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Chapter 11
INSTRUMENTATION

11.1 GENERAL

11.1.1 Overview

There are two general categories of geotechnical instrumentation used on MDT projects:

- The first category is subsurface investigations to determine soil or rock properties (e.g., strength, compressibility, permeability) and normally occurs during the exploration phase of the project. These instruments include cone penetrometers, pressuremeters and groundwater monitoring systems and are discussed in Chapter 8.

- The second category is for monitoring soil and rock performance and normally occurs during the construction or the operational phase of a project. In addition, it is also possible to use performance-monitoring instruments as part of the design. Performance monitoring during construction can involve measuring groundwater levels or porewater pressures, soil stresses, soil or rock deformations and load or strain in structures. Instrumentation monitoring during design can include the construction of test fills to obtain information about settlement properties at a site, or pile-load tests to address significant issues regarding the constructability or the performance of piles in a specific geologic formation.

This Chapter focuses on the second category of measuring instruments. The following Sections summarize the general role of geotechnical instrumentation on MDT projects, possible types of instrumentation, factors that should be considered during the instrumentation planning process and interpretation and report requirements.

11.1.2 General Role of Geotechnical Instrumentation

Every geotechnical design involves uncertainties and every construction job involving soil or rock runs the risk of encountering surprises because of uncertain soil conditions or soil behavior. These circumstances are the result of working with materials created by nature, which seldom provides uniform conditions. The inability of exploratory procedures to detect all possible properties and conditions of natural material requires the project geotechnical specialist to make assumptions and select equipment and construction procedures without full knowledge of what might be encountered. Field instrumentation can reduce these uncertainties and can aid in the selection of appropriate field equipment and construction procedures.

11.1.2.1 Need For and Objectives of Geotechnical Instrumentation Program

Information from a geotechnical instrumentation program provides the project geotechnical specialist with data that can be used to design reliable and efficient projects. Therefore, field instrumentation is vital to the practice of geotechnical engineering. The success of the field instrumentation program is tied to development of well-defined needs and specific objectives for collecting and interpreting the field instrumentation information.

During design, use field instrumentation monitoring for a variety of purposes, including the following:

- definition of initial site conditions,
- data for back calculating soil parameters,
- establish the behavior of geologic formations when loaded or unloaded,
- confirmation of foundation response through performance or proof testing, and
- fact finding at a failure or emergency situation.

Advanced planning is required to meet these design objectives. The planning process includes selection and installation considerations and establishing a budget for installation and interpretation of the instrumentation. For other than emergencies, it is often difficult to obtain sufficient funding to cover the cost of the field instrumentation before construction. Consequently, the instrumentation program is often deferred to the construction phase of a project. In this case, the objectives change from evaluating performance to confirmation of engineering assumptions or design methods.

The most common deployment of field instrumentation monitoring is during construction. In this case, use instrumentation to address the following:

- safety,
- validate engineering design assumptions,
- construction control,
- liability protection,
- measurement of fill quantities,
- enhance public relations, and
- advance the state-of-the-practice.

The objectives for instrumentation during construction will change depending on the size and type of construction, the geotechnical conditions and the project schedule. Some types of instrumentation monitoring are a required part of construction (e.g., testing of soil nails, tieback anchors). Other types of instrumentation monitoring can only be implemented if construction durations are sufficiently long to make the data collection useful and relevant. Preload monitoring is an example of this category.

After establishing a clear set of objectives, the project geotechnical specialist identifies the potential need for instrumentation monitoring and communicates the preliminary instrumentation plans with the Design Project Manager to confirm that the objectives of the instrumentation work are justified and fit within the likely construction plans.

11.1.2.2 Types of Instrumentation

Geotechnical field instrumentation can range from settlement and porewater pressure devices used for monitoring the construction of embankments to slope deformation systems in landslide areas. Geotechnical instruments can involve simple mechanical measurement systems where data are manually recorded, or they can involve complex electronic systems where data are recorded on a datalogger with remote downloading capabilities. As the sophistication of the measuring instrument increases, so do the costs. Consequently, the project geotechnical specialist will need to judge the benefits of the different systems, relative to costs for purchasing and recording data.

