Chapter 10
Instrumentation

10-1. Scope

This chapter provides general guidance for the selection and use of instrumentation to monitor cut slopes such as might be necessary for the construction of rock foundations and roads as well as structures founded on rock such as dams, lock walls, and retaining structures. Instrumentation for monitoring ground vibrations, water levels, and pore-water pressure measurements are discussed in more detail than other instrumentation because of their widespread use. The limitations as well as data interpretation and evaluation considerations are also discussed. Detailed descriptions and installation considerations, of the various types of instrumentation discussed herein, can be found in the referenced publications. The chapter is divided into four sections as follows: Planning Considerations; Typical Applications; Types of Instruments; and Data Interpretation and Evaluation.

Section I
Planning Considerations

10-2. General

Instrumentation is necessary on a project to assure that design criteria are being met, thereby assuring the safety of the structure, gain information valuable to future project design, monitor suspected problem areas to determine safety and remedial measures required, and monitor effectiveness of remedial measures.

10-3. Program Initiation

An instrumentation program should be planned during the design of a project. The specific areas and phases of the project from which data need to be gathered are determined using the rock mechanics analyses and models discussed in previous chapters. In order to obtain the most complete picture of how a rock mass is responding to the construction and operation of a project, instrumentation should be installed where possible before or during construction. Early installation rarely increases the cost of the instrumentation program, but does require more planning.

10-4. Cost Control

The instrumentation program should be well planned to assure that all necessary data will be collected and that excessive costs are not incurred. The main expenses of an instrumentation program include instrument purchase, installation, maintenance, data gathering, and data interpretation. Excessive costs in each of these areas are incurred if instrument types and placement are planned unwisely leading to more instrumentation than is necessary for the intended purpose or difficulty in interpreting data due to lack of information. The instrumentation program must be flexible enough to allow for changes necessary due to actual conditions encountered during construction.

10-5. Types and Number of Instruments

The parameters which are most often measured are deformation, load/stress, pore-water pressures and water levels, and ground vibrations. The types of instrumentation used to measure these parameters are listed in Table 10-1. The number of instruments and various types that will be required on a specific project are dependent on the purpose of the structure and the geologic conditions. The instrumentation program for every project should be designed specifically for that project and the expected conditions and should use the principles of rock mechanics. Rock instrumentation must reflect conditions over a large area of rock. Measurements made over small areas will yield data so influenced by small random features that it will be meaningless. Great care should be taken to assure that the particular instrumentation used will yield the type of information required at the necessary accuracy. An instrumentation program should be kept as simple as possible and still meet the objectives of the

Table 10-1
Types of Rock Foundation Instruments

Deformation	Load/Stress	Pore-Water Pressure	Ground Vibration
Surveying Inclinometers Extensometers Settlement Indicators Heave Points	Load Cells Piezometers Uplift Pressure Cells	Piezometers	Seismographs

program. A complicated instrument is generally harder to maintain and less reliable than a simple type. Simple, direct measurements are most easily and quickly interpreted.

Section II
Applications

10-6. General

This section describes some of the more common applications of rock mechanics instrumentation. The discussions are divided into two general topic areas related to project features addressed in this manual. These two topic areas include cut slope instrumentation and structure/foundation instrumentation.

10-7. Cut Slope Instrumentation

The number, types, and location of instruments used in cut slopes are highly dependent on the cut configuration, the geologic conditions that are involved, and the consequence should a failure occur. As a rule, however, instrumentation associated with cut slopes can be grouped into instruments used to make surface measurements and those used to make subsurface measurements.

a. Surface measurements. Surface measurement instruments are primarily used to measure surface deformations. Since surface instrumentation reveals little as to underlying mechanisms causing deformation, the instrumentation is used to detect new areas of distress or precursor monitoring of rock masses subject to impending failure. The degree of precision required by the intended purpose of instrumentation dictates the type of instrument used to measure deformation.

