaries. It can also be used to determine the horizontal coefficient of consolidation of the soil by performing dissipation tests (Baligh and Levadoux, 1980).

Various soil identification and classification charts based on tip resistance, friction ratio, and excess pore water pressure (in the case of the CPTU) have been proposed (e.g., Robertson, 1990). The use of these charts is recommended only when experience with similar soil conditions exists.

The advantages of cone penetrometers over other field testing devices are numerous, including the limited influence of the operator and hardware on the values of the measured quantities, and the fact that they provide continuous records. In addition, these devices are very versatile and many different **sensors** can be incorporated into the cone, facilitating measurement of additional quantities, such as the shear wave velocity V_s along the penetration path (Robertson et al., 1986), and a number of properties of interest in geoenvironmental projects, including temperature, electrical resistivity, organic content in the pore fluid, and other pore fluid chemistry parameters (e.g., Mitchell, 1988; Sinfield and Santagata, 1999). Finally, various analytical models describing the advancement of the cone penetrometer through soil have been developed, allowing a more rational interpretation of the data (e.g., Salgado et al., 1997a, b; Salgado and Randolph, 2001; Yu and Mitchell, 1998).

Jamiolkowski et al. (1985) discuss many details of both performance and interpretation of the CPT. Additional references, focusing on interpretation of CPT results include the following: theoretical relationships for cone resistance (Salgado et al., 1997b; Yu and Mitchell, 1998; Yu et al., 2000; Salgado and Randolph, 2001); estimation of friction angle in sands (Salgado et al., 1997b), using the Bolton (1986) relationship for friction angle in terms of relative density and stress state; estimation of undrained shear strength in clays (Yu and Mitchell, 1998); estimation of liquefaction resistance in sands (Robertson and

Campanella, 1986; Mitchell and Tseng, 1989; Stark and Olson, 1995; Bandini and Salgado, 2002; Mitchell and Brandon, 1998); estimation of the settlement of shallow foundations in sand (Schmertmann, 1970; Schmertmann et al., 1978; Lee and Salgado, 2002); estimation of the load capacity of drilled shafts and driven piles in sand (Lee and Salgado, 1999); load capacity of both closed and open-ended pipe piles in sand (Lehane and Randolph, 2002; Paik et al., 2002); summary of methods to estimate capacity of all types of piles in all types of soils (Bandini and Salgado, 1998).

Pressuremeter Test

The PMT is performed by expanding a cylindrical membrane (Fig. 28.2) in the soil while simultaneously measuring the pressure (p) inside the membrane and the displacement of the membrane. From these data, the expansion curve (usually expressed in terms of p versus the hoop strain) is obtained. There are essentially two methods for installation of the pressuremeter: in one, a borehole is prebored and the pressuremeter is lowered into it (this is known as the Menard pressuremeter); in the other, the pressuremeter has a drilling tool at its lower end that is used to install it at the desired depth (this is the so-called self-boring pressuremeter). Apart from any disturbance due to drilling (and unloading in the case of the Menard pressuremeter), the expansion curve obtained in a PMT, as well as any unloading-reloading

FIGURE 28.2 A pressuremeter. (Picture courtesy of A. Bernal and A. Karim, Bechtel Geotechnical Laboratory, Purdue University.)

loops, can be related to the stress-strain relationship of the soil. In addition, the limit pressure extrapolated from the pressuremeter curve provides an indication of the shear strength of the material. In practice, the pressuremeter is most commonly used to determine the friction angle of cohesionless soils and the modulus degradation behavior. The pressuremeter is also the only device that can provide a direct measurement of the horizontal effective stress, σ'_h. While the use of the PMT for this purpose is considered somewhat reliable in soft clays, its reliability and accuracy in the case of stiffer soils, such as sands, remains questionable (e.g., Fahey, 1998).

The main problems with the use of the pressuremeter are related to assessing the degree of disturbance due to installation and the effect of the length-to-diameter (L/D) ratio of the membrane. While interpretation methods are generally based on the assumption that the expansion of the membrane can be approximated by a cylindrical cavity expansion, for typical values of the L/D ratio this assumption deviates from reality, and correction for L/D effects are needed.

References on pressuremeter test performance and interpretation include: ASTM D 4719–87, Baguelin et al. (1978), Clark (1995), Hughes et al. (1977), Mair and Wood (1987), Manassero (1992), and Yu (1990).

Dilatometer Test

The DMT is performed by pushing down into the soil the blade shown in Fig. 28.3. Penetration is halted at preselected depths, and the circular membrane on one of the sides of the dilatometer is expanded and the pressures at deflections of zero and 1.1 mm are recorded and corrected for membrane stiffness. Based on these two fundamental parameters, a number of empirical relationships have been proposed for soil parameters of interest in design (Marchetti, 1980; Schmertmann, 1986; Fretti et al., 1992).

A shortcoming of the DMT is that the membrane expansion is accomplished against soil that has been considerably disturbed by penetration of the device. This obscures, more than for other *in situ* tests, the relationship between measurement and undisturbed soil properties, reducing the reliability of correlations proposed for this test.

FIGURE 28.3 A dilatometer. (Picture courtesy of A. Bernal and A. Karim, Bechtel Geotechnical Laboratory, Purdue University.)

Field Vane Test

The FVT involves pushing a four-bladed vane having a height-to-diameter ratio of two into the soil and then rotating the blade at a rate of 0.1 degrees/sec (ASTM 2573). This test provides a simple and inexpensive means of estimating the undrained strength of cohesive soils, which is derived from the maximum torque measured during rotation of the blade, assuming full and uniform mobilization of the shear strength along the cylindrical surface created by the rotating vane. The use of this test is advocated particularly in the case of relatively homogeneous clay deposits, in absence of shells, granular layers, varves and fibers (Ladd, 1990). A correction (Bjerrum, 1972, 1973), based on the plasticity index of the soil, is generally applied to the shear strength measured with the FVT, to obtain a "field" value of the strength to be used in design. A correction for end effects that are associated with the mobilization of shear strength on the top and bottom of the cylindrical volume of soil sheared by the vane is also necessary. Despite the simplicity of the test, a number of procedural aspects (e.g., rate of rotation of the blade, delay between vane insertion and testing); influence the test results (Ladd et al., 1977), and adherence to standard practice and equipment is essential.

28.3 Instrumentation for Monitoring Performance

Planning of an Instrumentation Program

There are multiple reasons to use **instrumentation.** It may be that a project design has enough flexibility to be changed if measurements made during early stages of construction indicate that changes are required or could be beneficial. Alternatively, the facility under construction may be so important and its loss may lead to so much damage or danger that instrumentation must be used to detect any deviations from the assumed or predicted behavior of the facility, to allow timely implementation of previously planned actions to either correct the deviation or minimize losses. In other cases, the construction procedure (e.g., staged construction) may rely on indications of changes in the *in situ* conditions for proper execution of the construction plan. Finally, when a new construction concept is used, instrumentation is sometimes used to show or ascertain that the concept indeed works. Whatever the reason, detailed planning is essential for a successful instrumentation project.

