Chapter 24

CONSTRUCTION SUPPORT

GEOTECHNICAL DESIGN MANUAL

January 2019

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CHAPTER 24

CONSTRUCTION SUPPORT

24.1 INTRODUCTION

The purpose of this Chapter is to provide a basic understanding of construction support as it is applied to geotechnical construction issues. Typically geotechnical construction issues are the verification of foundation resistance and integrity, review and acceptance of foundation installation plans, the implementation, review and acceptance of geotechnical instrumentation or the review and acceptance of shop plans.

24.2 QUALITY CONTROL/QUALITY ASSURANCE

Construction support performed by the GEOR typically consists of review of Quality Control (QC) and conducting Quality Assurance (QA). QC is a system of routine technical activities implemented by the Contractor to measure and control the quality of the construction materials being used on a project. QA is a systemic review and auditing of procedures and the testing of a select number of samples by the Department to provide an independent verification of the Contractor's QC program and to provide verification that the construction materials meet the project specifications. QC is performed by the Contractor, while QA is performed by the Department. Ultimately the Contractor is responsible for all materials brought on to a project site; however, it is incumbent on the Department to assure that materials meet Departmental criteria. Construction support performed by the GEOR consists of the review of the results of both QC and QA testing to assure that the project specifications are being met. Construction QA/QC is performed on foundations, some ground improvement installations and geotechnical instrumentation.

24.3 SHALLOW FOUNDATIONS

Shallow foundations are typically not used to support bridges; however, if shallow foundations are used, contact the PC/GDS for guidance in developing QA/QC procedures for shallow foundation verification.

24.4 DEEP FOUNDATIONS

24.4.1 <u>Driven Piles</u>

The Standard Specifications require the Contractor to submit a *Pile Installation Plan* (PIP) for review and acceptance prior to commencing pile installation. The PIP will be submitted to the Department in accordance with the contract documents. For consultant designed projects, the PIP should be forwarded by the RPG/GDS to the GEC for review. The GEOR shall review the PIP for adequacy and for containing the information required by the specifications and plans. The review is to include hammer analysis as described below and should include comments on items such as adjusting hammer fuel settings if needed to protect the pile integrity during driving. On consultant reviewed projects, the GEC will return the PIP to the RPG/GDS with a cover letter containing appropriate comments concerning the PIP. The PIP will be accepted or rejected by the RPG/GDS, regardless of who designed the project, (i.e. either the Department or a consultant) and shall be forwarded to the Bridge Construction Office for distribution to the Contractor. As required, rejected PIPs shall be resubmitted. One of the components of the PIP is the "Pile and Driving Equipment Data Form." Using the information contained on this form, the GEOR shall perform a Wave Equation Analysis of Pile Driving (WEAP). The WEAP analysis is used to verify that the pile driving hammer should be capable of installing the piles to the correct tip elevation and resistance without inducing excessive stresses in the pile. Piles are typically installed using 1 of 2 criteria, either resistance or elevation (depth). In some cases, both criteria may be required. Resistance driven criteria is typically based on a required blow count being achieved. The exception to this is if practical refusal is achieved. Practical refusal is defined by Section 711.4 of the Standard Specifications as 5 blows per ¼ inch of penetration. Practical refusal driving criteria may be used as long as the minimum tip elevation has been achieved. The wave equation analysis uses a range of resistances, bracketing the required (nominal) resistance, and range of different strokes. A typical Pile Installation Chart (also known as a Bearing Resistance Chart or Graph) providing driving criterion is depicted in Figure 24-1.

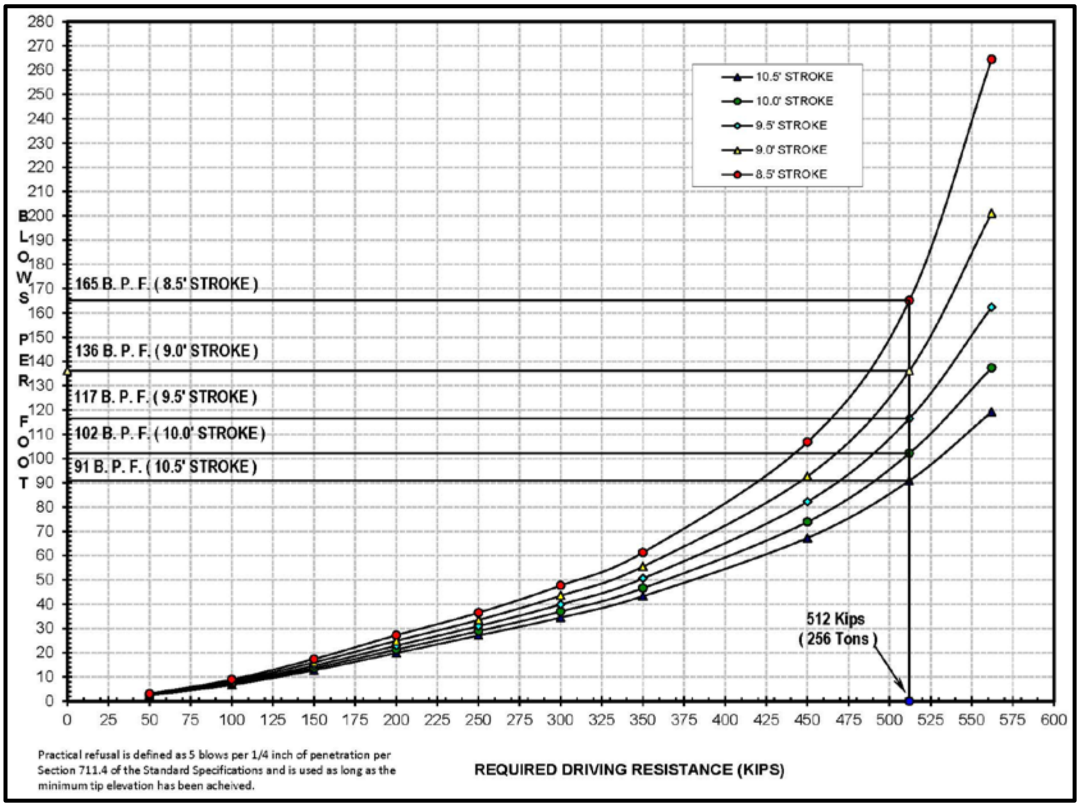

Figure 24-1, Pile Installation Chart

After the GEOR reviews and accepts the PIP, the GEOR shall be responsible for developing Pile Installation Charts as described above or if a PDA or load test is performed as described below. The GEOR shall be responsible for recommending pile lengths as needed based on index pile and/or previous production pile data.

The other criterion to control the installation of a pile is elevation (depth). This criterion is used when it is anticipated that the piles will gain strength with time or the lateral stability of the pile controls the tip elevation. Using both criteria, the GEOR should ensure that the hammer will achieve blow count criteria as set forth in the Standard Specifications. The stresses induced by the hammer should be checked to ensure conformance with the Standard Specifications.

Depending on the resistance factor (φ) selected during design, (refer to Chapter 9), load testing may be required. The load testing may consist of either high-strain (Pile Driving Analyzer (PDA)), rapid (Statnamic®) or static load tests. PDA testing may be conducted during initial driving or on restrike or sometimes both. PDA testing can confirm resistance and driving stresses. However, the resistance obtained from PDA testing is approximate and may require further refinement by using CAse Pile Wave Analysis Program (CAPWAP). Production piles that are to be tested using PDA should be 2 feet, minimum, longer than production piles to allow for the attachment of the PDA gauges. Index piles should be detailed 2 feet, minimum, longer than production piles to get full driving data to be used in determining pile lengths. Using the results from CAPWAP, a second WEAP analysis should be performed to more accurately model the installation of the pile. This is especially important when the pile is being driven to a specific resistance at a specific blow count. The GEOR shall also develop a Pile Installation Chart for this second WEAP analysis. Monitoring of stresses using the PDA is critical when piles are installed into or through dense formations or partially weathered rock (PWR), or through very soft formations. PDA testing shall conform to the requirements of ASTM D4945 – *Standard Test Method for High-Strain Dynamic Testing of Deep Foundations* as well as the requirements contained in the Standard Specifications.