A variety of situations may warrant the use of geotechnical instrumentation for field performance monitoring on MDT projects, including:

1. <u>Monitoring Settlements, Lateral Displacements and Porewater Pressures Beneath Embankments</u>. These measurements can be made to control embankment stability. In this case, the next lift of fill may not be added until porewater pressures have dissipated to a level that would preclude embankment slope instability or bearing capacity failure.

2. <u>Monitoring Earth-Retaining Structure Deformations</u>. These measurements are used to determine if active or at-rest pressures are developing, if deformations could jeopardize facilities behind the walls or if the wall is performing in a suitable manner (e.g., creep of tieback anchors under performance or proof loads).

3. <u>Monitoring Slopes in Landslide Areas or Where Slope Stability is Marginal</u>. These measurements are used to either identify the rate of movement and location of failure planes within the moving soil or rock mass or confirm that construction fills or excavations are not causing excessive ground movements.

4. <u>Monitoring Groundwater Elevations</u>. These measurements are used to evaluate initial effective stresses and changes in effective stresses caused by loading the soil, or simply the change in groundwater elevations due to seasonal fluctuations caused by snowmelt, heavy rainfalls or irrigation.

11.1.2.3 Instrumentation Selection, Installation, Monitoring and Interpretation

After the decision is made to include field instrumentation monitoring, plans are developed to select and install the appropriate instrumentation and collect and interpret the data. This step is often the most difficult to accomplish. The project geotechnical specialists lead the planning process. Implementation and data collection could be the responsibility of the project geotechnical specialist or the contractor, depending on the specifics of the project. For many MDT projects, the contractor will purchase and install the instrumentation following drawings and special provisions in the contract documents. In other cases, the MDT Geotechnical Section or designated consultant will install the instrumentation. The project geotechnical specialist or other designated representative will be responsible for collecting the data. The project geotechnical specialist will be responsible for interpreting the data or reviewing the data collection if performed by an independent consultant.

The project geotechnical specialist will usually develop the instrumentation plan during design, and will often be required to prepare drawings and specifications describing the type, installation and monitoring requirements. During construction, the project geotechnical specialist should be prepared to:

- review instrumentation submittal information prepared by the contractor,
- observe or coordinate the installation of the instrumentation,
- collect or review data from the instrumentation,
- interpret the data, and
- troubleshoot when unusual data are acquired.

Guidelines for selecting, installing, monitoring and interpreting instrumentation data can be found in the FHWA *Geotechnical Instrumentation Manual* and in *Geotechnical Instrumentation for Monitoring Field Performance* (Dunnicliff, 1993). Companies selling instrumentation typically have detailed information describing equipment capabilities, installation procedures and monitoring alternatives. The project geotechnical specialist should research these areas before selecting the instrumentation. The success of the instrumentation program will often be determined on the basis of instrument suitability, instrument performance and data quality.

Two important considerations during the instrumentation selection process are as follows:

1. Redundant Measurements. Redundant measurements are critical to account for the effects of load variations and soil variability on the measurements, the result of damage during installation or from construction equipment, or simply from malfunctions that occur with time (e.g., leaks in sealed pressure cells, instrumentation cables). Consider all of these possibilities during selection of type, number and location of the instrumentation. One guiding principle during instrumentation planning is to assume that the instrument most important to design will be the one that fails and, therefore, an appropriate contingency must be identified. This contingency planning can often be handled by redundant measurements.

2. Instrument Calibration. Calibrate each instrument before use. Instruments purchased from a supplier will usually come with instrumentation calibration curves or may be calibrated to a standard atmospheric pressure. It is often good to check these calibration curves in a bench test before installation to confirm that shipping has not changed the calibration or, where applicable, to perform calibrations to account for elevation changes that will effect the atmospheric pressure calibration. If instrumentation is being reused on a project (e.g., vibrating wire piezometer in a standpipe piezometer), it is critical to check the calibration before deployment.

When planning the instrumentation program, anticipate the requirements for baseline measurements. Make these measurements after installation of instruments and before construction begins. The duration of baseline recordings will depend on the particular type of instrument. For example, some instruments (e.g., settlement target on a building) require little to no time between installation and data monitoring, while other equipment (e.g., groundwater piezometers) could require several weeks of monitoring. The project geotechnical specialist needs to identify the baseline periods for each instrument when planning the program.