(1) Surveying. If the slope is stable, then periodic surveying of the floor and sidewalls using permanent monuments and targets may be the only instrumentation required. Precise, repetitive surveying of a network of such survey points is a relatively inexpensive method of detecting slope movement, both vertical and lateral. When a problem is detected, surveying can be used to define the area of movement. Evaluation of problem areas is required to determine if additional instrumentation is required. Depending on other factors, surveying may be continued, perhaps with increasing frequency, until remedial measures appear to be inevitable. In other cases, the failure of the slope may be more acceptable than the cost of the remedial measures and surveying would be continued until the slope failed, to insure the safety of personnel and equipment when failure occurs. Details of the instruments and surveying methods used may be found in TM 5-232, “Elements of Surveying” and TM 5-235, “Special Surveys.”

(2) Surface deformation. In most cases, however, additional instrumentation will be required to provide the information which enables the investigator to find or to define the causes of the movement and to monitor the rate of movement. Tension cracks which appear at the crest of a slope or cut face may be monitored by surface type extensometers. This type of extensometer generally consists of anchor points installed on either side of the zone to be monitored. The zone may be one joint or crack or several such features. A tape or bar, usually composed of invar steel, is installed between the anchor points. A Newcastle extensometer may be installed on the tape to allow for very accurate readings which are necessary to measure the small initial indications of movement. For measuring larger movements, which would occur later and when continuous measurements are required, a bar and linear potentiometer can be installed between the stakes. See Chapter 8 of the Canada Centre for Mineral and Energy Technology (1977b) for details. If very large measurements are expected, a simple inexpensive system, which uses a calibrated tape to measure the change in distance between the two anchor points should be used. The tape can be removed after a reading is made. This instrument aids in the determination of the surface displacement of individual blocks and differential displacements within an unstable zone. Dunnicliff (1988) provides an excellent review of the various types of surface monitored extensometers.

b. Subsurface measurements. Subsurface instrumentation provides greater detail of mechanisms causing distress. Because subsurface instruments require installation within a borehole and the cost associated with such installations, their use is typically limited to monitoring known features of potential instability or to investigate suspected features. Subsurface deformation measurements monitor the relative movement of zones of rock with respect to each other. Piezometric pressure measurement along zones of potential instability monitor the influence of ground water with respect to stability.

(1) Subsurface deformations. Subsurface deformations within rock slopes are commonly measured with one of two types of downhole instruments, inclinometers, or borehole extensometers.

(a) Inclinometers are installed behind the slope, on flat slopes where drilling access is available, or into the slope and are bottomed in sound, stable rock. Successive measurements of deflections in the inclinometer are used to determine the depth, magnitude, and rate of lateral movement in the rock mass. While commonly installed in vertical boreholes, inclinometers are available that allow installation in inclined to horizontal boreholes. Because successive deflection measurements can be made at small intervals, the device is ideally suited to precisely locate and define as well as monitor zones of instability. Detailed descriptions of inclinometers can be found in EM 1110-2-1908 (Part 2), “Instrumentation of Earth and Rock Fill Dams” and Dunnicliff (1988).

(b) Borehole extensometers are often placed into the face of a cut or slope to help in determining the zones behind the face which are moving. When a deep cut is being made, extensometers may be installed in the walls as the excavation progresses to monitor the response of the slope to an increasing excavation depth. Multiposition borehole extensometers (MPBX), rod or wire, are able to monitor relative movement of a number of different zones at varying distances behind the cut face. Such measurements help to determine which zones are potentially critical and rate of movement. MPBX’s are particularly helpful in distinguishing between surficial and deep-seated movement. Extensometers may be equipped with switches that automatically close and activate warning devices when a preset movement limit is reached. Unless care is taken to isolate downhole wires or rods, installations at great depths are not always practical due to the difficulty of obtaining a straight borehole. It is necessary to eliminate, as much as possible, the friction effects between the extensometer wire or rod and the borehole wall. Friction effects can introduce large errors which make interpretation of the data impossible. The maximum measurable deformation is relatively small ranging from approximately 0.5 to several inches, but this limit can be extended by resetting the instrument. Extensometers are described in EM 1110-2-1908, Part 2 and Dunnicliff (1988).

(2) Piezometric pressure. Drainage of a cut slope is often necessary to increase its stability by reducing pore-water pressures in the slope. The effectiveness of any drainage measure should be monitored by piezometers. Piezometer data should also be used to determine when maintenance of a drainage system is necessary. Piezometers should be installed during site investigation activities to determine the ground-water system. Preconstruction installation is important not only for design of the project but also to determine if construction will adversely affect nearby ground-water users. Data should be obtained before, during, and after construction so that a cause-affect trend can be determined, if there is one. This information is very important if there are claims that conditions in nearby areas have been changed due to activities at the project. Piezometers are discussed in Section III, of this manual.