Statnamic® and static load testing are performed after the installation of the pile, if required. These tests are normally performed prior to production pile driving. Statnamic® is a rapid load test and is different from the PDA, in that the pile is subjected to a “fast push” rather than a sharp blow as would be observed from a pile hammer. Statnamic® load testing of piles can be relatively costly, especially given the capacity requirements. Statnamic® load testing, if used, should follow the standard testing method developed and presented in ASTM D7383 – *Standard Test Methods for Axial Compressive Force Pulse (Rapid) Testing of Deep Foundation* and should also comply with STS SC-M-712-3 for *Rapid Axial Load Testing of Drilled Shafts.* It should be noted that modification of the STS (i.e., a Special Provision) may be required to use this STS with driven piling. In case of conflict between the ASTM and the STS, the STS shall govern. Static load testing, if required, follows the standard testing method developed and presented in ASTM D1143 – *Standard Test Methods for Deep Foundations Static Axial Compressive Load*. Static load testing can not only be expensive, but also time consuming, and is therefore not used except in design testing programs. When static load testing is performed, the results of the testing shall use the Davisson failure criterion.

24.4.2 Drilled Shafts

Similarly to driven piles, the Standard Specifications require the Contractor to submit a *Drilled Foundation Installation Plan* (DFIP) for review and acceptance prior to commencing drilled foundation installation. The DFIP will be submitted to the Department in accordance with the contract documents. On consultant designed projects, the DFIP should be forwarded by the RPG/GDS to the GEC for review. The GEOR shall review the DFIP for adequacy and for containing the information required by the specifications and plans. On consultant reviewed projects, the GEC will return the DFIP to the RPG/GDS with a cover letter containing appropriate comments concerning the DFIP. The DFIP will be accepted or rejected by the RPG/GDS, regardless of who designed the project (i.e., the Department or a consultant) and shall be forwarded to the Bridge Construction Office for distribution to the Contractor. As required, rejected DFIPs shall be resubmitted.

To verify the acceptability of constructed drilled shafts, crosshole sonic logging (CSL) testing should be required and tubes shall be installed as required by the Standard Specifications, project plans or Special Provisions. A testing report will be generated by a testing firm for review. If the CSL testing indicates no areas of concern, then the drilled shaft is accepted. However, if the CSL testing indicates areas of concern, then the following forms should be requested by the GEOR for review:

- Drilled Shaft Log
- Drilled Shaft Excavation Log
- Slurry Inspection Log
- Drilled Shaft Inspection Log

- Drilled Shaft Concrete Placement Log
- Drilled Shaft Concrete Volumes Log
- Concrete Slump Loss Test

After reviewing these logs, the GEOR should consult with the Bridge Construction Engineer on required actions. On consultant designed projects, the project team shall be responsible for evaluating the drilled foundation to determine if it meets both the structural and load resistance design requirements. The GEOR shall provide written recommendations to the Department concerning drilled foundation acceptance and/or actions to be taken as developed by the project team.

Depending on the resistance factor (φ) selected during design (refer to Chapter 9), a load test may be required. Load tests can be used to verify the existing design or modify the design based on the load test results. The GEOR should evaluate the test results and provide written recommendations concerning the diameter, penetration depth relative to a particular stratum, and/or tip elevation of the production shafts. Drilled foundation load testing consists of static (uni-directional and bi-directional), rapid (Statnamic®) or high-strain (dynamic) load testing. In a uni-directional static load test, the load is applied at the top of the drilled shafts, usually by means of a reaction beam and anchorage foundations. Typically, this type of test is impractical for drilled shafts, unless the drilled shafts have diameters ranging from 3 to 4 feet. Typically drilled shafts in this range have nominal resistances of 1,200 kips, which require a reaction system and jack to have 2,400 kips of reaction capacity. Drilled shafts having larger diameters would require very large reaction systems that would become impractical and potentially unsafe. Therefore, uni-directional static load tests are not normally performed on drilled shafts. Uni=-directional testing, if required, follows the standard testing method developed and presented in ASTM D1143 – *Standard Test Methods for Deep Foundations Static Axial Compressive Load*. Uni-directional testing can not only be expensive, but also time consuming, and is therefore not used except in design testing programs. When uni-directional testing is performed, the results of the testing shall use the Davisson failure criterion.

Bi-directional static load tests are performed by applying the load with an expendable jack(s) located between an upper and lower loading plate cast into the drilled shaft. The test is conducted by using the upper portion of the shaft as a reaction element against the base and lower portion of the drilled shaft and vice versa. An effective example of this bi-directional loading system is the Osterberg cell (O-cell) (see Figure 24-2). The maximum test load is limited by the resistance of the shaft above and below the O-cell or the maximum resistance of the O-cell. Therefore, the O-cell should be placed at the point in the shaft where the resistance above the O-cell is approximately equal to the capacity below the O-cell. The use of multiple O-cells may be used to counter the effect of either too much side resistance or too much end resistance, when compared to end or side resistance respectively (see Figure 24-3). The Davisson failure criterion shall be used to interpret the results of uni-directional and bi-directional static load tests. Refer to STS SC-M-712-1 for *Bi-Directional Static Load Testing of Drilled Shafts* construction requirements.

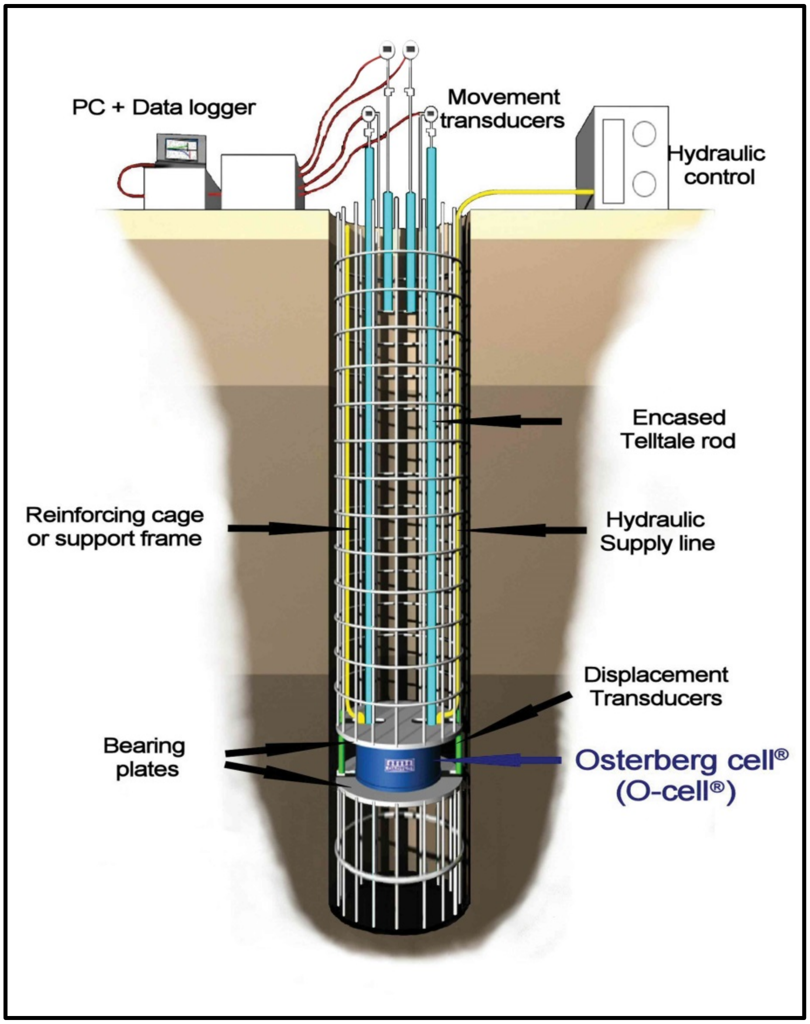

Figure 24-2, Bi-Directional Testing Schematic (LOADTEST, Inc. (2015))

Listed below are some advantages of the bi-directional static load test:

