Chapter 25

CONSTRUCTION MONITORING AND INSTRUMENTATION

Final

SCDOT GEOTECHNICAL DESIGN MANUAL

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Table of Contents

List of Tables

Table **Page**

CHAPTER 25

CONSTRUCTION MONITORING AND INSTRUMENTATION

25.1 INTRODUCTION

This Chapter provides a general overview of the selection and use of geotechnical instrumentation on SCDOT construction projects. There are two general classes of geotechnical instrumentation. The first class is those instruments used to investigate and evaluate soil and rock properties. This class of geotechnical instrumentation is presented in Chapter 5 – Field and Laboratory Testing Procedures. The second class is those geotechnical instruments that monitor performance during and after construction. Excluded from this Chapter is the instrumentation of deep foundations (see Chapter 24), surveying, and construction materials testing. This Chapter is not intended to provide specifications for individual instruments, but rather to provide a systematic approach to the planning for and implementation of an instrumentation and monitoring plan. For more specifics regarding the information presented herein, please refer to the references cited at the end of this Chapter. This Chapter will cover typical types of field instrumentation used on SCDOT highway construction projects.

Field instrumentation on highway projects can play several vital roles, including the following:

- Verification of Design Parameters – Data obtained from instrumentation can be used to verify that the constructed embankment, slope, wall, etc. behaves as predicted during and after construction. Initial data can be used to modify the design if necessary.

- Evaluate Performance During Construction – Field instrumentation can be used to monitor construction performance of the embankment, slope, wall, etc. that may affect or be affected by construction activities and that may affect the construction schedule.

- Evaluate Performance of Existing Structures – Existing embankments, slopes, walls, etc. can be instrumented to assess the existing conditions and to guide remediation measures, if necessary.

- Detect short and long-term trends – Before potential problems are visible to observers, instrumentation can provide the first indication of how a structure is going to perform over short-term and long-term periods.

- Safety – Field instrumentation can serve as the first warning sign of a potentially unsafe situation. An instrumentation and monitoring program can also play a role in easing public concerns over safety of areas surrounding the construction site.

- Legal Protection – Instrumentation can provide documentation as to the relationship between construction and surrounding structures. In the event of litigation, data from these instruments can be used to prove/disprove connection of damage in surrounding areas to construction activity.

Planning an instrumentation and monitoring program should be guided by a systematic approach. The steps listed in this Chapter provide a typical list of planning considerations that can be applied to most highway construction projects. The overall objective for the program should be decided before selection of instruments commences. As part of the planning process, the need for instruments should be gauged against such factors as relevance of the data obtained, impedance of construction, and cost.

Although the goal of this Chapter is not to provide specific guidelines on field instrumentation, the general philosophy given in the references cited below should be applied to nearly every project where field instrumentation is to be used. First, every instrument should be installed to answer a specific question. More instrumentation than is required produces additional, perhaps harmful, discontinuities in the structure and may provide a false sense of security. Second, in general the simpler the instrumentation is, the more desirable it should be. Although some situations may arise where sophisticated instrumentation cannot be avoided, such as the need for remote monitoring, simpler instruments generally provide data that is just as reliable while having less chance of malfunction, and at a reduced cost. Third, redundancy, or a system of checks, should always be built into the monitoring program to add another level of reliability beyond what is provided by a single instrument. If sophisticated instruments are to be used, standard, “low-tech” instruments can also be installed to maintain the flow of incoming data in case of malfunction in the sophisticated instruments.

25.2 MONITORING PLAN

Before field instruments are to be installed, a thorough monitoring plan should be submitted for review by the geotechnical engineer-of-record. The elements to be included in this plan are detailed below and generally follow the guidelines set forth in Geotechnical Instrumentation (FHWA-HI-98-034) dated October 1998. Table 25-1 provides a list of the elements used in developing a monitoring plan.