Design of the instrumentation program must rely on a clear definition of the geotechnical problem that is being addressed and on the fundamental understanding of the mechanisms that control the behavior. Once the objectives of the monitoring program are identified, its implementation requires selection of the following: type and number of instruments to be used, specific locations where measurements are to be made, installation procedures, and data acquisition system, methods for analyzing and interpreting the data. Figure 28.4 illustrates the main steps in the planning and implementation of an instrumentation program.

Ultimate selection of the instruments depends on the quantities to be measured and estimates of the magnitudes of changes in these quantities resulting from construction or operation of the facility. The maximum expected change of the parameter to be measured will define the range for the instrument selected to measure it. The minimum expected change defines the sensitivity or resolution of the instrument. Such predictions are also required in defining criteria for remedial action, if the purpose of the instrumentation is to ensure proper and safe operation of the facility.

When selecting instruments, several characteristics must be evaluated carefully:

1. Conformance: the instrument should conform to the surrounding soil or rock in such a way that it does not alter the values of the properties it is intended to measure.
2. Accuracy: the measure should be as close as possible to the true value.
3. Repeatability: under identical conditions, an instrument must measure the same value for the quantity it is intended to measure whenever a measurement is taken.

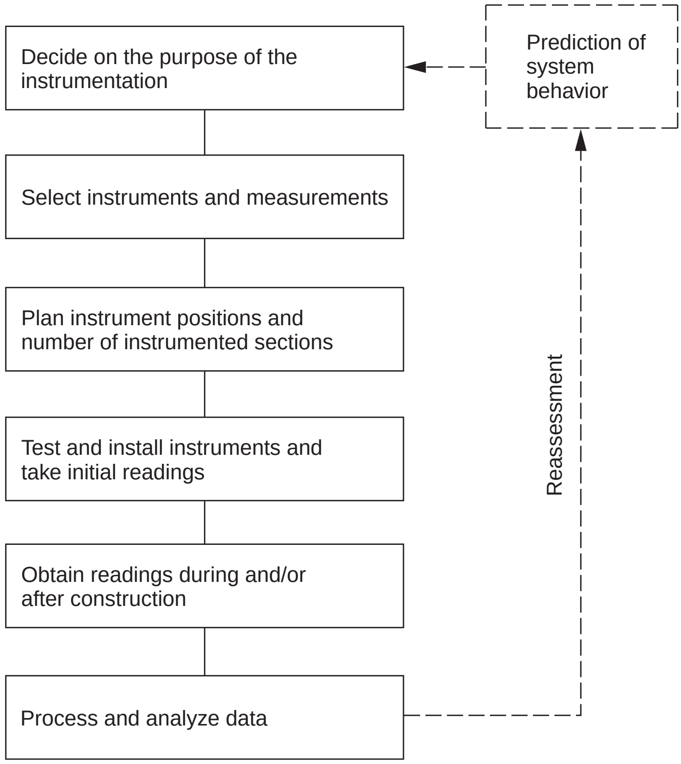

FIGURE 28.4 Planning of an instrumentation program. (From Ortigão, J.A.R. and Almeida, M.S.S. 1988. Stability and deformation of embankments on soft clay, in *Handbook of Civil Engineering Practice*, P.N. Chereminisoff, N.P. Chereminisoff and S.L. Cheng, eds., Technomic Publishing Co., New Jersey, vol. III, 267–336, With permission.)

4. Resolution: the smallest division of the instrument read-out scale must be compatible with the minimum expected change in the quantity being measured.
5. Sensitivity: the change in output per unit change in the input should be as large as possible to optimize data acquisition and limit the effects of noise.
6. Linearity: the relationship between input and output should be as linear as possible for the range in which the input is to be measured to facilitate data reduction.
7. Hysteresis: it is undesirable that a different value for the quantity of interest be measured depending on whether the quantity is increasing or decreasing; this difference should be kept to a minimum, particularly if cyclic measurements are needed.
8. Noise: random variations in the measurement should be limited.
9. Environmental compatibility: the instruments' readings should not be affected by changes in environmental conditions (e.g., temperature, relative humidity).

There are two approaches for selecting instrument location. Instruments can be installed in "trouble spots," such as points where it is expected there will be large stress concentrations or large pore pressure increases, or where difficult soil conditions exist. Alternatively, they can be placed at a number of representative points or zones. In either case, the designer should make every effort to ensure that the instrument locations are consistent with the expected behavior of the facility and with the data required for the analysis. It is also important that there is some redundancy in the instrumentation to filter anomalies in measured quantities and ensure that the required information is obtained.

Testing and installation of the instrumentation is the next major step. All instruments should be properly calibrated and tested before placement. Installation is one of the most critical steps in the entire monitoring program because minor variations in the process can have significant effects on the performance of the devices and the reliability of the data. In many cases, hiring instrumentation specialists might be justified.

During installation, steps should be taken to ensure the protection of the instrument (e.g., protection from impact, water-tightness if required) and the instrument should be installed to minimize disturbance of the medium under investigation.

Once installed, initial readings should be obtained and verified to ensure that changes from the time of installation are represented accurately.

Data acquisition, processing, and analysis must be carried out in a systematic, organized way. Careful recordkeeping is crucial and should include documentation of all construction activities and any significant events that may later be correlated with unanticipated or significant changes in the quantities measured. Techniques and schedule for data acquisition depend on specific instruments and on the requirements of the particular project. While many instruments still require on-site personnel, there is increased availability of systems providing automated data acquisition and storage.

Instruments

In general, three primary quantities are measured in monitoring programs for traditional geotechnical projects: loads and stresses, deformations, and pore pressures.

Instruments for Measurement of Loads and Stresses

In geotechnical engineering applications, load measurements are often required for load testing of deep foundations, load testing and performance monitoring of tiebacks and rock bolts, and monitoring of loads in strutting systems for deep excavations.

In most instances, such measurements are made with **load cells**. When accuracy is not a great concern, a calibrated hydraulic jack can also be used. Based on the operating principle, there is a variety of different types of load cells, including hydraulic, mechanical, electrical resistance, and vibrating wire cells.

Hydraulic cells consist of a chamber filled with fluid and connected to a pressure sensor. Load is applied to a flat element that is in contact with the fluid and is free to move with respect to the rest of the cell. The pressure generated in the fluid is measured by a pressure sensor, which can be a Bourdon gage, which requires access to the cell for reading, or an electrical or pneumatic transducer for remote reading.