- Large reaction capacity allows testing of production-sized shafts
- With multiple cells or proper instrumentation, the base and side resistance are isolated from the resistance of other geomaterial layers
- Loading is static and can be maintained to observe creep behavior

Following are some of the disadvantages of bi-directional static load testing:

- The test shaft must be preselected so that the O-cells can be included
- It is not possible to test an existing shaft
- For each installed device, testing is limited to failure of 1 part of the shaft only, unless multiple O-cells are used
- The performance of a production shaft subject to top down loading must be computed and may require extrapolation of data in some cases
- Limitations exist related to using a test shaft as a production shaft
- The effect of upward directed loading compared to top down loading in a rock socket is not completely understood
- Displacement/capacity of shaft is limited by the stroke of the O-cell
- O-cell must be calibrated for anticipated displacement prior to testing or max capacity may not be achieved

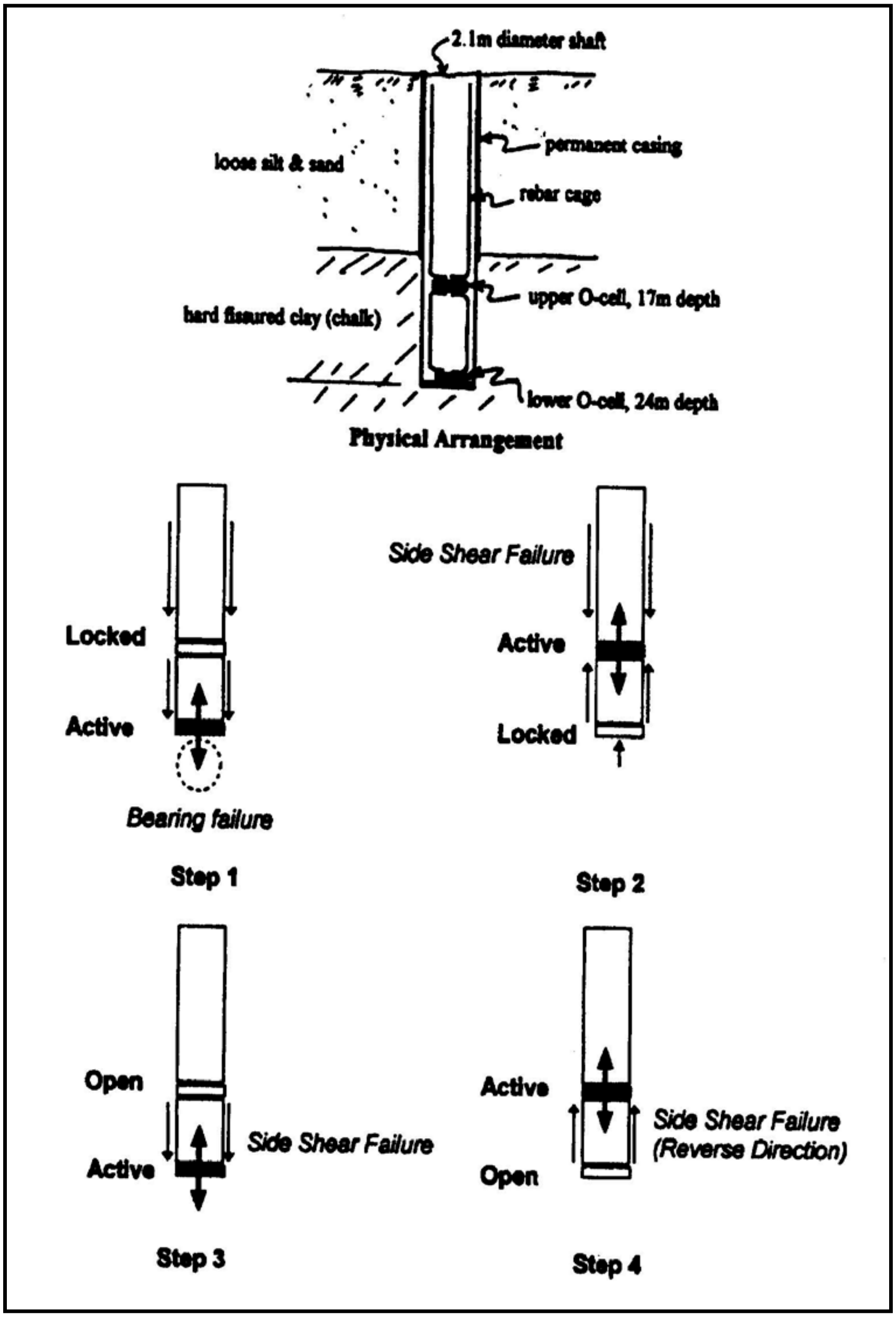

Figure 24-3, Multiple O-cell Arrangement
(O'Neil and Reese, 1999)

Rapid load testing is between static load testing and high-strain testing of drilled shafts. Rapid load testing is typically performed on a test shaft that will not be incorporated into the structure. In rapid load testing the drilled shaft is subjected to a "fast push" instead of a sharp blow as would be delivered by a pile driving hammer or a falling weight. In a rapid test, the drilled shaft acts essentially as a rigid body with the top and base of the shaft moving together. Refer to STS SC-M-713-3 for *Rapid Axial Load Testing of Drilled Shafts* construction requirements.

There are 2 methods of inducing load during the rapid test. The first method consists of dropping a weight onto the shaft, but having a soft cushion located at the top of the shaft. The soft cushion causes the weight to decelerate over a required time interval. The second method, and most common, is to accelerate a heavy mass upward using combustion gas pressure, thus pushing the shaft into the ground. Using the second method, commercially available as the Statnamic® load test apparatus, a reaction mass is accelerated vertically while an equal and opposite reaction occurs in the drilled shaft.

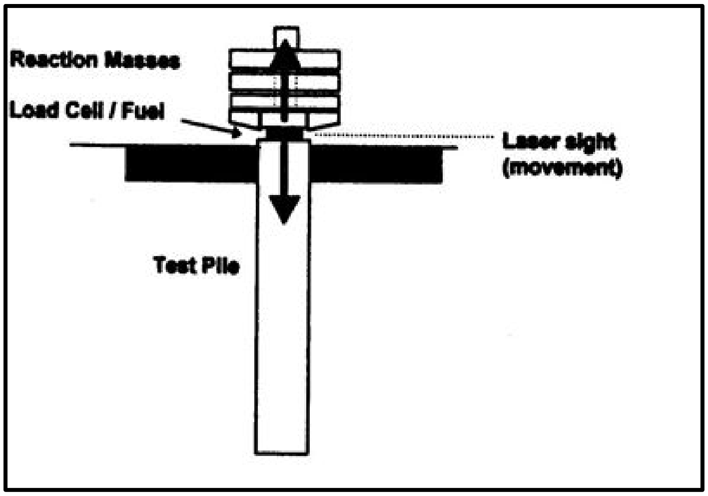

Figure 24-4, Rapid Load Test Setup
(O'Neil and Reese, 1999)

Listed below are advantages of the rapid load test method:

- Test resistances up to 10,000 kips (Statnamic®)
- Can test existing or production shafts
- Economies of scale for multiple tests
- Easily used for verification testing on shafts
- Reaction system not needed

Some disadvantages are:

- High capacity, but still limited compared to bi-directional tests
- Rate effects must be considered
- Mobilization costs for reaction weights

High-strain load testing of drilled shafts uses the same equipment and principles as PDA testing and CAPWAP analysis in driven piles. High-strain load testing uses a hammer or weight to strike the top of a shaft inducing a compression wave that propagates the length of the shaft and reflects back to the top. High-strain load testing is typically performed on a test shaft that will not be incorporated into the structure. The impact load can be induced using drop weights (see Figure 24-5) or a large pile driving hammer. If suitable measurements are obtained, then the applied load and drilled shaft response can be determined. The measurements are obtained using transducers and accelerometers mounted directly to the top of the shaft. A computer model of the shaft response to the blow is calibrated to the measurements using a signal matching technique (i.e., CAPWAP). The high-strain dynamic load test setup should always be modeled prior to testing using a wave equation model for specific shaft size and axial capacity. Because the high impact velocity can produce significant compression and tension forces in the shaft, the blow is typically cushioned using a cushioning material such as plywood or a striker plate. Refer to STS SC-M-712-2 for *High Strain Dynamic Load Testing of Drilled Shafts* construction requirements.