Table 25-1, Monitoring Plan Elements

1. Definition of Project Conditions	2. Objectives of Instrumentation
3. Predicted Magnitude of Change	4. Define Remedial Actions
5. Establish Responsibilities and Chain of Command	6. Types of Instruments and Locations
7. Recording of Outside Factors	8. Procedures for Ensuring Data Validity
9. Estimate Costs	10. Installation and Protection Plans
11. Calibration and Maintenance of Field Instruments	12. Data Processing

The monitoring plan as well as certain construction related items, such as monitoring, calibration and maintenance, data collection, processing, presentation, interpretation and reporting, are considered “professional services” and should not be left to the Contractor to perform. The monitoring plan shall be prepared by the geotechnical engineer-of record, whether by SCDOT personnel or the geotechincal consultant. On most SCDOT construction projects geotechnical instrumentation is installed by the Contractor under the supervision of a licensed engineer. In addition, in many cases the monitoring, calibration and maintenance and data collection are made the responsibility of the Contractor. In these cases, the Contractor shall be required to retain the services of a licensed engineer, familiar with the instrumentation being used. The processing, presentation, interpretation and reporting are typically provided by the geotechnical engineer-of-record, whether by SCDOT personnel or the geotechnical consultant.

25.2.1 Definition of Project Conditions

This Section of the instrumentation plan should include a summary of existing conditions and of proposed construction, if applicable. If a Geotechnical Base Line Report has been completed for the site to be monitored, a short summary of the relevant information from this report should be included in the monitoring plan. Other information that may be relevant to monitoring, such as condition surveys of existing structures or reports of environmental conditions, should also be summarized in the monitoring plan. All pertinent information about the project related to the monitoring program should be properly referenced in the monitoring plan. If additional information is needed to fully characterize the site, a plan for obtaining this information shall be submitted with the monitoring plan.

25.2.2 Objectives of Instrumentation

The objectives of field instrumentation to be used on the project shall be clearly defined in the monitoring plan. The first step to defining objectives for field instrumentation is to predict potential failure mechanisms that may occur during or after project completion. Secondly, instruments can be installed to monitor parameters such as pore water pressure, horizontal and/or vertical displacements, in-situ stresses, etc. that are indicative of a failure. Finally, the information gained from the field instruments shall be used to support any further action that may be necessary. If the objectives of the instrumentation cannot be clearly defined, delete the instrumentation. Only use instrumentation that have clearly defined objectives.

25.2.3 Predicted Magnitudes of Change

The lower bound of predicted magnitudes will provide the required accuracy of field instruments, while taking into account the full range of predicted magnitudes will convey the required data range of field instruments. Threshold levels which correspond to escalating need for remedial action shall also be determined and included with the monitoring plan. A table or similar graphic illustrating these levels should be displayed in a prominent place and all personnel associated with monitoring shall be aware of both the threshold level readings and required remedial actions. The threshold values are chosen based on experience with similar projects, similar subsurface conditions or construction methods, case histories of similar projects, and engineering judgment of project personnel.

25.2.4 Define Remedial Actions

In relation to threshold levels, remedial actions corresponding to each escalating level shall be defined in the monitoring plan. Remedial actions will be project specific but may range from simply informing someone higher up the chain of command of a possibly unsafe situation, to stopping work, or to emergency measures in the event of an impending failure. A detailed description of each action may not be feasible at the time the plan is written, but the plan shall at least describe each action in general terms. Pre-project planning ensures that the required labor and materials will be available in case of emergency.

25.2.5 Establish Responsibilities and Chain of Command

The responsible parties for each phase of a monitoring program, from planning to collection and interpretation of data, shall be designated either in the monitoring plan or in another suitable document. Responsibilities and authority of each party in relation to the other parties regarding the monitoring program shall also be clearly defined. Regardless of their role and level of authority on the project, monitoring personnel shall always have a direct line of communication between themselves, the construction Contractor, and the geotechnical engineer-of-record in case a situation arises that needs immediate attention.

25.2.6 Type of Instruments and Locations

The type, number, and manufacturer of each instrument to be used on the project shall be provided in the monitoring plan. The reasons for selecting particular instruments to monitor the conditions described above shall also be explicitly spelled out, keeping in mind that every instrument is installed to answer a specific question. The overriding factor in choosing field instrumentation is reliability. Other factors such as ease of installation, difficulty of interpretation, and cost, may also play a role. Instrument manufacturers can provide valuable information during the instrument selection process about relevance of the instrument to the specific application and limitations of the instrument.

The locations for instrument installation shall be chosen based on potential failure analysis, preexisting information (if for an existing structure or slope), subsurface conditions, and any other pertinent information. If site conditions are generally homogenous, instruments may be installed at selected intervals. If it appears that certain areas will be more critical or have a higher probability of failure, instruments shall be concentrated at these locations. Provisions should be made to order more instruments than necessary to account for damage during installation or malfunction once the instrument is installed. Field instrument locations shall be clearly marked on a plan view of the site. Instrumented cross-sections, if applicable, shall also be included with the monitoring plan.