(3) Anchor loads. When the instruments discussed above indicate that remedial measures such as rockbolts are necessary to stabilize a slope, then these same instruments are used to monitor the effectiveness of the remedial measures. The actual load or tension acting on a rockbolt is monitored with a load cell. This information is to assure that bolts are acting as designed and that the maximum load on the bolt is not exceeded. A representative number of bolts in a system are usually monitored. The types of load cells include the hydraulic, mechanical, strain gaged, vibrating wire, and photoelastic. The strain-gaged load cell is the type most often used to monitor rockbolt systems. Load cells are described in the Rock Testing Handbook as well as Dunnicliff (1988).

10-8. Foundation/Structure Instrumentation

As in the case of cut slopes, foundations and structures such as dams, lock walls, and retaining structures may require a large number and variety of instruments. These instruments are frequently similar or the same as those required for slope monitoring and are divided into three general categories dependent upon what observation is being measured. The three categories include deformation measurements, piezometric pressure measurements, and load/stress measurements.

a. Deformation measurements. Deformations of foundations and structures are generally observed as apparent translation, rotation, or settlement/heave. Apparent deformations may actually be the result of a combination of the above deformation modes.

(1) Translation. Translation deformations caused by foundation/structure interactions are generally apparent as sliding along planes of weakness. It is essential to define the planes along which translation occurs and evaluate the severity of the problem at an early stage. Translation measurements of foundations and structures are generally monitored with subsurface techniques discussed under cut slope instrumentation.

(2) Rotation. A tiltmeter may be used to determine the rate, direction, and magnitude of angular deformation which a rock mass, a structure, or a particular block of rock is undergoing. A tiltmeter, unlike an inclinometer, measures only at a discrete, accessible point. The device may be permanently buried with a remote readout or may

be installed directly on the rock or structure surface. If there is weathered rock at the surface, the device may be mounted on a monument which is founded in or on intact rock. The tiltmeter consists of a reference plate, which is attached to the surface that is being monitored, and a sensing device. A portable sensing device may be installed on the reference plate for each reading or a permanent, waterproof housing containing the sensing device may be installed directly on the surface to be monitored. In the second case, readings may be made from a remote readout station. Tiltmeters may also be installed directly on a structure. Tiltmeters are described in more detail in the Rock Testing Handbook and Dunnicliff (1988).

(3) Settlement/Heave. Settlement refers to compression of the foundation material whereas heave refers to expansion. Mechanisms that cause settlement are discussed in Chapter 5. Mechanisms which cause heave were also briefly discussed in Chapter 5, but are discussed in greater detail in Chapter 12.

(a) Settlement of a foundation beneath a structure may be determined by repeated surveying of the elevation of a settlement gage monument installed directly on the foundation and protected from frost and vandalism. Points on the structure itself may likewise be surveyed to determine settlement, especially if direct access to the foundation is not possible. Settlement indicators may also be used to measure settlement. Settlement indicators are capable of measuring single or multiple points and operate on the same principle as a manometer. In areas beneath buildings or other areas where direct access to the instrument is not available, a remotely read instrument may be used as described by Hanna (1973). The instrument is installed in the foundation before the structure is built. The elevation of the measuring point is calculated using the elevation of the readout point and a pressure reading at the measurement point. The original elevation of the measuring point must be determined for comparisons to later readings.