Mechanical and electrical resistance and vibrating wire cells function by measuring the deformation of a load-bearing member and are based on the existence of a direct and unique relationship between deformation and load.

In the case of a mechanical load cell, the deformation of either a torsion lever system or an elastic cup spring is measured by dial gages. In electrical and vibrating wire load cells, the load-bearing member is usually a steel or aluminum cylinder, the deformation of which is measured by **electrical resistance strain gages** or vibrating wire transducers mounted at mid-height on its surface. Some of the gages (or transducers) are oriented for measuring axial strain, others for measuring tangential strains. The arrangement and the connections are designed to minimize errors associated with load eccentricity.

Strain gages can be used effectively for measurement of loads or stresses in a structural member, provided that the stress-strain relationship of the material on which they are mounted is known with some accuracy. Their main advantages are that they can be placed almost anywhere in a structure, and that, due to their limited cost, measurements can be performed at a number of different locations. A distinction is generally made between surface-mounted strain gages, which are applied to an exposed surface (for example, to the surface of a steel strut) and embedment strain gages, which are placed inside a mass, for example, a concrete tunnel lining.

Pressure cells are used to measure total stresses behind retaining walls or underneath shallow foundations, as well as within soil masses, such as fills. They are circular (Fig. 28.5) or rectangular pads with metallic walls, and are of two types: hydraulic and diaphragm cells. In hydraulic cells, a fluid, such as oil, is contained between the metallic walls. A pressure transducer positioned at the end of a rigid tube connected to the inside of the cell measures the pressure in the fluid, which corresponds to the stress

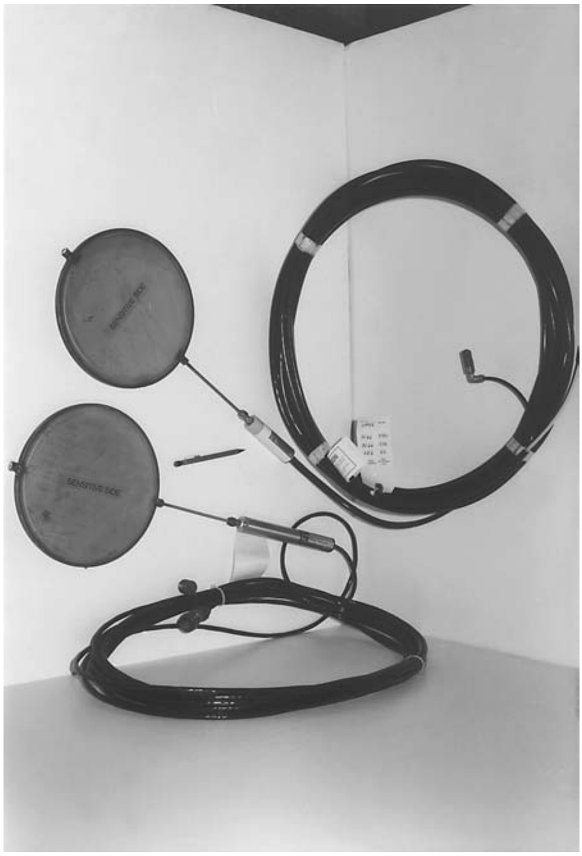

FIGURE 28.5 Pressure cells for measurement of stresses in soil masses or contact stresses between soil masses and concrete or steel surfaces. (Picture courtesy of A. Bernal and A. Karim, Bechtel Geotechnical Laboratory, Purdue University.)

acting on the face of the cell. In diaphragm cells, the pressure acting on the cell correlates with the deflection of the face, which is measured through strain gages or vibrating wire transducers mounted on the inside of the cell. Many factors, including characteristics of the cell, such as size, thickness, and stiffness, affect the measurements performed. The accuracy with which total stresses are measured is limited by conformance problems between the cell and soil arising from the difference in stiffness, the effects of the installation procedures, and difficulties in calibrating the cell to represent field conditions (Dunnicliff, 1988). When pressure cells are embedded for measurement of stresses inside a fill, arching of stresses around the cell is often the source of considerable error in the measurements.

Instruments for Measurement of Deformations

A reliable way of measuring displacements of the ground surface or parts of structures that can be observed above the ground surface is by surveying techniques.

The measurement of absolute motions requires that reference points be established. The reference for the measurement of a vertical displacement is called a **benchmark**; for horizontal displacement measurements, a **reference monument** is used. Reference stations should be motionless. If no permanent structure, known to be stable and free of deformation, exists, a reference station (benchmark or monument) must be installed. A benchmark may consist of a rod or pipe extending all the way down to a relatively incompressible layer, isolated from the surrounding soils to avoid deformation. This can be accomplished by placing the rod inside a pipe without allowing any contact between the rod and the pipe.

Points where deformations are to be determined are called **measuring points** and should satisfy three requirements: first, that they are well marked so measurements are consistent; second, that they are placed at the actual seat of movement; and third, that they last for the time during which measurements will be needed. For measurements on structures, the first requirement can be satisfied by the use of bolts embedded into wall surfaces. Sometimes a grid, scale, or bullseye may be used for improved readings.

If ground surface displacement measurements are desired and a pavement exists, particularly if it is a structural pavement, it is important to place the measuring point below the pavement, in the ground, to get an accurate measurement of the displacement. It is also important to go beyond the freeze-and-thaw depth, and any layer of expansive or collapsible soil, unless it is desired to know the motions related to these phenomena.

In addition to techniques that rely on direct visual observations, a number of other instruments are used for measurement of deformations. The most common instruments include tiltmeters, inclinometers, extensometers, settlement plates, and telltales.

Tiltmeters are instruments used for measuring the rotational component of motion of points on a structure or in the ground, usually inside a borehole. They rely on a servo-accelerometer, an electrolytic tilt sensor, or another gravity sensing device for the measurement. More common applications are for measuring the rotation of retaining walls and concrete dams, and for monitoring landslides.

Inclinometers are devices used to measure the inclination with respect to the vertical. Their applications include monitoring of landslides, measurement of horizontal displacements of embankments on soft ground and of motion of retaining structures, evaluation of deformations produced around a deep excavation, and assessment of the location of a possible failure surface. In addition, inclinometers can also be placed horizontally; for example, to determine the settlement or heave profile under an embankment or a foundation.