25.2.7 Recording of Outside Factors

The recording of all outside factors, that can be reasonably assessed, that may influence field instrument data shall be specified in the monitoring plan. This is especially important for monitoring during construction activities, as heavy construction traffic and altering of the site conditions can have a significant effect on instrument data. Monitoring personnel must keep or have access to a detailed record of construction activities in order to correlate monitoring results and filter out anomalies caused by nearby construction activities. Other outside factors that may influence instrument readings include environmental conditions such as temperature, rainfall, sunlight, and seismic activity.

25.2.8 Procedures for Ensuring Data Validity

Procedures shall be in place to ensure the validity of each instrument installed for the project. Redundancy is an effective way to reduce error in instrument data. For example, an open-standpipe piezometer can be installed near a pore-pressure transducer, screened at the same interval, to ensure that pore pressure readings are accurate. Optical or GPS surveying of surface monuments can be used to validate apparent movements indicated by subsurface instruments. Visual observation of site conditions by trained personnel can also be an effective means of validating instrument data. Systematic checks of data reliability should be planned for each type of instrument to be installed.

25.2.9 Estimated Costs

An estimated cost tabulation sheet for both materials and labor associated with the proposed monitoring procedures shall be compiled and submitted either with the monitoring plan or with another suitable document. Contingencies shall also be put in place to cover additional monitoring should the need arise.

25.2.10 Installation and Protection Plans

A detailed set of installation plans, including at least a work plan and sketches, shall be included with the monitoring plan. Oftentimes, the instrument manufacturer will provide detailed installation plans for their instruments. If necessary, the appropriate ASTM or AASHTO standard shall be referenced with regard to installation. Included with the installation plan shall also be methods to assure that the instrument is installed correctly and for the initial calibration of the instrument. If the instrument is to be installed in an active construction zone, plans must include methods for handling, protecting and repairing the instrument.

25.2.11 Calibration and Maintenance of Field Instruments

The instrument manufacturer is required to provide a recommended schedule for calibration and maintenance of field instrumentation. A calibration schedule of at least once per year is recommended, although many instrument manufacturers recommend shorter time periods between calibrations. Periodic calibration checks should also be performed by monitoring personnel to ensure that the instruments remain in calibration throughout the life of the project.

25.2.12 Data Processing

The procedures to be used for data collection, processing, presentation, interpretation, reporting, and implementation shall be provided in the monitoring plan. Field instrument reading schedules shall be spelled out in the monitoring plan, but must remain flexible depending on project progress and the results of initial readings. The plan shall also indicate specific software that may be required for processing data. Typically, field instruments are read on a relatively tight schedule at the beginning of a project and then relaxed as baseline conditions emerge and/or the project progresses beyond critical stages. Management of instrument data from methods of field collection to data storage and backup shall be accounted for in the planning stages of the project. The time needed for post-processing of instrument data will be dependent on instrument type and level of sophistication. Sufficient effort shall be planned for data interpretation by trained personnel. The results of data analysis shall be provided in periodic reports corresponding either to a set time interval (i.e. weekly, monthly, etc.) or to project milestones.

25.3 MONITORING PLAN EXECUTION

As discussed previously, the installation of geotechnical instrumentation is the responsibility of the Contractor. The Contractor shall be required to submit an installation plan for review. The plan should include the items in Table 25-2.

Table 25-2, Monitoring Plan Execution

1. Instrumentation Supplier	2. Factory calibration of instrumentation
3. Pre-Installation testing requirements	4. Calibration and Maintenance Requirements
5. Installation methods	6. Protection plan
7. Installation records	8. Installation report
9. Data Collection methods	10. Qualifications of personnel collecting data

25.3.1 Instrumentation Supplier

The Contractor shall be required to provide the name of the supplier of the geotechnical instrumentation and all literature provided by the supplier. The literature shall be used to verify that the instrumentation selected meets the requirements of the project.

25.3.2 Factory Calibration of Instrumentation

All instrumentation shall be calibrated at the factory prior to shipment and calibration certificates shall be provided by the Contractor. Any additional calibration requirements contained in the Special Provisions or Supplemental Specifications shall also be met.