Figure 24-5, High-Strain Load Testing Apparatus (GRL Engineers, Inc. (2015))

Listed below are advantages of high-strain load testing:

- Large load applied at top of shaft
- Can test existing or production shafts
- Economies of scale for multiple tests
- Easily used for verification testing on production shafts
- Reaction system is not needed

Some disadvantages are:

- High resistance possible, but still limited compared to bi-directional tests
- Test includes dynamic effects which must be considered
- The applied force is interpreted from measurements on the shaft rather than from direct measurement of load and therefore is sensitive to the shaft modulus, area, and uniformity in the top 1 to 1-1/2 diameters
- Test must be designed to avoid potential damage to the shaft from driving stresses
- Mobilization costs for a large pile driving hammer or drop hammer
- Location and configuration of reinforcing steel must be accommodated
- Changes in impedance along the length of the shaft can be confused with changes in axial resistance, and therefore the impedance profile of the shaft must be reliably known.
- There may be incomplete mobilization of base resistance at early blows and loss of side resistance after multiple blows, and this issue complicates the interpretation of results.

24.5 EARTH-BORNE CONSTRUCTION VIBRATION MONITORING

Earth-borne vibrations are the motion of a ground particle, at a point in the subsurface or on the ground surface, caused as vibration energy passes through that point. The actual distance that the ground particle moves, either positively or negatively, from it's at-rest position is called displacement and is typically very small and is reported in units of inches or mils (thousandth of an inch). Construction induced vibrations may also be described as velocity, measured in inches per second (ips), and/or acceleration measured in inches per second per second (in/sec^2). Velocity is the speed at which the ground particle oscillates and should not be confused with the velocity which the wave travels through the ground (i.e. propagation velocity). Acceleration is the rate of change of velocity with time and is often normalized with the gravitational acceleration on the earth's surface (32.2 ft/sec^2 or 386.4 in/sec^2) and is reported in g's as a percent of gravity. The most common way of determining the impact of earth-borne vibrations is velocity with the peak particle velocity (PPV) being the maximum instantaneous positive or negative peak of the vibration signal. Earth-borne vibrations may be generated by various construction activities including but not limited to: pile driving (both impact and vibratory), compaction efforts (both static and vibratory), drilled shaft installation, normal construction traffic (i.e. loaded dump trucks, bulldozers, etc.), and paving operations including pavement breaking. Monitoring of earth-borne vibrations is a relatively specialized area and may be performed on construction projects that have no other instrumentation; therefore, monitoring of earth-borne vibrations is exempted from the requirements of the Geotechnical Instrumentation Monitoring Plan (GIMP), as discussed in later Sections of this Chapter. However, the GEOR may elect to include the monitoring of earth-borne vibrations in the GIMP if other geotechnical instruments are required during construction.

24.5.1 General

Construction induced ground motions are divided into 3 main wave types: compression (P), shear (S) and surface (R – Rayleigh). P- and S-waves are called "body" waves, while the R-wave is "surface" wave. The "surface" may be the ground surface or a boundary of the halfspace. R-waves consist of horizontal and vertical components that attenuate (i.e. dampen out) rapidly with depth. P- and S-waves tend to propagate through the soil in a hemispheric shape, while R-waves tend to propagate cylindrically through the soil. P-, S-, and R-waves travel at different speeds, with the P-wave being the fastest, followed by the S-wave with the R-wave being the slowest. Therefore, the P-wave arrives first at the receptor, then the S-wave, followed lastly by the R-wave (see Figure 24-6). According to Andrews, Buehler, Gill, and Bender (2013) approximately 67 percent of the wave energy is transmitted by the R-wave, 26 percent by the S-wave and the remaining 7 percent by the P-wave.

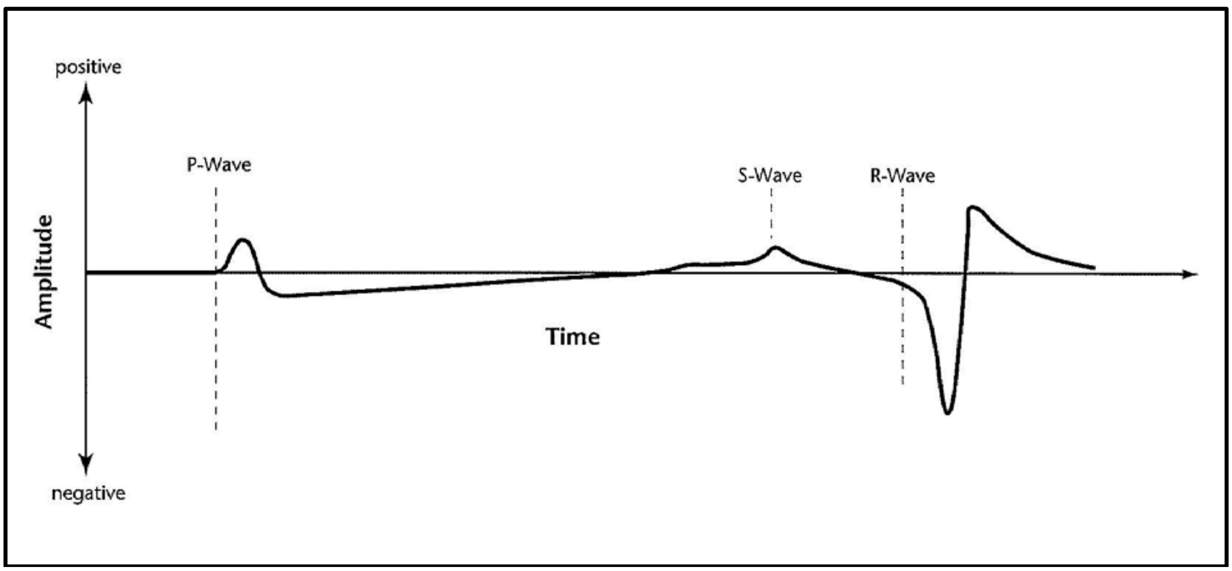

Figure 24-6, Arrival Time for P-, S-, and R-waves (Andrews, et al. (2013))

To properly describe the ground motion as the earth-borne vibrations passes through it, 3 mutually perpendicular components must be measured. A triaxial geophone has 3 independent transducers, each aligned at mutually perpendicular directions. The longitudinal direction is aligned with the axis of vibration propagation and the longitudinal geophone measures the compression or P-wave. The transverse direction is at a right angle to the longitudinal direction within the same horizontal plane. The transverse geophone measures the shear or S-wave. The vertical direction measures the movement in the vertical plane, which often has the highest amplitude.

Vibration-producing activities such as blasting, pile driving, vibratory compaction, and the 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. Please note that earth-borne vibrations induced by blasting are not included in this Manual, contact the PCS/GDS if blasting is required on a project for specific instructions on design and preparation of a Special Provision to monitor earth-borne vibrations induced by blasting.

Earth-borne construction vibrations can adversely impact 3 types of receivers: structures, people and equipment/operations. Of these 3 types of receivers, structures typically can sustain the highest vibration levels without being impacted; these impacts are normally described as damage. The impacts to humans are best described as annoyance or disturbance, while the impacts to equipment/operations are described in terms of hindering or reducing functionality. The impacts to these receivers are discussed in the following paragraphs.

24.5.2 Structures

The use of the term damage can be a very misleading term since damage can range from hairline cracks in sheetrock walls to complete collapse of the structure. Dowding (1996) provides a more precise definition of damage as generally used by the blasting industry. The definitions are provided below:

- Cosmetic cracking including threshold damage – Opening of old cracks, and formation of new plaster cracks; dislodging of loose structural particles such as loose bricks in chimneys
- Architectural or minor damage – Superficial, not affecting the strength of the building (e.g. broken windows, loosened or fallen plaster), hairline cracks in masonry
- Structural cracking or major damage – Serious weakening of the building or adjacent facilities (e.g. large cracks or shifting of foundations or bearing walls, major settlement resulting in distortion or weakening of the structure, walls out of plumb)

Project vibration limits are typically established to prevent threshold or cosmetic cracking.