An inclinometer system typically consists of a casing, a probe, and a readout unit. The casing, which is generally formed by sections of grooved plastic pipe, may be installed in a borehole, embedded in a fill or in concrete, or attached to a structure. Measurements are obtained by periodically lowering the probe inside the casing all the way to a depth where no motion is expected. Grooves in the casing act as guides for the inclinometer probe, maintaining its orientation. The probe consists of a tube with two sets of hinged wheels 0.50 m apart (Fig. 28.6), and typically contains two sensors: one aligned in the

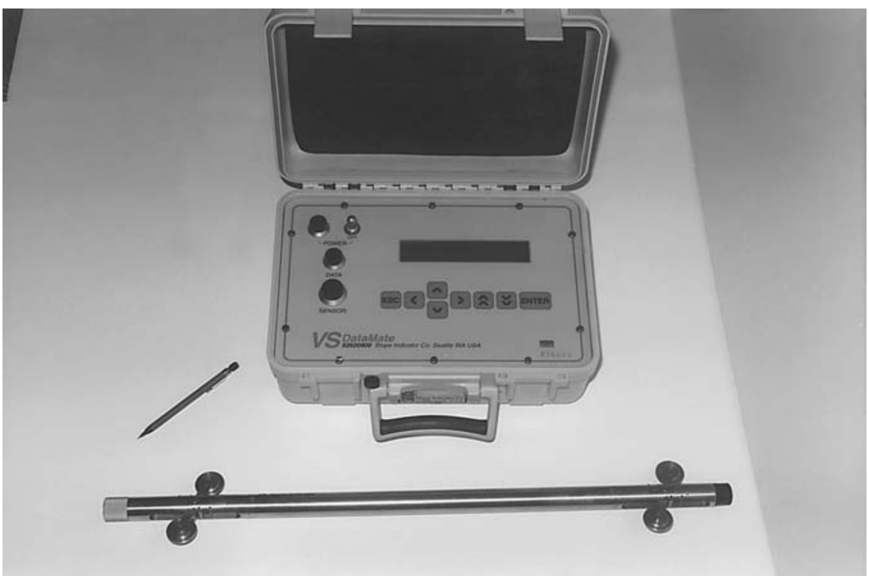

FIGURE 28.6 Inclinometer and read-out unit. (Picture courtesy of A. Bernal and A. Karim, Bechtel Geotechnical Laboratory, Purdue University.)

plane of the wheels and the other at 90 degrees. While various types of inclinometers are available, the most common are based on servo-accelerometers, vibrating wire strain gauge transducers, and magneto-restrictive sensors. Two sets of readings are typically obtained by rotating the probe 180 degrees to check for errors in the data produced by faulty equipment or poor technique.

From the readings of the two sensors, which measure the angle of inclination to the vertical, the two components of horizontal movement can be determined. Using as reference the initial profile of the casing determined from the first set of measurements, the evolution of the entire borehole profile can be assessed. Because errors in the use of inclinometers are often associated with spiraling of the casing, particularly in the case of deep installations, a spiral sensor that allows correction of the inclinometer data may be used.

In addition to the portable inclinometer probe, which is the most standard device used in practice, in-place inclinometers may be used in critical applications requiring real time observations such as for construction control and safety monitoring. These devices consist of a string of inclinometer sensors connected in sequence through pivot points.

Extensometers are instruments for measuring the relative displacement between two points. Depending on how they are deployed in the field, these instruments can be classified as surface or borehole extensometers. **Surface extensometers** include devices such as jointmeters and strainmeters used to monitor cracks in structures, rock, or behind slopes, as well as gages used for monitoring convergence within tunnels and braced excavations. All these devices function in a similar manner, by measuring the relative movement of two pins or anchors fixed to the soil or rock with techniques as simple as a tape measure or a dial gage or as sophisticated as **vibrating wire transducers**, **LVDTs**, and optical sensors.

Borehole extensometers are used to monitor the change in distance between two or more points along the axis of a borehole, and are used for a variety of purposes including monitoring of settlement or heave in excavations, foundations, dams and embankments, and monitoring of compression of piles.

Measurements are typically obtained by lowering a probe inside a casing and measuring the position of reference points, typically rings or magnets, relative to a fixed point at the surface or at the bottom of the borehole. Settlement and heave are determined comparing the initial and current values of these measurements. Borehole extensometers are often used in conjunction with inclinometers and may share the same casing.

In addition to the probe-based systems previously described, other devices permanently installed in a borehole can be used to monitor changes in vertical position at one or more points. These instruments typically consist of one or more anchors connected to rods, which extend to the surface. Movement at depth is detected from the change in distance between the top end of each rod and a reference point.

Settlement plates carry out the same function for monitoring of deformations underneath embankments constructed on soft clays. A 1- to 1.2-m square steel plate is embedded under the embankment and connected to a 25- to 50-mm diameter coupled pipe, which extends all the way to the surface and is isolated from the soil by a casing. The displacement of the plate is determined by measuring the elevation of the top of the pipe.

The principle is also essentially the same for **telltales**, which are rods extending from a point inside a structural element, such as a drilled shaft, and isolated from the surrounding concrete (or other material) by means of a casing. Measurement of the displacement of the tip of the rod with respect to a reference provides a measure of the displacement at the inaccessible point in the structure.

Instruments for Measurement of Pore Water Pressure

Piezometers are used to measure groundwater pressure. This is an essential parameter in all geotechnical engineering projects, required for computation of effective stresses and earth pressures exerted on retaining systems. Calculation of pore pressures may be straightforward if the depth to the groundwater table is known and hydrostatic conditions are known to exist, but there are many situations where there is enough uncertainty about pore pressure values to warrant the use of piezometers.

Piezometers are commonly used for monitoring groundwater draw-down around excavations; for evaluating rates of consolidation during embankment construction on soft soils so that the fill may be

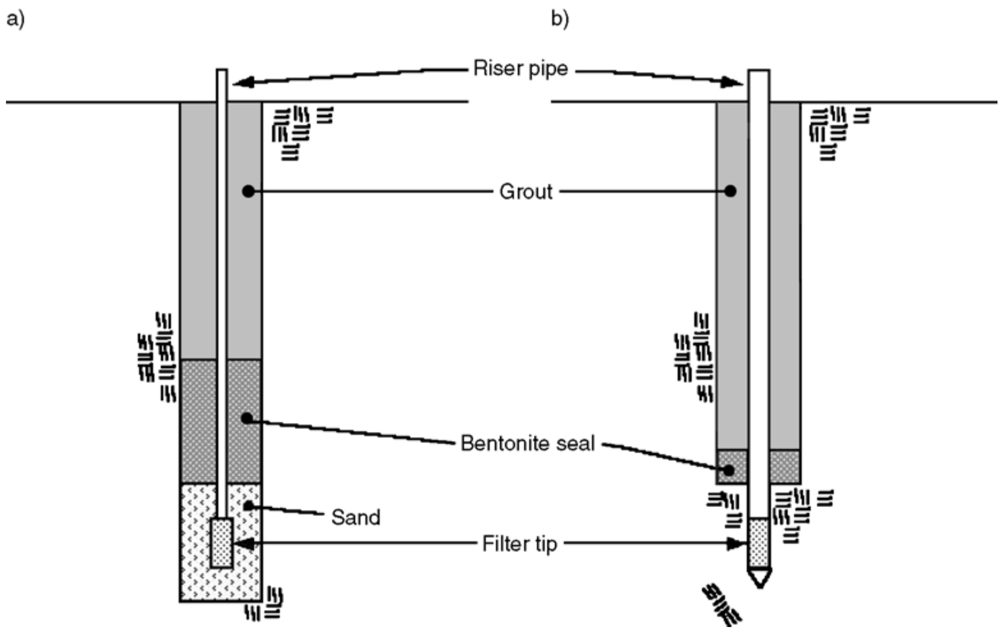

FIGURE 28.7 Schematic of standpipe piezometer (a) installed at bottom of a borehole and (b) pushed into base of borehole.