Consider the sensitivity of the data measurement during the planning process. The sensitivity will depend on the range of values that could occur during the recording period. Often these values will be determined as part of the engineering design process. For example, if constructing a lift of embankment fill is expected to cause a 5 psi (35 kPa) porewater pressure increase, the sensitivity of the recording should be roughly 10% of the measurement. At the same time, the total range of porewater pressure measurement could be much higher at deeper depths, thereby, requiring more sensitive transducers at the ground surface than at deeper depths.

Consider requirements for data interpretation in the instrumentation planning process. Too often data are collected and not reviewed until it is too late to implement a remedial plan. For this reason, the project geotechnical specialist must decide not only what to monitor and where to monitor, but also how the information is going to be used once it is collected. This step could include estimating the amount of staff time that will be required to interpret the data each day. For some projects, an action plan must be developed that tells the field personnel or contractor what actions will be taken if, for example, porewater pressures or displacements reach a predetermined level. One of the primary responsibilities of the project geotechnical specialist is to ensure data interpretation in a timely manner.

Section 11.4 presents additional discussion of the instrumentation planning, interpretation and reporting process.

11.1.3 References

For further guidance on instrumentation, review the following documents:

- *Geotechnical Instrumentation Reference Manual*, FHWA HI-98-034; and
- Dunnicliff, J., *Geotechnical Instrumentation for Monitoring Field Performance,* Wiley, New York, 1993.

11.2 TYPES OF INSTRUMENTATION

Instrumentation systems are broadly classified into the following basic types:

- vertical deformation,
- lateral deformation,
- optical surveys,
- earth pressure,
- porewater pressure, and
- load/stress on structural members.

The FHWA *Geotechnical Instrumentation Reference Manual* and *Geotechnical Instrumentation for Monitoring Field Performance* (Dunncliff, 1993) present detailed discussions on each basic type. These discussions range from the sensitivity of the equipment to installation considerations and long-term monitoring requirements. A summary of each type is provided below.

11.2.1 Vertical Deformation

Vertical deformations are monitored in a number of different situations for transportation projects. The most common involves locations where embankments are constructed on soft fine-grained soils (e.g., silt, clay, organic material). In these situations, the load from the new embankment causes compression in the underlying soil, resulting in settlement at the roadway surface or in adjacent areas. This settlement can result in increased pay quantities for embankment construction, poor ride quality after the completion of construction or damage to existing facilities (e.g., buildings, utilities). While monitoring the vertical settlements of embankments is most common, vertical settlements may also need to be monitored for bridges supported on spread footings or piles, drainage culverts or natural hillsides as an indicator of slope movement. The following Sections identify the most common instrumentation types for monitoring vertical deformation of structures and embankments.

11.2.1.1 Settlement Plates

Settlement plates are typically used to monitor settlement below embankments on soft ground. There are two basic types of settlement plates:

1. Mechanical Settlement Plates. Mechanical settlement plates involve a rectangular or circular plate, ranging from 12 in to 24 in (300 mm to 600 mm) in diameter, placed at the original ground surface. A rod extends from the plate to the top of the new fill. As more fill is placed, the rod is extended so that it is above the top of fill. An isolation tube is often placed around the rod to prevent downdrag from adding load to the settlement plate. The top of the rod is surveyed for elevation. Settlement is determined by taking the difference between the initial rod elevation and subsequent elevation readings.

2. Pneumatic or Hydraulic Settlement Plates or Sensors. This type of device uses a hydraulic or pneumatic pressure head from air or from a liquid to determine settlement. Use the difference between the initial and current pressure heads to estimate

settlements. The sensor or plate system can be located at the ground surface before the embankment or structure is constructed, or it can be located in a borehole for subsurface monitoring.

The pneumatic or hydraulic settlement plate/sensor system allows settlements to be made remotely from the sensor locations and, therefore, the monitoring system is out of the way during construction. This location is in contrast to settlement plates with rods extending to the ground surface. The settlement plates with rods have to be protected from construction activities and also extended upward through the fill as fill heights increase. The benefits of the remote systems are offset by the higher purchase costs, the greater complexity of the equipment and requirement to use more specialized people for installation and monitoring.