24.5.3 People

Earth-borne construction vibrations affect people in 2 ways; the vibrations can annoy people and/or the vibrations cause the perception of damage. People can feel vibrations far below the level that causes damage to structures, but can be very annoying or cause loose items within the structure to rattle (i.e. windows, dishes, etc.). When people feel vibrations or hear items rattling, they almost immediately think of damage and start looking for evidence of damage. Often people discover cracks in walls, ceilings, or foundations that hadn’t been previously noticed and now associate the cracks with the earth-borne construction vibrations.

24.5.4 Equipment/Operations

Vibrations can adversely impact sensitive equipment and/or operations, such as hospitals, computerized industries, research centers or industrial machinery. Some equipment (i.e. optical microscopes, cell probing devices, magnetic resonance imaging (MRI) machines, scanning electron microscopes, photolithography equipment, micro-lathes, and precision milling equipment, etc.) can be more sensitive than humans since the operation of the equipment can be impaired below the vibration perception threshold. However, most of this equipment and/or operations must be isolated within the building housing the equipment or operations to prevent normal building activity from disturbing the equipment and/or operation. Because of this earth-borne construction vibrations rarely impact sensitive equipment/operations.

24.5.5 Impact of Earth-borne Construction Vibrations

Based on research performed by the Minnesota Department of Transportation (MnDOT), cosmetic damage cannot typically be attributed to construction vibration levels below 0.5 ips. Therefore, MnDOT established the distance at which earth-borne construction vibrations will be below 0.1 ips. This level (0.1 ips) was selected since people complain about vibrations having a velocity of more than 0.1 ips. These distances are provided in the following table for various construction activities and may be used for preliminary estimating.

Table 24-1, Distance where Vibration drops below 0.1 ips (MnDOT (2013))

Construction Activity	Distance[1] (feet)
Embankment Compaction	50
Subgrade Compaction	100
Vibratory Pile Driving[2]	150
Pavement Breaking	180
Bituminous Overlay	200
Impact Pile Driving	200
Construction Blasting	300

[1]For estimating purposes only
[2]SCDOT assumes that vibration of drilled shaft casing would have the same distance

Pile driving can create earth-borne vibrations that can cause damage to structures and disturb people nearby. Other construction activities, such as pavement breaking, vibratory compaction, and the general use of heavy hauling and excavating equipment, typically produce earth-borne vibrations that are below the level necessary to cause damage, unless the source of the vibrations is very close (< 25 feet). Therefore, these lower intensity vibrations can be considered annoying and may cause people to believe that the building is being damaged, when in reality it is not being damaged. However, there are certain conditions such as close proximity to historical buildings or buildings that house historical or antique artifacts that may require special attention to avoid damaging the structure or the artifacts in the structure.

People's perception of vibration is not an accurate gauge of the damage potential of vibration. Therefore, when assessing the potential for impacts due to earth-borne construction vibrations, it is necessary to consider both: the actual potential to cause damage and the potential for causing complaints about being damaged. Vibrations do not affect all structures similarly. Some of the factors that may affect a structures ability to withstand vibrations are: condition, type of construction, geometry, orientation, subsurface geology, etc.

Structures are typically strongest immediately after construction and become weaker through the years as the structure receives many cycles of stress-strain caused by changes in temperature and humidity, ongoing vibration events, and settlement of the foundation soils. Damaged structures are typically more susceptible to additional damage caused by an external vibration event. Historic structures are typically in poorer condition than more modern structures due to their longevity and inferior building materials. Therefore, historic structures are typically given a lower vibration limit than more modern structures, since materials to make repairs may no longer be available and permanent loss of the historic structure may not be considered tolerable to the public. The existing condition of a historic structure shall always be assessed within a given radius of the source of earth-borne construction vibrations. This radius is normally established based on prior experience; calculations based on damage probability and predicted vibration levels; political concerns; or a combination of all 3.

Structures that have been engineered are typically constructed of stronger, more durable materials (e.g. steel and concrete) than non-engineered structures constructed of materials like wood. The engineered structures are often founded on deep foundations or on improved soil to increase bearing resistance and decrease settlement.

24.5.6 Vibration Prediction

Andrews, et al. (2013) provides various equations to estimate the PPV for various pieces of construction equipment at differing distances from the construction equipment. The construction equipment includes impact pile drivers, vibratory pile drivers, hydraulic breakers, and other general construction equipment (i.e. vibratory rollers, bulldozers, loaded trucks, etc.). The equation for estimating the PPV for impact pile driving (IPD) is:

$$PPV_{IPD} = 0.65 * \left(\frac{25}{D}\right)^{n} * \left(\frac{E_{IPDEquip}}{36{,}000}\right)^{0.5}$$ **Equation 24-1**

Where,

PPV_{IPD} = Peak Particle Velocity induced by impact pile driving, ips
D = Distance from pile driver to the receiver, ft
n = A value related to the vibration attenuation rate through ground, see Table 24-2
$E_{IPDEquip}$ = Rated energy of impact pile driver, foot-pounds (ft-lbs)

The constant 0.65 in the above equation is the reference PPV for the reference pile driver at a distance of 25 feet from the pile driver and has units of ips. The constant 36,000 is the rated energy of the reference pile driver in ft-lbs. The term "n" is determined using Table 24-2 to more accurately account for in-situ soils.

Table 24-2, Suggested "n" Values Based on Soil Class (Andrews, et al. (2013))

Soil Class	Description of Soil Material	"n"
I	Weak or soft soils: loose soils, dry or partially saturated peat and muck, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, top soil. (shovel penetrates easily)	1.4
II	Competent soils: most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel)	1.3
III	Hard soils: dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, need pick to break up)	1.1
IV	Hard, competent rock: bedrock, freshly exposed rock. (difficult to brake with hammer)	1.0

The equation for estimating the PPV for vibratory pile driver (VPD) is very similar to the equation for impact pile drivers; with the exception the rated energy of the pile hammer is not required. The equation below is used to estimate the PPV_{VPD}:

$$PPV_{VPD} = 0.65 * \left(\frac{25}{D}\right)^n$$ **Equation 24-2**

Where,

PPV_{VPD} = Peak Particle Velocity induced by vibratory pile driving, ips
D = Distance from pile driver to the receiver, ft
n = A value related to the vibration attenuation rate through ground, see Table 24-2

The constant 0.65 in the above equation is the reference PPV for the reference pile driver at a distance of 25 feet from the pile driver and has units of ips.

The equation for estimating the PPV for hydraulic breakers (HB) (also called hoe-rams, mounted impact hammers, etc.), for the demolition of concrete structure or pavement (i.e., asphaltic concrete or Portland cement concrete) is very similar to the equation for impact pile drivers; with the exception that the referenced energy of the hydraulic breaker is reduced to 5,000 ft-lbs and the PPV_{REF} is reduced to 0.24 ips for the reference hydraulic breaker. The equation below is used to estimate the PPV_{HB}:

$$PPV_{HB} = 0.24 * \left(\frac{25}{D}\right)^n * \left(\frac{E_{HBEquip}}{5{,}000}\right)^{0.5}$$ **Equation 24-3**

Where,

PPV_{HB} = Peak Particle Velocity induced by hydraulic breaker, ips
D = Distance from hydraulic breaker to the receiver, ft
n = A value related to the vibration attenuation rate through ground, see Table 24-2
$E_{HBEquip}$ = Rated energy of hydraulic breaker, foot-pounds (ft-lbs)

Andrews, et al. (2013) recommend that the PPV for other construction equipment ($PPV_{ConstEquip}$) can be estimated using the following equation. The reference PPV (PPV_{Ref}) for different pieces of construction equipment can be obtained from Table 24-3.