placed without risks of failure; for verification of pore pressure dissipation around a pile after driving to determine the right time to start a static load test; and for monitoring of pore pressure build-ups produced by ineffective drainage in earth dams.

Piezometers can be classified in five main groups: open standpipe, hydraulic, pneumatic, electrical, and vibrating-wire.

Open standpipe (or Casagrande) piezometers consist of a porous tip installed at the point where the pore pressure readings are to be made. These piezometers are usually installed at the base of a borehole with a diameter of 50 to 100 mm. They can be placed on the base of the borehole, which is then backfilled with sand that will completely surround the porous tip, and sealed to prevent vertical migration of water (Fig. 28.7(a)). Alternatively, they can be pushed into the base, so they are surrounded by natural material (Fig. 28.7(b)). A single pipe (10–50 mm in diameter) is connected to the porous tip, which extends to the ground surface and is generally open to the atmosphere. The level to which the water rises in the tube is measured with a water level indicator and reflects the pore pressure at the porous tip.

In a hydraulic piezometer, twin tubing filled with de-aired water connects the porous tip to remote pressure-reading devices, which may be mercury **manometers**, electrical pressure transducers, or **Bourdon gages**. The double-tube system allows verification that there is no entrapped air, as well as flushing of the system. The use of this type of device is advocated for long-term monitoring of pore water pressures in embankment dams (Dunnicliff, 1988).

Pneumatic, electrical resistance and vibrating-wire piezometers, all contain a pressure diaphragm. Water pressure acts on one side of this diaphragm, via a filter, and the difference between the piezometers resides in the mechanism on the other side of the diaphragm used to measure the pressure.

In a pneumatic piezometer (Fig. 28.8(a)), a pneumatic indicator is connected to the diaphragm through twin tubes. Measurement of the pressure at the diaphragm is performed by increasing the pressure of a gas inside one of the tubes until it exceeds the water pressure, resulting in flow of the gas back up to the indicator through the second tube.

In vibrating-wire piezometers (Fig. 28.8(b)) and electrical resistance (Fig. 28.8(c)), the diaphragm is the sensing element of a pressure transducer contained in the same housing that holds the filter. The transducers function by measuring the deflection of the pressure-sensitive diaphragm through a resistance

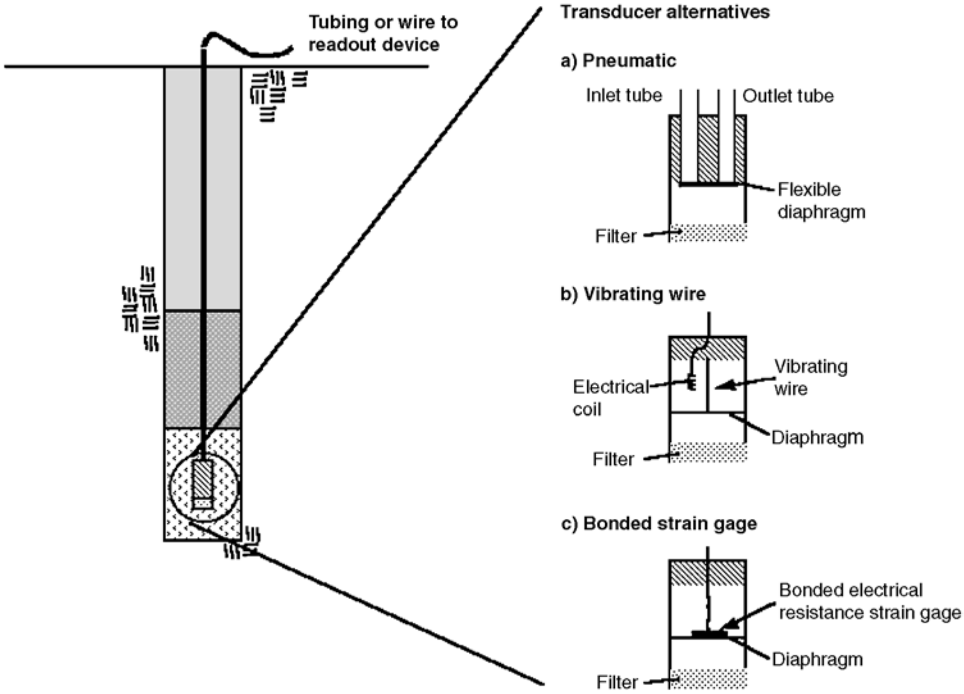

FIGURE 28.8 Schematic of (a) pneumatic, (b) vibrating wire piezometer, and (c) bonded strain gage electrical resistance.

strain gage bridge (two configurations are available: unbonded and bonded strain gages) mounted on the diaphragm, or through measurement of the resonant frequency of a tensioned wire connected to the diaphragm.

In addition to being installed in boreholes as shown in Fig. 28.8, pneumatic, electrical resistance, and vibrating wire piezometers are all available also as push-in instruments. Dunnicliff (1988) points out that while push-in piezometers are installed more easily and at less cost than in a borehole, problems arise due to the potential for inadequate seal and for smearing and clogging. Selection of the appropriate piezometer is a function of the purpose and the duration of the measurements, and is based on considerations of accuracy, ease of installation, reliability, and durability of the instruments. In addition, an important characteristic is the hydrodynamic lag time of the piezometer, which is the time required for equalization of the pore pressure. Because it depends on the time necessary for water to flow in or out of the porous tip, the lag time depends on the type of piezometer and on the permeability of the soil in which it is installed. For example, Ortigão and Almeida (1988) show that in a soil with a hydraulic conductivity of 10^{-10} m/sec, the lag time corresponding to 95% pressure equalization can vary from approximately 1000 hours for a typical Casagrande piezometer to approximately 10 seconds for a vibrating-wire piezometer.