(b) The floor of an excavation may require monitoring for heave or rebound. Heave is not common in all rock or foundation conditions. Heave measurements give valuable information for use in design of other structures in similar rock masses and conditions. These measurements are also important to correlate performance with design assumptions, especially when the foundation is to support precise industrial or scientific equipment where little departure from the design criteria can be tolerated. Heave points are the most common technique used to measure rebound during excavation. Heave points usually consist of an anchor point that is placed in a borehole at or below the expected elevation at the bottom of the excavation. The elevation of the anchor is determined. The drill hole is filled with a bentonite slurry which contains a dye to aid in relocating the instrument hole during construction. As excavation proceeds, a probe of known length is lowered to the top of the anchor point and the elevation of the anchor point is determined by optical leveling. An alternative method uses a linear potentiometer as the sensing element in the borehole. This type of settlement gage is described by Hanna (1973). Settlement/heave gages are also described in EM 1110-2-1908 (Part 2) and Dunnicliff (1988). The method used for anchoring the reference point to the rock and protection of the instrument during construction are important considerations.

b. Piezometer pressure measurements. As in rock slopes, piezometers are often installed during site investigations and monitored to determine preconstruction conditions. A thorough understanding of the preconstruction conditions is very important not only for determining the effects of such conditions, especially seasonal variations, on the construction and operation of the structure but also for determining the effects of the structure on the groundwater flow system. Dewatering activities, construction of ground-water cutoffs, and reservoir filling may affect local ground-water elevations and flow systems at some distance away from the project possibly producing adverse affects. Once construction begins, piezometers that are not destroyed should continue to be monitored. This information can be used as an indication of how groundwater conditions and pore pressures change due to various construction activities such as removal of overburden or the added weight of the structure. Additional piezometers are installed when the structure is finished to monitor the performance of cutoffs and drainage systems as well as to measure pressures in the foundation underneath a structure or in abutments. The flow rate through the drainage system should be measured as another method of monitoring its performance. Unexplained changes in seepage rates may warn of a serious problem even before it is reflected by piezometer or other instrumentation data. Calibrated weirs or simply a stopwatch and calibrated container for lower flows are commonly used to measure drain flows. Other critical areas should also be instrumented as determined during design. Piezometers are described in more detail in Section III.

c. Load/stress measurements. Instrumentation is frequently required to check design assumptions relating to stress distributions caused by rock/structure interactions as well as to monitor zones of potential distress.

Measurements of stress change in a foundation are made with earth pressure cells which may be installed at the interface of the structure and the rock or in a machined slot within the rock mass. Three commonly used pressure cells, to include vibrating wire, hydraulic (Gloetzl) and WES (similar to Carlson stress meter) type cells, are discussed in EM 1110-2-4300. It is necessary to install a piezometer near a pressure cell to isolate earth pressure changes from pore-water pressure changes. Pressure cells must be installed carefully to eliminate error caused by small localized stress concentrations.

d. Combined measurements. As discussed in Chapter 5, settlement or heave frequently is not uniformly distributed across the foundation. In such cases it may be necessary to monitor the effects of both settlement/heave and structural rotation. Instruments capable of monitoring these combined effects include plumb lines, inverted plumb lines and optical plummets. These devices are thoroughly discussed in EM 1110-2-4300.

Section III
Types of Instruments and Limitations

10-9. General

Section II discussed the general application of a number of different types of instruments commonly used to monitor the performance of cut slopes and foundation rock/structure interactions. References were given that provided detailed descriptions, installation procedures, and limitations as well as advantages and disadvantages of various devices. This section will address two specific types of instruments, piezometers and ground motion/vibration monitoring devices. Piezometers have been mentioned previously but will be covered in greater detail here. Ground motion devices, considered to be location/site specific devices, will be briefly discussed in this section.

10-10. Piezometers

Piezometers are used to measure pore-water pressures and water levels in the natural ground, foundations, embankments, and slopes. Piezometers are also used to monitor the performance of seepage control measures and drainage systems and to monitor the affect of construction and operation of the project on the ground-water system in the vicinity of the project. There are three basic types of piezometers: open-system (open standpipe), closed-system (hydraulic), and diaphragm (pneumatic and electrical, e.g., vibrating wire). The operation, installation, and construction of these piezometers are covered in detail in EM 1110-2-1908. The basic criteria for selecting piezometer types are reliability, simplicity, ruggedness, and life expectancy. Other considerations are sensitivity, ease of installation, cost, and the capability of being monitored from a remote observation point. Sometimes two or more types of piezometers may be required to obtain the most meaningful information at a particular site. One of the most important factors to be considered is the impact of hydrostatic time lag on the intended use of the piezometer data. Table 10-2 compares the different types of piezometers.