$$PPV_{ConstEquip} = PPV_{Ref} * \left(\frac{25}{D}\right)^n$$ **Equation 24-4**

Where,

$PPV_{ConstEquip}$ = Peak Particle Velocity induced by various pieces of construction equipment, ips
PPV_{Ref} = Reference PPV for various pieces of construction equipment at 25 ft, ips, see Table 24-3
D = Distance from construction equipment to the receiver, ft
n = A value related to the vibration attenuation rate through ground, see Table 24-2

Table 24-3, Reference PPV for Various Pieces of Construction Equipment (Andrews, et al. (2013))

Equipment	PPV_{Ref} at 25 ft (ips)
Vibratory roller	0.210
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003
Crack-and-seat operation	2.400

24.5.7 Vibration Criteria

Vibrations can be created by either continuous/frequent intermittent sources or by transient sources. Continuous sources of vibrations include: excavation equipment; static compaction equipment; tracked vehicles; traffic on a highway; vibratory pile drivers; pile-extraction equipment; and vibratory compaction equipment. Transient sources of vibrations include: impact pile drivers; blasting (not covered by this Manual); drop balls; "pogo stick" compactors; and rubblization (i.e., break-and-seat or crack-and-seat) equipment. Single transient vibration sources will not be considered for developing criteria; however, some of the sources of transient vibrations such as impact pile driving and crack-and-seat operations will be considered frequent intermittent sources for this Manual. Provided in the following table are structure types including condition and the maximum allowable PPV.

Table 24-4, Maximum Allowable PPV for Structures

Structure Type and Condition	Maximum PPV[2] (ips)
Extremely fragile historic buildings, ruins, ancient monuments[1]	0.08
Fragile buildings[1] (i.e. sensitive structures and hospitals)	0.10
Historic and some old buildings[1]	0.25
Older residential structures (i.e. built with plaster and lathe)	0.30
New residential structures (i.e. built with sheetrock)	0.50
Modern industrial/commercial buildings (i.e. engineered)	0.50

[1]Contact SCDOT Environmental Services or the Program Manager for a list of historic structures adjacent to the project site.
[2]PPVs will have frequencies in the range of 1 to 100 Hertz.

As indicated previously, people living near a construction site can feel the earth-borne vibrations that are induced by construction. An individual's reaction may include annoyance and/or the perception that damage is being caused by the vibrations. Provided in the following table are various PPVs that could lead to annoyance of those people who reside around the construction site.

Table 24-5, Maximum Allowable PPV to Avoid Annoyance

Human Response	Maximum PPV (ips)
Barely Perceptible	0.01
Distinctly Perceptible	0.04
Strongly Perceptible	0.10
Severe	0.40

No maximum PPV values have been established for sensitive equipment or operations. Project specific PPVs will need to be developed for ultra-sensitive/sensitive equipment or operations.

24.5.8 Earth-borne Vibration Monitoring Evaluation

The GEOR shall evaluate the potential impact of earth-borne vibrations from a construction site on the surrounding/adjacent properties. Previous studies have shown that blasting, pile driving and pavement breaking have been documented to have the potential to cause damage to structures. As indicated previously, blasting will not be covered by this Manual. If blasting is required on a project site, contact the PCS/GDS for further instructions. For pile driving and pavement breaking, the potential damage from earth-borne vibration is at locations in relatively close proximity to the activity. However, because the threshold of perception for vibration is much lower than the threshold for damage, claims of damage often arise because of perceptible vibration and not because of actual damage. To limit the potential for damage claims related to earth-borne vibrations, Andrews, et al. (2013) has developed the following process:

1) Identify potential problem areas surrounding the project site
2) Determine conditions that exist before construction begins
3) Inform the public about the project and potential vibration-related consequences
4) Schedule work to reduce adverse effects
5) Design construction activities to reduce vibrations
6) Notify nearby residences and property owners that vibration-generating activity is imminent
7) Monitor and record vibration from the activity
8) Respond to and investigate complaints

As part of first step, the GEOR shall estimate the PPV at various distances from the project for the various pieces of construction equipment anticipated being used for project construction. These estimated PPVs shall be provided in both the preliminary as well as final geotechnical reports for the project site. The PPVs estimated for the PGER should be anticipated being very approximate since no pile energy requirements will be developed at this stage. The estimated PPVs from this study will be used to determine if there is a potential earth-borne vibration concern at a project site. The distances provided in the table below shall be used. These distances are measured from the source of the vibration (i.e. from either end of the bridge for pile driving). However, it should be noted that the distance between potential vibration sources and receptors may need to be increased, especially if the project is not viewed by the general public as being beneficial or if the project is unpopular. The GEOR shall consult with the project team to determine if there is public perception concern with the project.

Table 24-6, Distance between Vibration Source and Potential Receptors

Potential Receptor	Distance (ft)
Sensitive structures	700
Hospitals	500
Extremely fragile historic buildings, ruins, ancient monuments[1], other historic or old buildings	300
Residential structures: Older residential structures (i.e. built with plaster and lathe) New residential structures (i.e. built with sheetrock)	250
Engineered structures (i.e., modern industrial/commercial buildings)	150

[1]Contact SCDOT Environmental Services or the Program Manager for a list of historic structures adjacent to the project site.

The identification of these potential receptors shall be made during the initial site visit prior to commencing field operations. The GEOR shall attempt to identify all potential receptors within the given radius. For example, if a hospital is located 450 feet from one end of the project, a 500-foot radius from either end of the project will be used and all residential and engineered structures within that radius will be identified. Therefore the larger distance shall be used for potential receptor identification purposes and all structures within that distance shall be considered regardless if the structure is located beyond the limit established for that structure, (i.e., a residential structure located 350 feet from the bridge with a hospital located 450 feet away from the bridge). The identification will include the type of structure (i.e. residential, engineered, historic, etc.), the name of the property owner, the street address of the property and unique identifier for each property. Names of property owners can be obtained from the SCDOT ROW Office or from local property tax records.

For the purpose of this Manual, sensitive receptors have equipment and/or operations similar to optical microscopes, cell probing devices, magnetic resonance imaging (MRI) machines, scanning electron microscopes, photolithography equipment, micro-lathes, and precision milling equipment. This list is not meant to be all inclusive. If industrial facilities are noted within 700 feet, contact the Program Manager for additional information. The Program Manager should either contact the facility or request the ROW Office to contact the facility to determine what the industrial process is and if it is vibration sensitive. A hospital as defined for this Manual is a medical facility that contains surgical suites; operating theatres or MRI machines. This could include some Medical Office Buildings that have the capability for having outpatient procedures performed. As indicated in Table 24-6, contact either the SCDOT Environmental Services Office or the Program Manager for a list of identified historic buildings, ruins and monuments. Residential structures can be single or multi-family. Engineered structures are typically constructed of steel and/or concrete, are used for non-residential purposes and do not contain sensitive operations as previously discussed.

Once the GEOR has identified the potential receptors or lack thereof around a construction site, in the second step, the Director of Construction in consultation with the project team, the SCDOT Construction Office, and the District Construction Engineer (DCE) will determine whether vibration monitoring is required or not.

There will be times when a property owner will not allow their structures to be surveyed. A notation shall be made as to time and date, the specific comment made as well as who made the statement. On some occasions, a property owner may terminate the preconstruction damage assessment survey prior to its completion. This termination shall be noted with the same information as that required when survey isn't permitted.

It may be advantageous to conduct a post construction damage assessment survey to verify that no additional damage has been caused by construction activities. The decision to perform a post construction damage assessment survey should be made by project team in consultation with the Director of Construction, the DCE and the RCE.

The third step in this evaluation process is notifying the public vibrations may be generated during construction. This announcement should be prepared by the project team and sent to all property owners previously identified in Step 1. This announcement will be made in whatever method is deemed appropriate by the project team, including the SCDOT ROW Office.

The fourth step is to schedule work to reduce adverse effects of earth-borne vibrations. For example, if pile driving is to be performed in a primarily residential area, the contract may include a Special Provision indicating that pile driving may only be performed during certain hours, with those hours coinciding with the normal work day. The Contractor will typically be responsible for determining the construction schedule and the Contractor should be aware of the potential impacts on the surrounding properties from earth-borne vibrations induced by construction activities.