For pore pressure measurements in unsaturated soils, any of the piezometers previously described can be used depending on the specific application, provided that they are equipped with a fine, high bubble pressure filter.

Table 28.2 summarizes some of the advantages and disadvantages of the described piezometers.

Examples of Applications of Field Instrumentation

Construction of Embankments on Soft Ground

Construction of embankments on soft soils presents risks associated with both short-term stability and excessive long-term settlements arising from both primary and secondary consolidation. In these projects, the use of the observational method is often valuable to ensure that construction proceeds safely and in

TABLE 28.2 Advantages and Disadvantages of Different Types of Piezometers

Piezometer	Advantages	Disadvantages
Open standpipe	• Highly reliable • Low cost • Simple to install • Easy to read • Can perform permeability tests • Can obtain groundwater samples	• Long time lag especially in low permeability soils • Interference with construction when used in embankments on soft soils • Susceptible to damage by construction equipment
Hydraulic twin tubing	• Reliable for long term monitoring • Flushing possible to remove air • Can perform permeability tests • Can measure negative pore pressure	• Complex installation • Very difficult and costly to implement automated data acquisition • Periodic flushing required • Limitation on elevation above piezometric head at which measurement is made • Freezing problems
Pneumatic	• Short time lag (provided tubing not excessively long) • No freezing problems • Can be used in corrosive environments	• Very difficult and costly to implement automated data acquisition • Reading time increases with length of tubing
Electrical resistance	• Simple to install • Short time lag • Simple to read • Easy to implement automated data acquisition • Some types can be used for dynamic measurements • Can measure negative pore pressure • No freezing problems	• Moderate to high cost • Susceptible to damage by lightning • Susceptible to damage by moisture • Low electrical output
Vibrating wire	• Simple to install • Short time lag • Very accurate • Simple to read • Easy to implement automated data acquisition • Can measure negative pore pressure • No freezing problems	• Moderate to high cost • Susceptible to damage by lightning

the most cost-effective manner; thus, monitoring of field performance plays an important role. This is true particularly when more complex construction designs and procedures are used, as in the case of staged construction, in which loading is applied in a controlled manner in different stages, relying on the increase in shear strength due to consolidation for stability.

In the case of construction of embankments on soft soils, the goals of the field monitoring program, which normally involves measurement of pore pressures as well as of vertical and horizontal deformations, are generally the following:

1. Evaluate the progress of the consolidation process. Knowledge of the rate of consolidation is essential so that construction schedules (e.g., placement of the pavement or structure, which would be damaged by excessive settlements; timing of subsequent loading stages in the case of staged construction; removal of surcharge in the case of preloading) can be safely and economically carried out. When vertical drains are used, information might also be gathered on the effectiveness of the drains.
2. Assess at all times the *stability* of the embankment so that, in case of incipient failure, remedial actions (such as the construction of a temporary berm, the reduction in the design fill elevation, or the removal of part of the fill) may be implemented.
3. Obtain data that will allow improvement of the prediction of behavior during subsequent construction phases, or even after construction. For example, if the project involves a preloading phase, data gathered during construction may allow modification of the thickness of the surcharge layer, based on revised estimates of soil compressibility.

As indicated by Ladd (1990) determination of the *in situ* rates of consolidation typically relies on measurements of pore pressures and vertical settlements performed under the centerline of the embankment with piezometers and extensometers, respectively. These data are also used to determine the *in situ* compression curve. Measurement of the boundary pore pressures is also in general necessary.

Additional piezometers are typically installed under the slope and, when applicable, under the berm(s) of the embankment. These instruments complement the data on rates of pore pressure dissipation, allowing, in the case of staged construction, definition of the current effective stress profile from which the updated undrained shear strength values to be used in the stability analysis can be estimated. In the use of vertical drains, Ladd (1990) suggests that care should be placed in positioning the piezometers near the midpoint of the drains and that part of the instrumentation be in place before the drains to measure excess pore pressures generated by their installation.

In addition to the measurements performed under the centerline of the embankment, vertical deformations of the soft soil layer may also be measured at other locations. This can be done, for example, by using settlement platforms to define the embankment profile.

Pore pressure field data are also used to assess the conditions of stability of the embankment; however, Ladd (1990) suggests that, as dramatic pore pressure increases often occur before or during actual failures, pore pressures may not provide timely warning of impending failure. Field measurement of vertical and especially horizontal displacements (which reflect deformations caused by undrained shear and are less affected by consolidation) better serve this purpose. In this context, data obtained from inclinometers installed at the toe of the embankment, which can be supplemented by monitoring of surface deformations with surveying techniques, provide the most unambiguous proof of foundation instability.

A thorough discussion on the use of field instrumentation in monitoring the performance of embankments constructed on soft soils, with emphasis on the role of the stress-strain characteristics of the foundation soil and on the interpretation of field data for stability analysis is provided by Ladd (1990). An extensive list of case histories of instrumented embankments on soft ground is presented by Dunnicliff (1988).

Static Load Tests on Deep Foundations

The main purpose of a standard **static load test** on a pile or drilled shaft is to obtain the relationship between the load and the displacement at the head of the pile. Instrumented load tests aim to obtain the load carried by the pile in each cross section, and, in particular, to separate the load carried by the pile base from the load carried by the pile shaft. These data are used to verify that the pile or shaft can carry the design load with an appropriate factor of safety, there are no major differences in behavior between piles, and the piles have been appropriately installed or constructed. Load tests may be performed in the design phase or during construction.

A typical arrangement for load-testing a pile is shown in Fig. 28.9 (ASTM D 1143). The figure refers to the most common load test performed, which involves the application of an axial compressive load using a hydraulic jack. (Testing under different loading conditions, such as tension or lateral loading, is also possible.) Load is applied in increments that are generally a constant fraction of the maximum applied load, which is either an estimate of the limit or plunging load or the design load multiplied by an appropriate factor of safety. The maximum load is maintained for a long time, following which the pile is completely unloaded in increments. Alternative loading protocols, in which loads are maintained for shorter times, are also possible, but do not provide the best estimates of long-term pile capacity.

Reaction is usually provided by two piles, which are installed on each side of the test pile, at a sufficient distance that they do not interfere (at least 5 to 8 pile diameters, according to Poulos and Davis [1990]). Alternatively, a weighted platform can also be used for reaction. The hydraulic jack or a load cell is used to measure the load applied at the pile head. A major concern is that the load is applied uniformly and with no eccentricity. For these purposes, steel plates of appropriate thickness are positioned on the pile cap and between the jack and the test beam and special care must be placed in centering the plates and the jack. For the same reason, spherical bearings particularly when a load cell is used should be used.