a. Open-system piezometers. Open-system piezometers are the simplest types of piezometers but they are also subject to the greatest hydrostatic time lag. They are best used in areas where slow changes in pore-water pressure are expected and the permeability is greater than 10^{-5} cm/sec. If rapid pore water pressure changes are expected, then open-system piezometers should only be used if the permeability is greater than 10^{-3} cm/sec (EM 1110-2-1908, Part 1 of 2).

b. Closed-system piezometers. The rate of pore-water pressure changes has little effect on the measurements obtained with this type of piezometer. This type is commonly used to measure pore pressures during construction of embankments. The readout can be directed to a central location so that there is little interference with construction. However, the device must be checked often for leakage and the presence of air. Open-system piezometers should be installed near key closed-system piezometers to provide a check on the operation of the closed-system piezometer.

c. Diaphragm piezometers. Diaphragm piezometers can be used in the same situations as open and closed system piezometers. They are very sensitive to pore-water pressure changes and the elevation difference between the piezometer tip and the readout point is not a limiting factor. The electrical diaphragm piezometer is complex and may be subject to instrument “zero” drift after calibration and installation, short circuits in the lead cable, stretch and temperature effects in long lead cables, and stray electrical currents.

10-11. Ground Motions/Vibrations

Ground motions/vibrations which can affect a rock foundation may be caused by earthquakes or blasting. Controlled blasting techniques, as discussed in Chapter 11, are used to minimize damage to foundations and adjacent

Table 10-2
Comparison of Piezometer Types

Basic Type	Relative Volume Demand	Readout Equipment	Advantages	Disadvantages
Open-System (standpipe)	High	Water Level Finder	Simple; comparatively inexpensive; generally not subject to freezing; relatively long life; fairly easy to install; long history of effective operation.	Long time lag in most rock types; cannot measure negative pore pressure; cannot be used in areas subject to inundation unless offset standpipe used; must be guarded during construction; no central observation station is possible; requires sounding probe. Must be straight; difficulties possible in small diameter tubes if water levels significantly below 100 feet, or dip less than 45 degrees.
Closed-System (hydraulic)	Medium to low	Usually Bourdon gauge or manometer	Small time lag; can measure negative pore pressures; can be used in areas subject to inundation; comparatively little interference with construction; can be read at central observation stations.	Observation station must be protected against freezing; fairly difficult to install; fairly expensive compared to open systems; sometimes difficult to maintain an air-free system; most types are fragile; some types have limited service behavior records; requires readout location not significantly above lowest water level.
Diaphragm	Low to negligible	Specialized pressure transmitter or electronic readout	Simple to operate; elevation of observation station is independent of elevation of piezometer tip no protection against freezing required; no de-airing required; very small time lag.	Limited performance data, some unsatisfactory experience; some makes are expensive and require expensive readout devices; fragile and requires careful handling during installation.
			Pneumatic. Electrical source not required; tip and readout devices are less expensive than for electrical diaphragm types.	Often difficult to detect when escape of gas starts; negative pressures cannot be measured; condensation of moisture occurs in cell unless dry gas is used; requires careful application of gas pressure during observation to avoid damage to cell.
			Electrical. Negative pressures can be measured; ideal for remote monitoring.	Devices subject to full and partial shortcircuits and repairs to conductors introduce errors; some makes require temperature compensation and have problems with zero drift to strain gages; resistance and stray currents in long conductors are a problem in some makes; zero drift possible.

Note:
1. Modified from Pit Slope Manual, Chapter 4, 1977 and EM 1110-2-1908 (Part 1).

structures caused by blasting. Seismographs should be used to monitor the levels of vibration actually being produced. Seismograph records (seismograms) are also used to provide a record of vibrations to assure maximum levels are not exceeded which could cause damage to adjacent structures. Seismograph is a general term which covers all types of seismic instruments that produce a permanent record of earth motion. The three main types of seismographs measure particle displacement, velocity, and acceleration. The instruments used in different applications are discussed below.