The fifth step is to design construction activities to minimize earth-borne vibrations. The GEOR may minimize earth-borne vibrations by using a smaller hammer, requiring a new pile cushion for each pile, etc.

As part of the sixth step, the project team is required to inform all property owners identified previously that vibration inducing activities will commence on a given date. In addition, provide a written notice 7 calendar days prior to the construction activity at a minimum. The notice should consist of a letter sent to each property owner.

Earth-borne vibrations shall be monitored and recorded in accordance with the project specific Special Provision for *Earth-borne Vibration Monitoring*.
The final step is to respond to and investigate all complaints that have been generated as a result of the earth-borne vibrations. The process for handling complaints and the investigation

of the complaints shall be determined by the RCE with consultation with the project team, the Director of Construction the DCE and the RCE.

24.5.9 Addressing Earth-borne Vibration Concerns

SCDOT has developed 2 levels of earth-borne vibration monitoring that can be provided on a project, depending on several things such as structure susceptibility to damage, proximity to vibration producing activities, etc.

Level 1 – No potential receptors within the specified distances previously provided. No vibration monitoring required.

Level 2 – Potential receptors are located within the specified distances indicated in Table 24-6. Earth-borne vibration monitoring may be required. The need for earth-borne vibration monitoring will be determined by the project team in conjunction with the Director of Construction, the DCE and the RCE. If required, earth-borne vibration monitoring will be performed by SCDOT. In addition, the project team, the Director of Construction, the DCE and the RCE will jointly decide if a pre-construction baseline vibration monitoring study is required. The RCE in conjunction with the project team, the Director of Construction, and the DCE will determine whether a pre-construction and/or post-construction damage assessment survey will be required and conducted. The GEOR shall prepare a Special Provision for each project that requires earth-borne vibration monitoring.

The appropriate level of Earth-borne Vibration Monitoring shall be indicated on the “General Notes” sheet of bridge plans. In addition, the appropriate level shall also be indicated on the “General Notes” sheet of road plans as required.

24.5.10 Earth-borne Vibration Monitoring Equipment

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.

Portable seismographs are typically used for monitoring the velocities of ground vibrations resulting from construction activities. The seismographs should have the following minimum features:

- Seismic range: 0.01 to 5 ips with an accuracy of ±5 percent of the measured PPV or better at frequencies between 1 and 100 Hz and with a resolution of 0.01 ips or less.
- Frequency response (±3 dB (decibels)) : 2 to 200 Hz

Three channels for simultaneous time-domain monitoring of vibration velocities in digital format on 3 perpendicular axes or components: 1 vertical and 2 horizontal (radial and transverse). The seismograph shall be positioned with the longitudinal axis toward the vibration source.

24.5.11 Baseline Earth-borne Vibration Study

For a Level 2 earth-borne vibration monitoring scenario, the project team, the Director of Construction, the DCE and the RCE may require a baseline earth-borne vibration study. This baseline study should be considered if sensitive structures, hospitals or historic buildings are located within the specified distances given in Table 24-6 of the proposed project site. In addition, the baseline earth-borne vibration study may be considered for other structures around the project. The purpose of the baseline earth-borne vibration study is to establish the background levels of vibration that are induced at a site by existing sources such as traffic, industrial machinery or railroads, etc. In some cases the vibrations from these sources may exceed the limits allowed in this Chapter. The baseline vibration study should be performed for at least 6 months but for no more than 12 months prior to the commencement of construction. The baseline earth-borne vibration study shall be performed by 1 of the consultants selected for the “On Call Structure Foundation Testing and Engineering Services” contract. GECs shall contact the RPG/GDS for list of consultants on the contract. The results of the baseline earth-borne vibration study shall be provided to the GEOR, who shall use the baseline study to prepare an Earth-borne Vibration Monitoring Special Provision.

24.5.12 Pre- and Post-Construction Condition Survey

As indicated previously, the RCE in consultation with the project team, the Director of Construction and the DCE will determine if Pre- and/or Post-Construction Condition Survey of the structures surrounding the project is required. The Pre- and Post-Construction Condition Survey will occur prior to the commencement of vibration inducing construction activities and immediately after completing vibration inducing construction activities. The purpose of this survey is to determine the condition of the structures surveyed prior to commencing vibration inducing construction activities and serves as evidence of or lack of damage induced by the vibrations. Measure the Source to Potential Receptor distance from both ends of the bridge or source of vibrations. Include documentation of interior floor surfaces whether slab-on-grade or floor with crawl space beneath and above grade accessible walls, ceilings, floors, roofs and the visible exterior as viewed from the ground level. The survey should detail (by engineering sketches (including measurements), digital video, digital photographs and/or field notes) any existing structural, cosmetic, plumbing or electrical damage. All documentation of existing building conditions and information concerning the type and location of crack monitors shall be presented to the GEOR in a report prior to or immediately after any vibration inducing construction activity. If crack montiors are used, the GEOR shall estiablish the schedule for when the monitors are to read. This schedule shall be provided to the RCE for the actual collection of the data by 1 of the consultants selected for the “On Call Structure Foundation Testing and Engineering Services” contract. The consultant shall provide the results to the RCE who will in-trun provide the results to the GEOR for evaluation. Likewise immediately after the completion of vibration inducting construction activities, conduct a Post-Construction Condition Survey to include documentation of any differences in the defects noted in the Pre-Construction Condition Survey as well as any new defects.

24.5.13 Earth-borne Vibration Monitoring Plan Notes

The GEOR shall ensure that 1 of the notes provided in Chapter 22 is placed on the appropriate plan sheets.

24.5.14 Earth-borne Vibration Monitoring Special Provision

The GEOR is required to prepare an Earth-borne Vibration Monitoring Special Provision for inclusion in the construction contract. The Special Provision shall indicate the Level of Earth-borne Vibration Monitoring required for that specific project. For Level 1 no earth-borne vibration monitoring is required since there are no potential receptors present within the indicated distances (see Table 24-6). As indicated previously, the project team, the Director of Construction, the DCE and the RCE will decide if earth-borne vibration monitoring is required for Level 2 based on the number, location and type of potential receptors near the project. Please note that Level 2 will be marked on the appropriate “General Notes” sheets because of the presence of potential receptors. If the decision is made to not perform earth-borne vibration monitoring, then no Special Provision will be required. If the decision is made to perform earth-borne vibration monitoring, then a Special Provision is prepared indicating to the Contractor that is a Level 2 site and the monitoring will be performed by the Department. The Special Provision should include at a minimum:

- The required threshold PPV to be below
- The distance to the nearest structure of concern
- If earth-borne vibration monitoring affects the Contractor's means and methods, any and all costs associated with changing means and methods are considered incidental to the construction item
- That RCE may halt construction if the threshold PPV is exceeded
- No time or money will be provided to the Contractor if the RCE halts construction due to exceeding the threshold PPV
- The Contractor is required to alter vibration producing activity to obtain PPVs below the threshold PPV
- Indicate if a Pre-Construction Condition Survey is conducted
- Indicate that the RCE will determine if a Post-Construction Condition Survey will be conducted
- All damage that occurs from exceedance of the threshold PPV will be the responsibility of the Contractor to repair at no additional cost to SCDOT
- Any damage that occurs below the threshold PPV will be the responsibility of SCDOT

24.6 GEOTECHNICAL INSTRUMENTATION

This Section provides a general overview of the selection and use of geotechnical instrumentation for SCDOT construction projects. There are 2 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. This Section 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 that includes a discussion of the requirements for the instrumentation, location of the instrumentation and monitoring of the instrumentation. For more specifics regarding the information presented herein, please refer to Dunnicliff (1998). Listed below are the Supplemental Technical Specifications (STSs) for selected geotechnical instruments. If a geotechnical instrument is required for which an STS is not written, then the GEOR is required to develop a Special Provision in accordance with Chapter 23.