11.2.1.2 Bench Marks and Heave Stakes

Install bench marks and heave stakes installed at the top of a new fill or in an excavation to determine vertical deformations. Place physical targets on structures to measure settlement. The physical target could be a PK nail or simply a painted mark on a wall. Use elevation survey to determine changes in elevation.

The key to this approach is having a good bench mark to serve as a reference level for the elevation monitoring. The reference monument must be located outside the area that is loaded or unloaded. As with most monitoring systems, collect the reference data in advance of any work to establish a sufficient baseline condition.

11.2.1.3 Horizontal Inclinometers

Slope inclinometer casing can be installed horizontally at the ground surface before the placement of fill. This system functions similar to a normal vertical inclinometer, but place the casing horizontally. A slope indicator is pulled through the tube after the fill is in place.

The horizontal measurement system can provide a profile of settlement below the fill as a function of time. Use horizontal inclinometers primarily for monitoring settlement below new embankment fills; however, they also can be used to monitor movement of a buried structure (e.g., drainage culvert).

11.2.1.4 Borehole Extensometers and Flexible Casing Systems

This type of vertical displacement monitoring system is installed in a borehole. The system provides a means of determining settlement at various depths below the ground surface. This type of information is often useful when confirming consolidation parameters determined by laboratory testing.

The borehole systems can be mechanical where an anchor is expanded against the borehole wall and a rod extends to the ground surface, or they can be semi-remote where a flexible (Sondex) tube is installed and grouted in the ground. The Sondex tube has metal rings at fixed depths. A sensor is lowered from the ground surface to identify the location of the ring. Changes in distance to the ring define the magnitude of incremental settlement. This type of device is best suited at locations where relatively large displacements are expected. A vertical inclinometer can be installed inside a Sondex tube to obtain both vertical and horizontal displacements. The advantage of this approach is that it isolates the inclinometer casing from downdrag caused by settling soil, thereby, avoiding the potential for bending of the inclinometer casing or the need to use telescoping couplings at the inclinometer casing joints.

11.2.2 Lateral Deformation

Concern over the presence and magnitude of horizontal movements usually occurs at sites where either vertical retaining walls or vertical excavations are constructed (e.g., standard CIP semi-gravity retaining walls, sheet piles, tieback anchor walls, soil nail walls, vertical cuts in rock) or where steep or unstable slopes occur. For these cases, it is often desirable to monitor lateral movement during the following situations:

1. During Construction. Lateral movement may be monitored during construction and sometimes following construction; specifically, where an existing building or utility is located behind the wall or vertical cut.

2. Anticipated Instability. Lateral movement may be monitored if a slope instability problem is anticipated. The lateral monitoring may also be conducted as part of design.

3. Expected Embankment Settlement. Lateral movement may be monitored if large embankment settlement is expected. In this case, the lateral displacement from squeezing or bearing failure of the foundation material occurs at the same time as vertical settlement. This lateral movement can be damaging to nearby roadways, utilities or structures.

For these cases, lateral deformation should be detected, recorded, analyzed and compared with wall or slope stability computations. Magnitudes and rates of deformation are the most important of these measurements, as well as understanding the area of deflection. A variety of sensing devices are available for making lateral deformation measurements. Determination of the optimal sensing devices is often complicated by the expense of covering significant areas or volumes of cut, fill earth or rock.

11.2.2.1 Inclinometers

Inclinometers are devices for monitoring lateral deformations in soil and rock boreholes, and along the face of retaining walls. They are also used to measure deformation during lateral load testing of deep foundations. These devices typically involve installing a casing that has four grooves at 90° spacing into a borehole. The casing can be either aluminum or PVC. MDT practice is to use PVC and grouting or sand packing the casing into the borehole.

A slope inclinometer sensor is lowered in the casing. Wheels on the sensor ride in the grooves, which maintains and controls the sensor orientation. A force-balance accelerometer in the sensor records deviation from vertical. Results from the inclinometer are processed through data acquisition system and computer software either to provide a displacement profile or to determine the change in horizontal location between readings taken at different times.