25.3.3 Pre-Installation Testing Requirements

Due to the potential for rough handling during shipment, all instrumentation shall be checked to ascertain that the equipment is in working order prior to installation. The pre-installation testing shall include a verification of the calibration data provided by the manufacturer, by checking two or three data points within the instrument measurement range. The verification testing shall be performed at a range of temperatures. Tests at the extreme temperature limits of the instrumentation may reveal malfunctions that could lead to erroneous data if not corrected. The pre-installation testing may consist of testing to determine if the instrumentation is in working order. This type of testing is also called function testing. Table 25-3 indicates some possible items for the pre-installation testing program.

Table 25-3, Possible Items in Pre-Installation Tests
(Geotechnical Instrumentation – October 1998)

Category	Item
Data Supplied by Manufacturer	• Examine factory calibration curve and tabulated data to verify completeness • Examine manufacturer's final quality assurance inspection checklist, to verify completeness
Documentation	• Check, by comparing with procurement document, that model, dimensions, and materials are correct • Check that quantities received correspond to quantities ordered
Calibration Checks	• Check two or three points, if practicable • Check zero reading, e.g. of vibrating wire piezometers
Function Checks	• Connect to readout and induce change in parameter to be measured • Make and remake connectors several times, to verify correct functioning • Immerse in water, if applicable, and check
Electrical	• Perform resistance and insulation testing, in accordance with criteria provided by the instrument manufacturer
Mechanical	• Check cable length • Check tag numbers on instrument and cable • Verify all components fit together in the correct configuration • Check all components for signs of damage in transit

25.3.4 Calibration and Maintenance Requirements

Calibrations or function checks are required throughout the life of the instrumentation. Typically these calibrations are performed by the same personnel responsible for data collection. All calibrations and function checks shall be traceable (i.e., can be checked). The Contractor shall be required to develop a field calibration plan as part of the overall geotechnical instrumentation plan.

In addition to calibration, the personnel collecting the data shall also perform maintenance of the equipment. All maintenance shall be conducted in accordance with the manufacturer's requirements (if any is required).

25.3.5 Installation Methods

There are numerous ways to install the geotechnical instrumentation. The Special Provisions and Supplemental Specifications will provide some general requirements. The actual installation methods are left to the Contractor and shall be included in the installation plan. As part of the installation methods, the qualifications of the personnel installing the instrumentation shall also be included. The Contractor is solely responsible for installation and the performance of the instrumentation after installation. Badly performing or inoperative instrumentation shall be replaced at no additional cost to SCDOT.

25.3.6 Protection Plan

Geotechnical instrumentation that terminates at the ground surface (natural or man-made) is subject to damage by construction activities. Therefore, special precautions are required. As part of the installation plan, the Contractor is required to specify how the instrumentation is to be protected, not only from construction activities, but also from vandalism.

25.3.7 Installation Records

Detailed installation records are required to be submitted by the Contractor. These records fill two purposes. First, by requiring detailed installation records, the installation is more likely to be performed in accordance with accepted installation plan. Secondly, the records function as an "as-built" record and can indicate why the instrumentation is performing poorly or incorrectly, thus aiding the geotechnical engineer-of-record in determining if less reliance should be placed on a particular instrument. Having the record will also remove doubt if an instrument performs erratically by removing installation concerns as a potential cause of the problem. Presented in Table 25-4 are some items for possible inclusion on the installation record sheet.

Table 25-4, Possible Content of Installation Record Sheets (Geotechnical Instrumentation – October 1998)

Category	Content
Heading	• Project Name • Instrument type and number, including readout unit • Personnel responsible for installation • Date and time of start and completion
Planned Data	• Planned location in plan and elevation • Planned orientation • Planned lengths, widths, diameters, depths, and volumes of backfill • Necessary measurements or readings required during installation to ensure that all previous steps have been followed correctly, including post-installation acceptance tests
As-Built Data	• As-built location in plan and elevation • As-built orientation • As-built lengths, widths, diameters, depths, and volumes of backfill • Plant and equipment used, including diameter and depth of any drill casing used • A log of appropriate subsurface data • Type of backfill used • Post-Installation acceptance test
Weather	• Weather conditions
Notes	• Any notes, including problems encountered, delays, unusual features of the installation, and any events that may have a bearing on instrument behavior