a. Earthquakes. Measurement of earthquake motion assists in damage assessment after a significant earthquake and is necessary for improving the design of structures, especially dams, to better resist earthquakes. Guidance is given in EM 1110-2-1908 for determining which structures require instrumentation. The strong motion accelerograph and peak recording accelerograph are the principal instruments used to record earthquake motions on engineering projects such as dams. The accelerograph measures particle acceleration in any direction or directions desired. The strong motion instruments generally record seismic motion between 0.01 g and 1.0 g. They are triggered by the minimum level of motion and record continuously during any motion above a preset minimum level and for a short time after motion ceases. The peak accelerograph records only the high amplitudes of the acceleration and does not make a continuous recording. This low cost instrument is used only to supplement data from other accelerographs. One or two strong motion accelerographs may be located on a project and several peak accelerographs may be located in other areas to obtain an idea of how the acceleration differs across the site. EM 1110-2-1908 provides additional discussions.

b. Blasting. As discussed in Chapter 11, construction blasting should be controlled in order to reduce damage by ground vibrations to the foundation being excavated and to nearby structures. Seismographs are used to monitor the ground vibrations caused by blasting. The peak particle velocity is normally used as an indication of potential damage, therefore, a velocity seismograph is normally used in engineering applications. The particle velocity can be inferred from the information obtained by other types of seismographs but it is preferred to measure it directly so that an immediate record is available without extensive processing. EM 1110-2-3800, the *Blaster's Handbook* (Dupont de Nemours and Company 1977), and Dowding (1985) provide additional instrument descriptions.

10-12. Limitations

There are certain requirements by which all types of field instrumentation should be evaluated. These include the range, sensitivity, repeatability, accuracy, and survivability of the instrument. The range must be adequate to measure the expected changes but not so great that sensitivity is lost. It is not always possible to accurately predict the magnitude of loads and deformations to be expected before construction. The most important of these factors may be repeatability because this factor determines the quality of the data. The sensitivity required will vary with the application. Good sensitivity is required for early detection of hazards but may mean a reduction in the range and stability of the instrument. If an instrument with too narrow a range is chosen, all the necessary data may not be obtained. If an instrument with too large a range is chosen, then it may not be sensitive enough. Accuracy is difficult to define and to demonstrate. The anisotropy of a parameter must be predictable if the accuracy is to be determined. Calibration, consistency, and repeatability are also used in determining accuracy. The instrument chosen for a particular application must also be able to survive the often severe conditions under which it will be used. Cost should also be considered and the least expensive way of obtaining good quality information should be used. Table 10-3 provides a summary of some of the major limitations of the various types of instrumentation that have been discussed. Ranges and sensitivities for different instrument types may vary between manufacturers and may change rapidly due to research and development and so are not listed in this table. Many of the instruments are also easily modified by a qualified laboratory to meet the requirements of a particular job.

Section IV
Data Interpretation and Evaluation

10-13. Reading Frequency

The frequency at which instrument readings are taken should be based on many factors and will vary by project, instrument type, availability of government personnel to take readings, and location and may even vary through time. The availability of government personnel to take the readings should be determined during the preparation of plans and specifications. If government personnel will not be available, provisions should be made to have this task performed by the construction contractor or by an A-E contractor. Some of the factors which should be evaluated include outside influences such as construction activities, environmental factors (rainfall events, etc.), the complexity of the geology, rate of ground movements, etc. Several sets of readings should be taken initially to establish a baseline against which other readings are to be evaluated. Daily or even more frequent readings may be necessary during certain construction activities, such as fill placement or blasting. The rate of change of the condition which is being monitored may vary over time, dictating a change in the established frequency at which readings are taken. For example, an unstable slope may move slowly at first, requiring infrequent readings on a regular basis until a near failure condition is reached, at which time readings would have to be taken much more frequently. Readings of different types of instruments should be made at the same time. Concurrent readings enables the interpreter to take into account all the factors which might impact individual readings of specific parameters. For example, an increase in pore water pressure might coincide with increased slope movement. Standard forms should be used to record data when available, or if