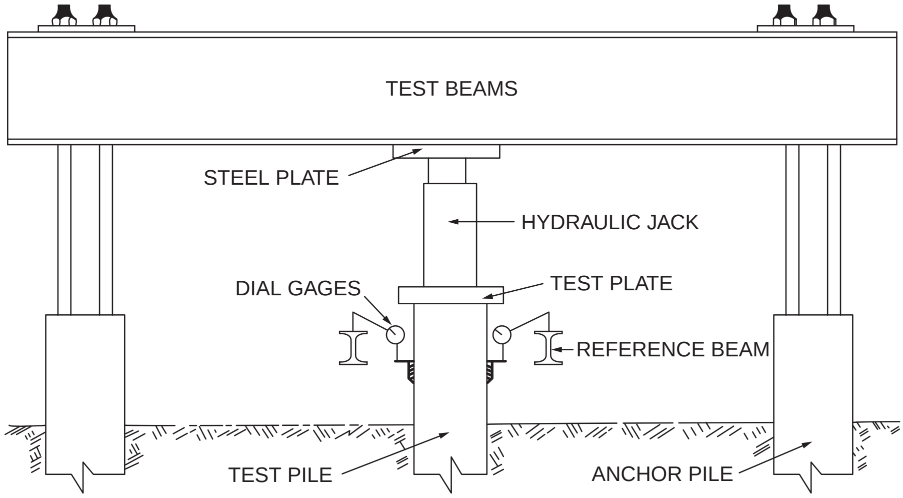

FIGURE 28.9 Set-up for pile static load test. (From ASTM D 1143 - 81 (Reapproved 1987). Standard method for piles under static compressive load. With permission.)

At least three dial gages or other devices for measurement of displacements (e.g., LVDTs) should be used to measure the displacement at the pile head with time, following the application of each load increment. Each sensor is affixed to a reference beam that should be protected from sunlight and temperature changes, and whose supports must be placed sufficiently far from the test and anchor piles so it does not move during the test. Measurements of the horizontal displacement of the pile cap are also recommended to verify that the load is properly applied.

Instrumented static load tests have the general objective of establishing the distribution of the load along the pile or drilled shaft, and determining what fraction of the applied load is carried by side friction and what fraction by base resistance for any given displacement of the pile head. To obtain the load distribution along the pile shaft, the axial strain at different depths is determined and then the axial stress and load are calculated with the appropriate modulus for concrete or steel based on the type of pile. The load carried by side friction between the surface and any depth is equal to the difference between the total load at the pile head and the normal load at the section of the pile at that depth. Measurement of the pile deformation can be accomplished by using telltales (Fig. 28.10), strain gages, or **Mustran cells** (Fig. 28.11) (Crowther, 1988). Telltales are particularly convenient for use in drilled shafts, in which they are installed inside polyvinyl chloride (PVC) tubes that isolate them from the surrounding concrete. This ensures that they will move freely and the displacement measured at the pile head with a dial gage (or other displacement sensor) will be equal to the displacement at the tip of the telltale. Dunnicliff (1988) raises a number of concerns regarding the use of telltales and suggests that they should not be used as the primary measurement system, but rather be used in combination with strain gages. Surface mounted strain gages are the most common solution for deformation measurement in the case of steel piles, while embedment strain gages are used for both concrete-driven piles and drilled shafts. The strain gages in these cases are attached directly to a rebar at appropriate intervals. A Mustran (multiplying strain transducer) cell consists of a short bar with a number of electrical resistance strain gages attached that are protected by a plastic sheath filled with an inert gas to avoid moisture intrusion. Mustran cells are occasionally used in instrumented tests of drilled shafts. Figure 28.12 shows how a Mustran cell or a telltale can be connected to a rebar before concrete placement. Note that strain gages and Mustran cells directly provide the strain at the location where they are mounted. In the case of telltales, an average strain between two telltale tips is computed from the ratio in the difference in displacements to the difference in depths.

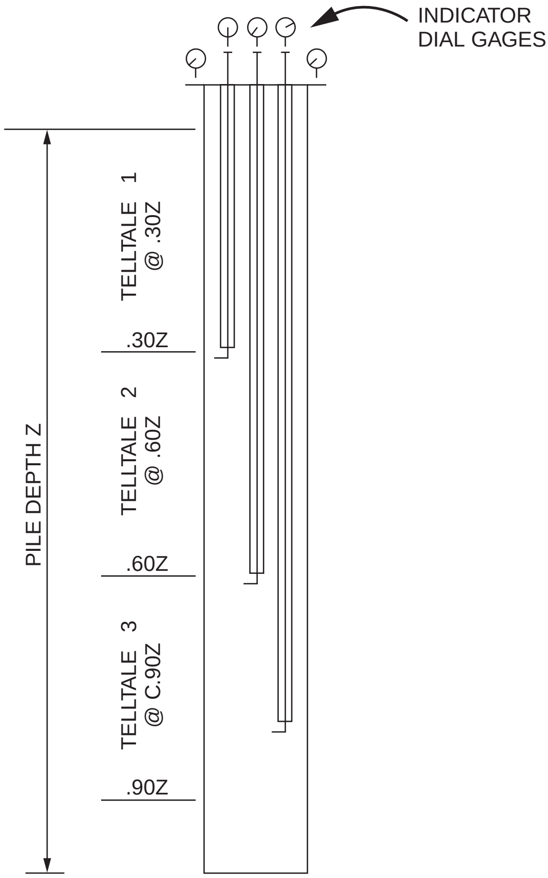

FIGURE 28.10 Possible arrangement of telltales to determine load distribution along shaft of a drilled shaft. (From Crowther, C.L. 1988. *Load Testing of Deep Foundations*. John Wiley & Sons, New York. With permission.)

For open-ended pipe piles, base capacity is due to both annulus and plug resistances, and in large projects, with a large number of piles, it may be attractive to accurately separate the two. Paik et al. (2002) describe in detail how this can be accomplished though the use of logically placed strain gauges.

Defining Terms

Benchmark — reference for measurement of vertical displacements using surveying methods.

Borehole extensometer — a device used to monitor the change in distance between two or more points along the axis of a borehole.

Bourdon pressure gage — a gage for measuring hydraulic pressure, consisting of a curved tube that, when pressurized, uncoils by an amount directly related to the pressure.

Electrical resistance strain gage — a conductor whose electrical resistance changes as it is deformed.

Extensometer — a device that gives the distance between two points (see also surface extensometer and borehole extensometer).

Inclinometer — device used for measuring lateral displacement that runs down inside a cased borehole.

***In-situ* tests —** tests performed to determine soil properties in the field.

Instrumentation — the collection of devices and the way they are arranged and linked to measure quantities deemed of interest in a particular project.