25.3.8 Installation Reports

The purpose of the installation report is to provide a convenient summary of the information that personnel might need who are involved in the data collection, and processing, presentation and interpretation of the data. Listed below are some of the items that should be included in the report:

- Plans and sections sufficient to show instrument numbers and locations
- Appropriate surface and subsurface stratigraphic and geotechnical data
- Descriptions of instruments and readout units, including manufacturer's literature and photographs
- Details of calibration procedures
- Details of installation procedures (photographs are often helpful)
- Initial readings
- A copy of each installation record sheet

25.3.9 Data Collection Methods

Typically on SCDOT projects the collection of data is the responsibility of the Contractor, with the Contractor's personnel meeting the qualifications in the next Section. Data collection is typically obtained manually. In other words, physical measurements are made or the readout device is directly connected to the terminals of the instrument. Automatic Data Acquisition Systems (ADASs) are available; however, SCDOT does not have much experience in the use of these systems. Therefore, a manual collection system will be required if an ADAS is used. ADASs have the potential for remote downloading of the data, if the communications are properly setup.

25.3.10 Qualifications of Personnel Collecting Data

SCDOT requires that all personnel involved in the collection of instrument data be familiar with the instrumentation being used. These personnel shall be familiar with the installation report, so that if anomalies are encountered, they can provide feedback to the engineers processing the data. In addition, the personnel obtaining the data shall report to a licensed engineer. In the case of settlement plate readings, a licensed land surveyor is required. The qualifications of all personnel involved with the installation, calibration, maintenance and data collections shall be included as part of the Contractor's installation plan.

25.4 FIELD INSTRUMENTATION

The most commonly used types of field instrumentation for highway projects are discussed below. Included in the discussion are the role and typical uses of each instrument, a short description of methods commonly used, and common problems to be aware of with installation, reading, and interpretation of the instrumentation. For more information about particular instruments, the references cited at the end of the Chapter, as well as manufacturer manuals and websites, are recommended.

25.4.1 Slope Inclinometers

These instruments are used to monitor the magnitude, direction, and rate of subsurface deformations. Typical applications include monitoring the rate and extent of horizontal movement of embankments or cut slopes, determining the location of an existing failure surface, and monitoring deflection of retaining walls. Inclinometers can be installed at several levels on an embankment or cut slope to define the extent and nature of subsurface movements. An inclinometer consists of a grooved casing grouted vertically in a borehole. The role of the casing is to deform with the surrounding ground such that readings taken within the casing reflect accurate measurements of ground movement. Typically the grooves are aligned parallel to the direction of movement. The probe is periodically inserted down the casing and deflection of the casing is measured. The inclinometer probe contains accelerometers at either end to measure the parallel and perpendicular tilt of the casing. Successive measurements are plotted to provide a chronological indication of the extent and rate of subsurface movements.

Installation of inclinometer casing must be continued into rock or dense material that is not expected to deform. This will provide a point-of-fixity at the bottom of the casing to which other measurements through the casing can be reliably correlated to. Once drilling has proceeded to the desired depth and the inclinometer casing has been set in the borehole, the annulus between the casing and borehole side is filled with a grout that has a similar strength to that of the surrounding soil. Because the grout will induce a buoyant force on the casing, a stabilization method will be required to keep the casing in place during grout placement. Methods involving anchoring or weighting the casing bottom in the borehole are commonly used to overcome this issue. The instrument manufacturer should be consulted for recommended procedures for overcoming buoyancy. Holding the casing in place at the ground surface while grouting will cause the casing to corkscrew within the borehole which may cause errors in future readings. Inclinometers are to be installed and read in accordance with AASHTO Specification R 45-08 and the manufacturer’s specifications.

25.4.2 <u>Settlement Monitoring</u>

These instruments are used to record the amount and rate of settlement under load. The most common installation of these instruments is for use with embankments where high settlements are predicted. The instruments listed below are the recommended methods for settlement measurement associated with highway embankments. Some instruments detailed below are designed to measure settlement through depth of strata. Because subsurface settlement instruments are often damaged during construction, some form of long-term settlement monitoring at the top of an embankment should be planned. This will provide a check of the readings obtained from subsurface instruments and can help to fill in the gaps from instruments that have either been damaged or have become unreliable.