Table 24-7, STSs Available from SCDOT

STS Name	STS Number
Settlement Plates	SC-M-203-4
Vibrating Wire Piezometer	SC-M-203-6
Settlement Sensors	SC-M-203-7
Vibrating Wire Rod Extensometer	SC-M-203-8
Slope Inclinometer Casing	SC-M-203-9
Total Pressure Cell	SC-M-203-10
Vibrating Wire Data Collection Centers	SC-M-899-1

This Section also discusses the interpretation of the results of geotechnical instrumentation. The results obtained from geotechnical instrumentation require review by the GEOR in order to determine if the data is meaningful. On projects in which the GEC reviews the results of geotechnical instrumentation, the GEC shall be responsible for evaluating the geotechnical instrumentation data to determine if it meets the design requirements. The first question concerning the results of geotechnical instrumentation is: "Was the data collected in a manner consistent with the plans, specifications and special provisions?" If the data was not collected in a consistent manner, every effort should be made to determine why not. If the data collected is consistent, next check to determine the numerical accuracy. Finally, the data should be checked for consistency with previous data. If the data is not consistent, does a hypothesis exist that explains all the data? If not, then consideration should be given to the point that the data is bad and should be discarded. The interpretation of data collected from the various forms of geotechnical instrumentation will be discussed within each Subsection that covers a specific geotechnical instrument.

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 activities 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.

The planning of 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 Dunicliff (1998) 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.

24.7 MONITORING PLAN

A Geotechnical Instrumentation Monitoring Plan (GIMP) shall be prepared and submitted by the GEOR when any of the following conditions are met:

- A Vibrating Wire Data Collection Center or other automated monitoring device is to be used for a project
- When more than 2 geotechnical monitoring instruments are required
- When the consequences of failure of the construction being monitored could lead to a potential loss of life
- When a Chain of Command is required
- A GIMP is required by SCDOT

The GIMP should be submitted as part of either the BGER or the RGER, but may be submitted as a stand-alone document if permitted by the PC/GDS. The GIMP shall be submitted at least 3 months prior to the project letting date. After review and acceptance of the GIMP, the GEOR shall convert the GIMP into a Special Provision. The following Section shall be added at the end of the GIMP Special Provision:

BASIS OF PAYMENT

No payment will be made for the Geotechnical Instrumentation Monitoring Plan (GIMP). All payments are considered incidental to the individual Geotechnical Monitoring Instruments required for this project.

The GIMP Special Provision shall be forwarded to the Letting Preparation Engineer for inclusion with the construction contract documents.

The elements to be included in the GIMP are detailed below and generally follow the guidelines set forth in Dunnicliff (1998). Table 24-8 provides a list of the elements used in developing a monitoring plan.

Table 24-8, 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. Estimated 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. 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 GEC, familiar with the instrumentation being used. The processing, presentation, interpretation and reporting are typically provided by the GEOR.

24.7.1 Definition of Project Conditions

This Section of the instrumentation plan should include a summary of existing conditions and of proposed construction, if applicable. A short summary of the relevant information from BGER or RGER 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.

24.7.2 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, what 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 has clearly defined objectives.

24.7.3 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.

24.7.4 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.

24.7.5 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 GEOR in case a situation arises that needs immediate attention.

24.7.6 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.

24.7.7 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.

24.7.8 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.

24.7.9 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.

24.7.10 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.

24.7.11 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.

24.7.12 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 detailed 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.

24.8 MONITORING PLAN EXECUTION

As discussed previously, the installation of geotechnical instrumentation is typically 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 24-9.

Table 24-9, 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

24.8.1 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.

24.8.2 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 STSs or Special Provisions shall also be met.

24.8.3 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 2 or 3 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 24-10 indicates some possible items for the pre-installation testing program.

Table 24-10, Possible Items in Pre-Installation Tests (Dunnicliff (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 2 or 3 points, if practicable • Check 0.0 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

24.8.4 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).

24.8.5 Installation Methods

There are numerous ways to install the geotechnical instrumentation. The STSs and Special Provisions 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.

24.8.6 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.

24.8.7 Installation Records

Detailed installation records are required to be submitted by the Contractor. These records fill 2 purposes. First, by requiring detailed installation records, the installation is more likely to be performed in accordance with the 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 GEOR 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 24-11 are some items for possible inclusion on the installation record sheet.

Table 24-11, Possible Content of Installation Record Sheets (Dunnicliff (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

24.8.8 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

24.8.9 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, such as Vibrating Wire Data Collection Centers. 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.

24.8.10 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 GEC processing the data. In addition, the personnel obtaining the data shall report to a licensed engineer working for the GEC. 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.

24.9 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.

24.9.1 Slope Inclinometers

These instruments are used to monitor the magnitude, direction, and rate of subsurface horizontal 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 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 45-13 – *Standard Practice for Installing, Monitoring, and Processing Data of the Traveling Type Slope Inclinometer* and the manufacturer's specifications. Inclinometer casing conforming to the requirements of STS SC-M-203-9 for *Slope Inclinometer Casing* shall be used.

The review of inclinometer data should indicate first that the bottom of the casing is placed firmly in material that is not moving (i.e., below the potential/actual failure surface). Second, the review should indicate that all subsequent data is indicating movement "downhill." If the data indicates movement in the opposite direction, review the procedures for obtaining the data with field personnel. In addition, the actual movement data should be compared to the theoretical (design) movements to determine if the predicted is similar to the actual. From this comparison, it may be possible to predict additional movements.

24.9.2 Settlement Monitoring

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 in the following Subsections 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.

The monitoring of settlement is probably the most common type of geotechnical instrumentation used by SCDOT. Typically settlement data consists of either survey (elevation) data or pore pressure data. Survey data is obtained from various points that are compared to established benchmarks, while pore pressure data is obtained from piezometers. The first check of the data is to determine if the numerical calculations are consistent. The second check and more important check, is the trend of the data, i.e. does the data continue to indicate downward movement. With pore pressure data, the second check is whether or not the pore pressures are approaching a static pore pressure level. It should be noted that the before construction pore pressure level will not be obtained, but some higher level will be. Both the survey data and the pore pressure data should approach a trend line where there is very little difference between readings. Once this happens, settlement is assumed to be over. While settlement monitoring is occurring, the amount of actual settlement should be compared to the predicted amount of settlement. One method for determining if settlement (based only on survey data) is complete is to use Taylor's square root of time method. Another method for determining the completion of settlement is the use Asaoka's method.

24.9.2.1 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 initial elevation of the 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. Settlement plates conforming to the requirements of STS SC-M-203-4 for *Settlement Plates* shall be used.

24.9.2.2 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. Extensometers conforming to the requirements of STS SC-M-203-8 for *Vibrating Wire Rod Extensometers* shall be used.

24.9.2.3 Settlement Sensor

The settlement sensor, 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 sensors 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. Settlement sensors conforming to the requirements of STS SC-M-203-7 for *Settlement Sensors* shall be used.

24.9.2.4 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.

24.9.2.5 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 2 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 2 dimensions; therefore, multiple gauges mounted at several locations on the structure will be required to monitor movement in 3 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.

24.9.3 Piezometers

Piezometer applications generally fall into 2 categories: 1) Monitoring the flow of groundwater, or 2) Providing an index of soil strength gain. 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 Dunnicliff (1998) 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. Piezometers conforming to the requirements of STS SC-M-203-6 for *Vibrating Wire Piezometer* shall be used.

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.

Often, 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 1 instrument malfunctions.

24.9.4 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 the PC/GDS. The need for special instrumentation and the selection of instruments will be evaluated on a case-by-case basis.

24.10 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 a single 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.

24.11 SHOP PLAN REVIEW

The Standard Specifications, Supplemental Specifications, Supplemental Technical Specifications, Special Provisions and design drawings occasionally require the Contractor to submit Shop Plans and Installation Plans in addition to the PIP and the DFIP. The GEOR shall review the geotechnical portions of the submitted Shop Plans and Installation Plans for conformance to the Standard Specifications, Supplemental Specifications, Supplemental Technical Specifications, Special Provisions and design drawings. If no review time is specified in the contract, then the GEOR shall conduct the review in 21 calendar days and shall submit the response to the Department.

24.12 REFERENCES

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