Alternatively, the inclinometer can be mounted to the outside of a wall. This is often done for mechanically stabilized earth (MSE) walls to determine face deformation during construction.

In general, inclinometers provide the most definitive means of detecting the changes in horizontal position of a slope or a wall. If the inclinometer is installed in a landslide, the approximate depth of the failure surface can also be detected. These devices can provide accurate indication of soil deformation with time.

An alternative involves the use of an in-place inclinometer. This device is similar to the inclinometer sensor that is lowered down the borehole; however, in this case, the sensing unit is left in the borehole to obtain continuous movement readings with time. The in-place inclinometer transmits data to a datalogger at the ground surface, which is downloaded periodically with a computer or by remote procedures.

11.2.2.2 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is an inexpensive system used for monitoring unstable slopes and for detecting roadway subsidence caused by large settlements (e.g., collapse of mine voids below roadways). The TDR analysis begins with the propagation of a step or impulse of energy into a system and the subsequent observation of the energy reflected by the system. By analyzing the magnitude, duration and shape of the reflected waveform, the nature of the impedance variation in the transmission system can be determined.

The primary application of TDR is to supplement inclinometer data by installing TDR cables in boreholes. The technology is a time saving and economic replacement for inclinometers in appropriate situations, and for monitoring the onset of slope failures during investigation and monitoring of landslides. A coaxial cable is installed in a vertical borehole passing through the region of concern. The electrical impedance at any point along the coaxial cable changes with deformation of the insulator between the conductors. A relatively brittle grout is installed around the cable to translate earth movement into an abrupt cable deformation, which shows up as a detectable peak in the reflectance trace.

11.2.2.3 Optical Surveys and GPS Tracking

Traditional positional surveys often represent the least complex and most economical instrumentation method for monitoring deformation. Optical instruments can be used to determine lateral and vertical movements with certain ranges and accuracy.

This approach normally uses a bench mark or target (see Section 11.2.1.2) as the reference point. The primary disadvantage of the optical survey is that a survey crew must be mobilized to the site each time a set of data are required. The optical survey is a very efficient method of monitoring large displacements. As the amount of displacement decreases, the accuracy of the survey becomes more of a concern.

A recent development in the area of surveying is the use of global position systems (GPS) for monitoring displacements of landslides. Methods are now capable of recording movements within a few inches (millimeters). Data can be collected remotely and uploaded to satellites for monitoring in an office.

11.2.3 Earth Pressures

Instrumentation is available for determining earth pressures. These measurements are made in terms of total stresses (i.e., both the earth and water pressure are recorded by the instrument). Total stress measurements in soil fall into two basic categories — measurements within a soil mass and measurements at the face of a structural element. Instruments that capture these measurements are referred to as earth pressure cells, soil stress cells and soil pressure cells. The FHWA *Geotechnical Instrumentation Manual* discusses each of these instruments.

The measurement of earth pressures using earth pressure cells is difficult and for some applications subject to large uncertainties. The problem is complicated by the disturbance associated with placing the measuring device (for detecting stress) at the subject point. For virgin ground, placement of the measurement device can cause disturbance to the soil, which changes the readings from what would be measured if the cell could be installed without disturbance. For engineered fills, placement of the instrumentation is not as great of a concern because the stress field grows and comes to a state of equilibrium during the construction process. However, it is still important to understand the relative compliance between the cell and the soil to avoid developing stress concentrations at the cell or arching around the cell, resulting in erroneous readings.

Earth pressure cells are available in several varieties, including:

- pneumatic;
- hydraulic;
- vibrating wire stain gauge;
- semi-conductor, pressure transducer;
- bonded-resistance strain gauge; and
- unbonded-resistance strain gauge.

The FHWA *Geotechnical Instrumentation Manual* and *Geotechnical Instrumentation for Monitoring Field Performance* publications provide detailed discussions of the available types of earth pressure cells and the relative advantages and limitations of each.