25.4.2.1 Settlement Plate

The simplest form of settlement indicator is the settlement plate, which typically consists of a steel plate placed on the ground surface prior to embankment construction. The elevation of the initial plate must be recorded before construction begins to provide a reference point for all future readings. A reference rod and protective casing are then attached to the plate. As fill placement progresses, additional rods and casing are added. Settlement is measured by determining the elevation of the top of the reference rod at specified time intervals by surveying methods. The reference rod and initial platform elevations are determined relative to several benchmarks placed outside the construction area. Settlement plates are often placed in areas where the highest settlements are predicted.

25.4.2.2 Extensometers

The probe extensometer is another instrument commonly used to measure settlement. In a typical arrangement, corrugated polyethylene pipe surrounded by rings of stainless steel wire at selected intervals is lowered into a borehole. A rigid PVC inner pipe is coupled to the corrugated pipe prior to installation. Inclinometer casing is often used as the rigid inner pipe, thereby eliminating the need for drilling two separate boreholes for measuring horizontal and vertical displacement. The annulus between the rigid inner pipe and outer corrugated pipe is filled with bentonite slurry to minimize friction and the space between the outer pipe and borehole side is filled with a grout that conforms as nearly as possible to the properties of the surrounding soils. A more rigid system consisting of PVC pipe with telescopic couplings and steel plates instead of wire rings may be more desirable in situations where the likelihood of crushing the corrugated pipe exists, such as in high fill embankments or where high settlements are predicted.

The reading device in a probe extensometer consists of an induction coil housed within a probe attached to a signal cable that leads to a readout unit at the surface. As the probe is lowered, the operator notes at what depth the probe senses the steel rings, indicated by a buzzer on the readout unit. By comparing these depths to the initial depths, a settlement profile can be obtained. A main advantage of this type of instrument to a conventional settlement plate is that a settlement profile is obtained through the entire depth of the strata in question, not just at the surface. Optical surveying is typically not required so long as the bottom of the extensometer is fixed in stable ground. Drawbacks to this method include disruption to construction activities and cost, as compared to conventional settlement plates.

25.4.2.3 Settlement Cell

The settlement cell, or liquid-level gage instrument, consists of a pressure transducer embedded beneath the embankment with liquid-filled tubes connected to a reservoir and readout unit installed on stable ground. As the transducer settles, greater pressure is imparted on the transducer by the column of liquid. Settlement is measured by converting the increase in pressure to feet or meters of liquid head. This method requires that the liquid-filled tubes be run in trenches to areas outside of the construction area. Although trenching may cause some disruption to construction activity, all readings are taken away from the construction area after the instrument is installed. Settlement cells are often installed at several depths at the same cross-section to better define the full settlement profile. The ease of automation tends to be highest for this type of settlement measurement, especially if the pressure transducer is of the vibrating-wire type. A limitation to this type of instrument is that the soils surrounding the instrument and in the trench must be installed to specifications similar to that of the surrounding fill. Otherwise harmful discontinuities may be introduced into the embankment. This instrument should be used for short-term monitoring, because this instrument can be extremely temperature sensitive.

25.4.2.4 Settlement Reference Points

Settlement reference points are installed on structures or embankments upon essential completion of construction or topping out. Settlement reference points are intended to provide long-term settlement data by relatively simple methods at the ground surface. Settlement reference points may also be installed on embankments or structures such as a retaining wall to evaluate distress or unanticipated movement.

Settlement reference points are monitored using conventional surveying methods. Settlement reference points may consist of pins driven into the ground or mounted on a structure, or may simply be a painted reference point on a structure. Data collected over time indicates the amount of settlement that has occurred at each reference point. Care should be taken to protect settlement pins from disturbance by construction equipment or traffic that will affect the validity of data.

25.4.2.5 Crack Gauges

Crack gauges refer to simple commercial devices installed on a structure, such as a retaining wall, to visually monitor vertical and horizontal movements. Crack gauges permit visual monitoring and measurement of structural movements without requiring the use of survey equipment. Several configurations of the gauges are available, such as gauges mounted on a flat surface, or gauges mounted on either side of a corner.