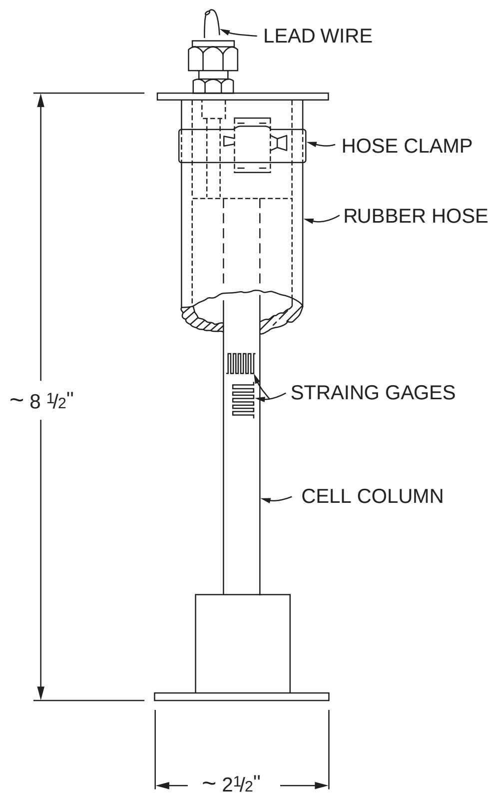

FIGURE 28.11 Mustran cell. (From Crowther, C.L. 1988. *Load Testing of Deep Foundations*. John Wiley & Sons, New York. With permission.)

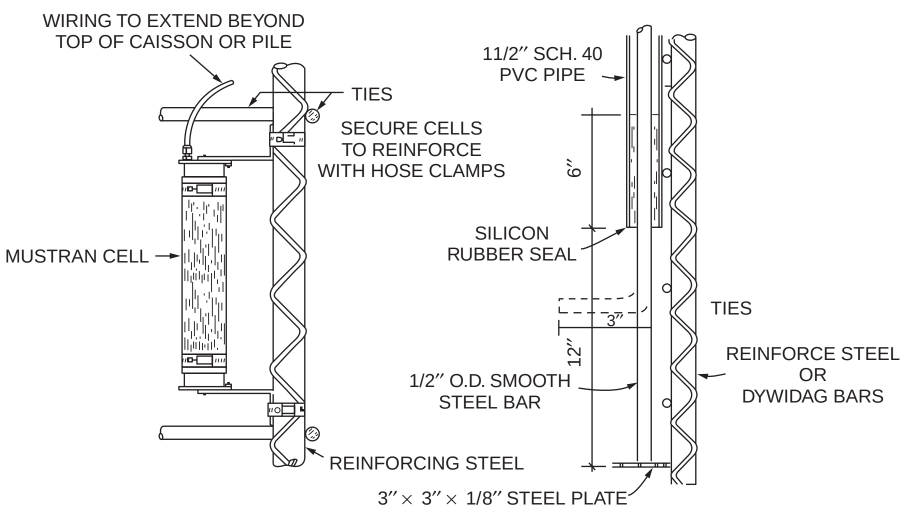

FIGURE 28.12 Attachment of Mustran cell or telltale to rebars in a drilled shaft. (From Crowther, C.L. 1988. *Load Testing of Deep Foundations*. John Wiley & Sons, New York. With permission.)

Instrumented static load tests — when said of a deep foundation, the measurement of displacements or strains at different levels in the deep foundation element as load is applied at the pile head (see also static load tests).

Load cells — devices used to measure load.

LVDT — the linear variable differential transformer, a device consisting of a central magnetic core and two coils used to measure displacements.

Manometer — a U-tube filled with two fluids, used to measure the pressure at their interface.

Measuring points — points where measurements are to be taken using surveying techniques.

Mustran cells — multiple strain transducers cells, devices consisting of a bar with strain transducers attached, used to obtain strain measurements inside drilled shafts or concrete piles.

Piezometer — device used to measure hydraulic pressure.

Pressure cell — cell used to measure total stresses inside a soil mass or at soil-concrete or soil-steel interface.

Reference monument — a reference for horizontal displacement measurements.

Sensor — a device that allows the measurement of a certain quantity at a point.

Settlement plate — plate that is embedded in a soil mass at a depth where the vertical displacements are to be determined.

Static load test — when said of a deep foundation, the measurement of the displacement at the pile head corresponding to a sequence of loads applied also at the pile head.

Strain gage — a gage used to measure strain (term is often used to refer to an electrical resistance strain gage – see definition above).

Surface extensometer — a device used to monitor the change in distance between two points located on the surface of the ground or of a structure.

Telltale — a steel rod or bar placed inside a structure, whose purpose is to determine the displacement at the location where its tip is located.

Tiltmeter — a device to measure the rotational component of a displacement.

Transducer — a device that transforms one energy type (such as mechanical) into another (such as electrical or pneumatic).

Vibrating wire transducer — a transducer that relies on measuring the natural frequency of a tensioned wire to determine a strain.

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Further Information

Books

The books by Dunnicliff, Hanna, and Hunt are excellent references to devices and procedures of field instrumentation. Pile load tests are better addressed in more specific publications, such as Crowther's book. For instrumentation of dynamic or vibratory problems, a good starting point is Richart et al. There has been much recent research on the interpretation of *in situ* tests, so it is best to review recent journal papers if that is the specific interest.

ASTM has standards for the use of many of the devices discussed in this chapter. A volume is published every year with standards for geotechnical engineering.

Journals

Geotechnical engineering journals are a good source for new improvements in the instruments and techniques, as well as for case histories where instrumentation has been used. Journals in English include the *Journal of Geotechnical and Geoenvironmental Engineering* of ASCE, *Géotechnique* of the Institute of Civil Engineers of Great Britain, *The Canadian Geotechnical Journal*, the *Journal of Soil Testing* of ASTM, and *Soils and Foundations* of Japan. Some foreign journals publish papers both in the native language of the country where the journal is published and in English. The *Rivista Italiana di Geotecnica* of Italy and *Solos e Rochas* of Brazil often carry interesting papers on *in situ* tests and field instrumentation.

Catalogs and Other Publications by Manufacturers

Catalogs and other publicity material of companies manufacturing instruments, as well as reference manuals for the instruments, are a good source of information, general and specific. Some companies manufacturing instrumentation devices include the Slope Indicator Company (Sinco) of Seattle, Washington; Durham Geo of Stone Mountain, Georgia; Geokon of Lebanon, New Hampshire; Geotest of Evanston, Illinois; Omega of Stamford, Connecticut; Phoenix Geometrix of Mountlake Terrace, Washington; and Dresser Industries of Newtown, Connecticut.

Also of interest are periodicals such as Experimental Stress Analysis Notebook of the Measurements Group, Inc., of Raleigh, North Carolina. They carry current information on transducers and other devices, as well as articles on the general subject of instrumentation and materials testing.