11.2.4 Porewater Pressures

Porewater pressure transducers are used to measure the porewater pressure in soil or rock. These devices measure the pore pressure based on a head of water. The head can be measured mechanically by lowering a sensor that detects the hydrostatic water level or by measuring the head using an electronic or mechanical sensor in combination with a readout device. Review the following:

1. Mechanical Systems. The mechanical method of monitoring porewater pressures typically involves installing standpipe piezometers. These instruments require sealing off a porous filter element (e.g., well screen) so that the well screen only responds to groundwater pressure around the filter element and not to groundwater pressures at other elevations. Piezometers can be installed in fill, sealed in boreholes, pushed or driven into place. The components are identical in principle to components of an observation well, with the addition of seals. The water surface in the standpipe stabilizes

at the piezometric elevation and is determined by sounding with a probe or through use of an electronic sensor with a datalogger (e.g., MiniTroll) installed in the standpipe to monitor groundwater elevations at preset intervals. Use care to prevent surface water runoff from entering open standpipes. An appropriate roadway valve box can be used to secure and protect the top of the standpipe and ensure the standpipe venting is not obstructed.

2. <u>Electronic or Pneumatic Systems</u>. Electronic or pneumatic porewater pressure transducers can be pushed into the bottom of a borehole or installed at the bottom of the borehole. In the latter case, the sensor is normally installed within a sand pack. The borehole above the sensor is grouted to prevent the hydrostatic conditions above the sensor location from affecting the pore pressure measurements. The sensor is connected to the ground surface using an electrical cable or a pneumatic line. A readout box is used to obtain the measurement. This type of device can be connected to a datalogger that can be downloaded using a laptop or through a satellite hookup for remote monitoring. These types of instruments are much faster to respond to changes in porewater pressure than mechanical systems.

One option for porewater pressure measurements is to install the electronic pore pressure transducer on the outside wall of a slope inclinometer or Sondex tube. The transducer is grouted in place with the slope inclinometer. No sand pack is used around the transducer. Laboratory and field tests have shown that the sand pack is unnecessary and reliable pore pressure measurements can be made through the grout. The advantage of this approach is that it is not necessary to drill an independent borehole when installing the pore pressure transducer, providing the instrumentation program already includes slope inclinometer or Sondex displacement monitoring systems.

The FHWA *Geotechnical Instrumentation Reference Manual* provides guidance on the various instrument used for measuring porewater pressures. For more information on piezometers and water-level measurement, see Section 8.3.8.

11.2.5 Load/Stress on Structural Members

The interaction between geomaterials and the engineered structure is critical to the maintenance of the construction process until all structural members are connected and the ground stress is equilibrated over the facility. Load and pressure cells, strain meters, strain gauges and flat jacks are designed for installation at key locations in the ground support system to measure ground stress on the structural system and loads at points over defined areas.

A load cell deforms because of applied stress. Cell deformation is measured by strain gauges bonded to the cell. The cell is laboratory-calibrated against known loads using a universal test machine. Load cell designs can be solid or hollow-cylinder. The hollow varieties are suitable for installation around rock bolts and tieback anchors. Load cells only measure axial loads, so their orientation must be carefully planned to provide stress accumulation data at key locations in the ground support system.

Determining the incident stress range is a critical part of the load cell design. The project geotechnical specialist must decide the level of sensitivity. The device should be capable of detecting incremental stress changes. Cells are usually required to be sensitive to a range of

50 to 100 parts of the total expected strain. Guidance on the selection of these cells can be found in the documents referenced in Section 11.1.2.3.

11.2.6 Vibration Monitoring

Some projects require that ground vibrations be monitored during construction. The two most common examples of vibration monitoring occur with blasting for rock excavation and installation of driven piles. The vibrations caused by blasting or pile driving can be damaging to nearby structures or be bothersome to people who feel the vibrations. While the most common source of vibration is from these activities, other sources of vibrations during construction can include vibratory compactors, large earth moving equipment and sheet pile installation.

Ground vibrations are normally monitored using velocity-sensitive transducers. The transducers are generally small, approximately 2 in (50 mm) in diameter and 2 in (50 mm) tall, and can be used above and below water. Typically, the velocity transducer consists of a package of two horizontal transducers, oriented orthogonally, and a single vertical transducer. The transducers can record vibrations to 0.001 in/sec (0.025 mm/sec) or less. Maximum vibration levels up to several inches per second (e.g., 3 in/sec; 75 mm/sec) or higher can be recorded.