Typical commercial crack gauges consist of two overlapping pieces of acrylic or PVC sheets fixed in place by epoxy. The sheets are installed so that the bottom sheet is fixed to the structure on one side of the crack, and the top sheet is fixed to the structure on the opposite side of the crack. The bottom sheet contains an opaque reference grid, and the top sheet is transparent with an intersecting vertical and horizontal marker. After measuring the width of the crack at the start of the monitoring period, horizontal and vertical movements of the structure can be monitored by noting the movement of the marker over the reference grid.

Crack gauges have some limitations and their use requires judgment and experience. Movements indicated on the gauge facing do not necessarily reflect the true peak movement which may occur in a dimension not recognized by an individual gauge as mounted. Crack gauges are typically only capable of monitoring movement in two dimensions; therefore, multiple gauges mounted at several locations on the structure will be required to monitor movement in three dimensions. When movements exceed the size of the reference grid, the size of the crack is recorded and new gauges can be installed to continue the monitoring program.

25.4.3 <u>Piezometers</u>

Piezometer applications generally fall into two categories: 1) Monitoring the flow of groundwater, or 2) Providing an index of soil strength. For highway construction, piezometers are typically installed to monitor pore water pressures associated with fill embankments and existing or cut slopes. Pore water pressure monitoring provides an estimate of effective stress within a slope. An increase in pore pressure indicated by a piezometer in a slope can be a signal of an impending slide. If a dewatering system is installed to stabilize a large excavation, piezometers can be used to gauge the effectiveness of the system. The most common use of piezometers in highway construction is to monitor the initial pore pressure rise and subsequent dissipation associated with consolidation of soils beneath an embankment. Pore pressure readings taken during construction of an embankment can be used to verify design settlement assumptions and to guide further construction activities.

The term piezometer is generally used to describe pore pressure monitoring instruments where seals are placed within the ground at selected depths, so as to monitor pore pressure conditions only within a certain strata. A device that has no seals is generally termed an observation well and should only be used in homogenous and continuously permeable soils. The simplest type of piezometer is an open standpipe piezometer. In this application, a section of slotted pipe attached to riser pipe is lowered to the desired elevation. A filter is generally placed around the slotted pipe and sand is placed in the borehole around the filter to create a reading interval. A bentonite seal is then placed atop the sand and a sealing grout is used to fill the remainder of the borehole. Open standpipe piezometers have a slower response time than some of the more sophisticated instruments described below, but are generally more cost effective to install and are more reliable than other methods.

Vibrating-wire piezometers are often used in applications where fast response to pore pressure changes is desired. Other advantages include less disruption to construction activity, less chance for damage in active construction zones (provided the lead cables are protected properly), and ease of reading and automation. A vibrating-wire piezometer consists of a diaphragm connected to a tensioned wire such that changes in pore-pressure affect the tension of the wire. A readout unit is used to pluck the wire and measure the change in wire tension, which can then be converted to pore-pressure readings. Vibrating-wire piezometers are typically installed in similar fashion to open-standpipe piezometers with the pressure transducer placed inside the screened reading interval, although recent research suggests that similar results can be obtained in a fully-grouted borehole. Please refer to the reference cited at the end of the Chapter for more information on the fully-grouted installation method. Push-in type vibrating-wire piezometers provide a quick and relatively easy installation and are commonly used to monitor pore pressure changes in successive lifts of an embankment. Open standpipe piezometers can also be converted to vibrating-wire piezometers simply by lowering a pressure transducer into the well to a specified depth. Most vibrating-wire type instruments currently come with some form of lightning protection housed inside the body of the instrument, though additional measures may be needed in areas prone to lightning activity.

Another piezometer type commonly used is the pneumatic piezometer, which consists of a flexible diaphragm and sensor body connected to a junction box at the surface with twin tubes. A filter is commonly used to separate the diaphragm from the surrounding material. Pressurized gas is introduced through the inlet tube. As gas pressure exceeds the pore water pressure, the diaphragm deflects, allowing gas to vent through the outlet tube. When the operator observes a return flow of gas, the gas supply is shut off and the diaphragm returns to its equilibrium position with the pore water pressure. The operator then obtains a reading from a pressure gauge connected to the input tube. This type of instrument also features a relatively short time lag and minimal disruption to construction. Some limitations of this instrument include the complexity of choosing the proper details of instrument, difficulty of reading, and the possibility of minute gas leaks within the system causing errors in data.