Table 10-3
Limitations of Rock Instrumentation

Instrument	Measured Parameter	Limitations
Inclinometer	Deformation	Life may be limited in hard rock due to sharp edges. Significant drilling costs.
Tiltmeter	Deformation	Measures one, near-surface discrete point. Subject to damage during construction. Difficult to detect spurious data. Must be protected from the environment. Subject to errors caused by bonding material.
Extensometers	Deformation	
Bar Single Point		Does not distinguish between deep-seated and surficial movement. Limited accuracy due to sag. Measures only one point. Significant drilling costs, a new drill hole required for each detection point.
Multipoint Rod Multipoint Wire		Limited to approximately 50-foot depth if each rod is not individually cased within the instrument hole. Experienced personnel should install them. May be damaged by borehole debris unless protected. Spring anchors may experience variable spring tension due to rock movement.
Settlement Indicators	Deformation	Hydraulic types require de-aired water. Corrections for temperature and barometric pressure differences are required. Access to drill collar is required for some types.
Heave Point	Deformation	Accuracy is limited by surveying techniques used.
Load Cells	Stress, Load	
Hydraulic		Large size, poor load resolution, temperature sensitivity.
Mechanical		Nonlinear calibration curves.
Strain Gage		Requires waterproofing, long term stable bonding method and periodic recalibration.
Vibrating Wire		Large size, expensive, poor temperature compensation, complicated readout, vulnerable to shock.
Photoelastic		Coarse calibration. Requires access to borehole collar.
Piezometers	Load, Stress	See Table 10-2.
Uplift Cells	Deformation	
Standpipe		Readings may require either of two methods, sounder or pressure gage.
Diaphragm		Susceptible to damage during installation.

not, then forms should be developed for specific instruments. Some forms are shown in EM 1110-2-1908. If possible, data should be reduced in the field and compared with previous readings so that questionable readings can be checked immediately. When large amounts of data must be managed, automatic recording devices that record data as printed output or on magnetic tape for processing by computer should be considered. Too many readings are not necessarily better than too few. An excess of data tends to bog down the interpretation process. A thorough evaluation of the purpose of the instrument program must be used to determine the optimum rate at which readings should be taken, thus assuring that data are obtained when it is needed.

10-14. Automatic Data Acquisition Systems

Automatic data acquisition systems and computer data processing are very popular for obtaining and processing instrumentation data. Computer programs are available for reducing and plotting most types of data. Some of the advantages and disadvantages of these systems are given by Dunnicliff (1988). Use of computer processing can speed much tedious processing but should not replace examination of all of the data by an experienced person.

10-15. Data Presentation

Most types of data are best presented in graphical form. Graphical presentation facilitates the interpretation of relationships and trends in the data. Readings are compared over time and with other instrument readings as well as compared with construction activities and changing environmental conditions. Observed trends should be compared with predicted trends to make an assessment of overall performance. The data should be displayed properly or significant trends may be obscured or may become misleading. A thorough knowledge and understanding of the instrumentation as well as some trial and error is required to successfully accomplish good data presentation. Cookbook interpretation methods are available for some types of data such as that from inclinometers. Cookbook interpretation is discouraged. Every instrument should be carefully and impartially analyzed by experienced personnel, taking all the available information into consideration.

10-16. Data Evaluation

Factors to consider when evaluating instrumentation data include instrument drift, cross sensitivity, calibration, and environmental factors such as temperature and barometric pressure. Instrument drift is the change in instrument readings over time when other factors remain constant. Drift can be caused by temperature fluctuations, power supply instability (weak battery), etc. If drift is not detected, it can lead to erroneous data interpretation. Periodic calibration of instruments when possible, can reduce drift problems. Making repetitious readings also helps to detect and account for drift errors. Field calibration units may be available for some instrument types such as inclinometers. Most instrumentation can be isolated from effects caused by changing environmental conditions through the use of protective housings or relatively inert material. Invar steel is one material that is not greatly affected by temperature change. Where protective measures have not been used, environmental effects must be taken into account or the data may not be useful. Additional information on data processing and presentation may be found in EM 1110-2-1908, Rock Testing Handbook, Hanna (1973) and Dunnicliff (1988).

10-17. Data Use

An instrumentation program can easily fail if the obtained data is never understood and used. A clear understanding of the purpose of the program is necessary for understanding of the data obtained. Some idea of the behavior that is expected of the structure, usually developed during design and adjusted during construction, is necessary in order to evaluate the actual behavior. This predicted behavior is the starting point from which all interpretations are made. With these ideas in mind, instrumentation data should prove to be a helpful tool in clearly understanding and evaluating the behavior of any rock foundation or slope.