Various types of recorders are available; however, a digital recorder should be used. Typically, the recorders can be programmed to collect data continuously, at different time intervals for preselected durations or only peak measurements. Download data to a computer or, in some older systems, printed on recording paper.

If necessary, specify vibration monitoring in the contract documents. The project geotechnical specialist may be asked to define the type of monitoring, the sensitivity and frequency of the monitoring and, for some projects, the maximum permissible vibration levels. Permissible levels of vibration depend on several factors, including:

- source to receptor distance, generally vibrations attenuate on a log-log basis;
- use of the structure (e.g., levels of vibration that will affect residential structures or hospitals are much lower than industrial buildings);
- type of structure; and
- soil conditions.

Charts are available showing the levels of vibration that are acceptable for many of these variables. Typically, the charts show whether the vibrations are noticed by people, disturbing or injurious to people, damaging to historic structures or causing cosmetic (e.g., minor cracking) or structural damage. Often, all vibration monitoring is the responsibility of the contractor (e.g., blasting special provision).

11.2.7 Automatic Data Acquisition Systems

Automatic data acquisition systems (ADAS) are self-contained recording devices and can record and store data for a number of days or even months. Some ADAS allow remote downloading of data. The benefit of the ADAS is that performance information can be obtained without sending personnel to the field to record data. Although the cost of the ADAS systems is decreasing, they are typically only used on major projects.

11.3 PLANNING INSTRUMENTATION PROGRAMS

The following is a checklist for planning instrumentation programs:

1. Define Project Conditions. Determine the project conditions, including:

   - project type,
   - project layout,
   - subsurface stratigraphy and engineering properties,
   - groundwater conditions,
   - status of nearby structures or other facilities,
   - environmental conditions, and
   - planned construction method and knowledge of crisis situation.

2. Predict Behavior-Controlling Mechanisms. Determine one or more hypotheses for mechanisms that are likely to control movements or result in changes in stress or porewater pressures.

3. Define Geotechnical Questions Requiring Solutions. Every instrument on a project should be selected to assist in answering a specific question — if there is no question, there should be no instrumentation.

4. Select Monitoring Parameters. Determine which parameters are most significant (e.g., groundwater pressure, joint water pressure, total stress, deformation, structural load, strain, temperature).

5. Estimate Magnitudes of Change. Predictions are necessary because instrument ranges and sensitivities must be selected. An estimate of the maximum value or the maximum value of interest is used to select an instrument range. An estimate of the minimum interest value leads to a selection of instrument sensitivity or accuracy.

6. Devise Remedial Action. Decide, in advance, on a positive resolution for problems that may be discovered by the observation results. If the observations require remedial action, they can be based on appropriate, previously anticipated plans.

7. Select Instruments. Complete numbers 1-6 above before selecting instruments. The overriding selection criteria are reliability and simplicity. Low cost should not determine the selection.

8. Select Instrumentation Locations. Selecting instrument locations should reflect predicted behavior and be compatible with the analysis method used for interpreting the data. Numerical modeling methods (e.g., finite element, finite difference) are often helpful to identify critical locations and preferred instrument orientations. Keep in mind the need for monitoring redundancy when selecting equipment types and locations.

9. Recording Influential Factors. Measurements alone are rarely sufficient to provide conclusions. Instrumentation use normally involves relating measurements to causes; therefore, complete records and diaries must be maintained of all factors that might cause changes in the measured parameters.

10. Establish Correct Reading Procedures. Personnel responsible for the instrumentation must ensure that the instrument is functioning correctly.

11. Prepare Budget. Include costs, being careful to make a realistic estimate of project duration, for the following:

    - planning monitoring program,
    - creating detailed instrument designs,
    - procuring instruments,
    - performing factory calibrations,
    - installing instruments,
    - maintaining and calibrating instruments on a regular schedule,
    - establishing and updating data collection schedule,
    - collecting data,
    - processing and presenting data,
    - interpreting and reporting data, and
    - deciding on implementation of results.

12. Prepare Instrumentation System Design Report. This report should summarize the results of all previous items. Review the report to ensure consistency and that the plan addresses the project needs. Reviewing the specifications at this point is too late. The report should include a section on the selected contract method, both for procurement of instruments and field instrumentation services, and the reasoning behind the selections. If the instruments will be installed by MDT, prepare a written workplan outlining the procedures for installing and checking the operation of the instrument. This workplan should include calibration and monitoring requirements, as well as data interpretation and presentation requirements, as discussed in Items 14-16.