Oftentimes, it is not immediately known which type of piezometer is better suited to a particular application. One way of narrowing the choice and alleviating concerns over data reliability is to install groups of redundant piezometers of different types at similar locations and depths. Generally, open standpipe piezometers are paired with vibrating-wire or pneumatic piezometers and the data are periodically compared to ensure data validity. This setup also ensures that the flow of data will not be disrupted if one instrument malfunctions.

25.4.4 <u>Tiltmeters</u>

Tiltmeters are used to monitor the change in inclination from the norm of points on the ground or on structures. Typical highway applications include monitoring the tilt of MSE or conventional retaining walls and bridge columns. The complexity of tiltmeters can range from relatively simple instruments based on a plumb line or bubble level, to more sophisticated devices equipped with accelerometers to measure inclination housed inside a protective cover. Two common transducer types are servo-accelerometers and pendulum and vibrating-wire setups. Tiltmeters can either be permanently affixed to a structure or be portable. For the portable versions, a reference plate is attached to the structure and the portable instrument takes readings after it is attached to the plate in a repeatable position. The portable tiltmeter can be used to measure tilt biaxially by rotating the instrument 180 degrees on the reference plate and taking another reading. Fixed tiltmeters can also be used biaxially by installing two transducers on the same bracket at 90-degree angles to one another.

It is imperative that the tiltmeter reference plate or mounting bracket is attached securely to the structure that is to be monitored. They are typically cemented or screwed into place. A limitation of tilt measurements is that they tend to be more localized than with other types of field instrumentation. Extrapolating tilt measurements across a structure involves assumptions about the rigidity of the structure and therefore can be very difficult. For this reason, tiltmeters are generally used in conjunction with other deformation measurement methods such as inclinometers or surveying points.

25.4.5 <u>Vibration Monitoring</u>

Vibration-producing activities such as blasting, pile driving, vibratory compaction, and operation of other heavy equipment are common activities on a highway construction project. It may be desirable to monitor the ground vibrations induced by these activities if sensitive equipment or structures are located close to the work zone. Before starting work in an area that may impact nearby structures or equipment, a condition survey shall be performed to establish base line conditions and identify any pre-existing deficiencies. A thorough post-construction condition survey should also be performed to ensure that no structures have been harmed.

A vibration-monitoring unit generally consists of some combination of geophones, sound sensors and connecting cables attached to an input and readout unit. Ground vibrations are typically reported in terms of the peak particle velocity (ppv), although other parameters such as peak acceleration, principle frequencies, and peak sound pressure levels can also be obtained with most monitoring units. Vibration monitoring results are then compared with pre-established threshold levels of structures or equipment to determine the level of risk involved.

Vibrations associated with construction activity are generally monitored at specified distance intervals away from the source to at least as far as what is perceptible to the unit operator. This distance typically varies from 100 feet to over 600 feet based on the level of anticipated vibration at the source and location of nearby structures of interest. For the initial data, readings to a distance of at least 300 feet are recommended. Vibration monitoring units should be capable of detecting velocities of 0.1 in/sec. or less.

25.4.6 Special Instrumentation

Situations may arise where field instruments other than those described above are desired for use on a project. Many instruments, such as earth pressure cells or strain gauges, are typically not used in construction projects but only in research and special projects. Other instruments, such as borehole extensometers for monitoring a rock slope or tie-backs, may serve a key role on a project. Less common methods, such as horizontal inclinometers or other specialized instruments, should only be specified in special circumstances and with prior approval from appropriate SCDOT personnel. The need for special instrumentation and the selection of instruments will be evaluated on a case-by-case basis.

25.5 CONCLUSIONS

After assuring its validity, data from field instruments shall be interpreted relative to other instrument data as well as outside factors that may affect the data. For example, during construction of an embankment on soft ground, pore pressure rises and subsequent drops can be correlated to settlement measurements as well as the level of fill placement. A measured change in one instrument but not in other corresponding instruments may signal error stemming from either the instrument itself or reading methods. Another effective way to validate instrument readings is through routine visual observation. Observation of the monitored area can provide early warning signals, such as a tension crack or evident seepage, which may not be picked up by nearby field instruments and can also guide remedial actions.

The monitoring program of a highway construction project must be able to adapt to changing conditions. Base line readings of installed instruments may paint a picture that is totally different from what was assumed during the design phase. Components such as reading interval, methods of collecting data, and presentation of data may change dramatically over the course of a project.

25.6 REFERENCES

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