13. Write Instrument Procurement and Installation Specifications. If the instrument is not addressed in the *MDT Standard* Specifications, prepare a special provision describing the requirements of the instruments, including accuracy and resolution and the desired results. Prepare written step-by-step procedures for installing the instruments, using the manufacturer's instruction manual and the project geotechnical specialist's knowledge of specific site geotechnical conditions at the site of installation. The procedures should include a detailed listing of required materials, tools and calibration checks that should be performed before and after the instruments are installed. Prepare installation record sheets for documenting factors that may influence measured data.

14. Plan Regular Calibration and Maintenance. Regular calibration and maintenance required during service life is usually performed by personnel responsible for the data collection. Damage, deterioration or malfunctioning devices should be repaired immediately. Maintenance requirements are usually provided in the manufacturer's instructional manual.

15. Write Field Instrumentation Services Specifications. Provide construction personnel with instructions on instrument installation, regular calibration and maintenance requirements, and data collection, processing, presentation, interpretation and reporting.

16. Plan Data Collection, Processing, Presentation, Interpretation, Reporting and Implementation. The project geotechnical specialist will be responsible for preparing the final report based on the data collection, processing procedures, design interpretation and implementation.

The applicability of the checklist above will depend on the specific project requirements, contracting mechanism for the instrumentation services and desired use of the instrumentation data. The project geotechnical specialist should review the list and decide which of the items are appropriate for the specific project.

11.4 INTERPRETATION AND REPORTING

11.4.1 Interpretation of Instrumentation Data

Data interpretation correlates instrument readings with other factors (cause and effect relationships) and includes an evaluation of reading deviations from the predicted behavior. Data interpretation is a manual activity; there is no technique for automating this process. The FHWA *Geotechnical Instrumentation Reference Manual* provides guidance on the data interpretation process.

11.4.2 Reporting of Conclusions

After each data set is interpreted, report conclusions in an interim monitoring report and submit this report to personnel responsible for data implementation. In addition, a final monitoring program report is often required.

11.4.2.1 Interim Monitoring Reports

Provide the conclusions from data interpretations to all parties with a role in the data implementation. Initial communication may be verbal, but confirmation should be in the form of an interim monitoring report. Distribute interim monitoring reports on a regular schedule to allow timely implementation of the following:

- updated summary plots;
- significant changes in the measured parameters obtained subsequent to the previous interim monitoring report, including the probable causes; and
- recommended action.

Another option for communicating instrumentation data is to use a password-protected internet site to communicate results of instrumentation programs. This can be an effective approach for keeping designers aware of monitoring information on a timely basis. The project geotechnical specialist may want to consider this approach for larger programs, where monitoring is being carried out by the contractor. This would allow the project geotechnical specialist to monitor data on a more frequent basis than when data are being distributed in weekly or monthly reports.

11.4.2.2 Final Report of Monitoring Program

Prepare a report or technical memorandum to document key aspects of the monitoring program, summarize the results of the monitoring and document the recommendations for remedial actions. Distribute the report to all personnel involved in the design and execution of the monitoring program so lessons learned are incorporated into subsequent designs. Contents of the final report may include some or all of the following topics, depending on the specific nature of the instrumentation program:

- summary of the report;
- introduction, including a brief description of the project and the reason for using the geotechnical instrumentation;
- summary of the instrumentation system design report. Alternatively the entire report can be included as an attachment;
- project design and construction information relevant to the monitoring program;
- instruments and readout unit descriptions, including model numbers and calibration information;
- plans and sections sufficient to indicate instrument numbers and locations;
- appropriate surface and subsurface stratigraphic and geotechnical data;
- methods of installation and results of baseline checks for equipment operation;
- observed behavior, including summary plots and factors that influence measured data;
- observed behavior analysis, including comparisons between measurements and predictions;
- discussion of significant changes and probable causes, and comparisons with published information; and
- conclusions, discussions and recommendations, including a statement of any remedial actions taken.