TEST METHODS FOR EVALUATING EXISTING FOUNDATIONS

by
The Structural Committee

of
The Foundation Performance Association

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PREFACE

This document was written by the Structural Committee of the Foundation Performance Association (FPA) and has subsequently been peer-reviewed, accepted, and issued by the FPA. This document is published as FPA document number FPA-SC-02, Revision 0, (FPA-SC-02-0) and is made freely available to the public at www.foundationperformance.org so all may have access to the information. To ensure this document remains as current as possible, it may be periodically reviewed and updated under the same document number but with higher sequential revision numbers.

The Structural Committee is a permanent committee of FPA. At the time of writing this document, the Structural Committee was chaired by Ron Kelm and 30 to 35 members were active on the committee. The Structural Committee sanctioned the development of this paper on 25 July 2007 and formed a subcommittee to write the document. The subcommittee's chair and members are listed on the cover sheet of this document and are considered this document's co-authors.

Suggestions for improvement of this document shall be directed to the current chair of the Structural Committee. If sufficient comments are received to warrant a revision, the committee will form a new subcommittee to revise this document. If the revised document successfully passes FPA peer review, it will be published on the FPA website, superseding the previous revision.

The intended audiences for the use of this document are engineers and others that may be involved in the evaluation of foundations that are located in the southeast region of the state of Texas, and primarily within the City of Houston and the surrounding metropolitan area. However, many of the considerations discussed for each of the test methods for evaluating existing foundations also apply to other geographical areas.

This document was created with generously donated time in an effort to improve the performance of foundations. The Foundation Performance Association and its members make no warranty, neither expressed nor implied, regarding the accuracy of the information contained herein and will not be liable for any damages, including consequential damages, resulting from the use of this document. Each project should be investigated for its individual characteristics to permit appropriate application of the material contained herein. Please refer to the FPA website at www.foundationperformance.org for other information pertaining to this document and other FPA publications.

Safety issues associated with the test methods described herein are not addressed in this paper. It is the responsibility of the user of this paper to establish adequate safety and health practices while using the methods described in this paper. It is also the responsibility of the user of this paper to comply with applicable local and federal safety and health regulations.

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1.0 INTRODUCTION

Scope

The purpose of this document is to provide general guidelines for common types of foundation test methods, based on sound science, used to troubleshoot problems and evaluate the conditions of existing foundations. This document is targeted for engineers and others familiar with the evaluation of existing foundations. This document does not include guidelines for quality control and quality assurance of foundations under construction or foundation repairs. The foundation evaluation methods discussed in this document are primarily intended for lightly loaded concrete foundations and pavements.

General Considerations

There are general considerations that apply to each test method described in this document. The general consideration categories include cost, portability of testing equipment, user skill level, data processing, invasiveness, qualitative/quantitative type of method, and others. Cost considerations for the test methods are based on the relative cost of rental or purchase of equipment, or engagement of contractor/professional services. The costs are quantified relatively into a range of five categories from least to most expensive using the following symbols:

Least Expensive — Most Expensive
$ ◄——— $$ ——— $$$ ——— $$$$ ———► $$$$$

In addition to the general considerations that apply to each test method described later in this document, there are other items to consider, which include the following:

1. Verification of test results, which could include core sampling, drilling, use of different test methods for comparison, and others, is required to calibrate the results obtained from the test methods.
2. The test methods that require the use of proprietary equipment should be calibrated and performed following the equipment manufacturer's written instructions.
3. Instruments suspected of inaccurate measurements should be serviced by qualified technicians.
4. The list of additional resources under each test method is not intended to be all inclusive.

The test methods described in Section 2 of this paper are listed in a table included in Appendix A. This summary table indicates which test methods are used to evaluate each of the foundation characteristics and defects described in Section 3.

2.0 DESCRIPTION OF TEST METHODS

The test methods used to evaluate existing foundations and described in this section are not intended to be all inclusive. The intent of this section of the paper is to provide general information regarding some of the test methods that can be used to evaluate defects and characteristics (Section 3.0) of existing foundations.

2.1 CARPENTER LEVEL

General Description

A carpenter level, also called a spirit level or bubble level, is a device consisting of a long, narrow, straight body inset with spirit-filled vials. The vials also contain a bubble, which due to the shape of the vials can indicate levelness and plumbness. The body is typically made from wood (traditional material), aluminum, or injection fiberglass. The vials are generally made from glass, and are normally filled with colored ethanol. Vials may be installed into the body though use of an insert, which will ease repair. The body and insert are cut out in order to easily view the bubble in the vial during use.

Of particular use in foundation repair work is a cutout allowing the vial to be viewed from above, as in Figure 2.1.1. Carpenter levels may vary in length from short, called a torpedo level, to 8 feet or longer. For foundation repair applications, relatively long levels that range in length from 4 to 8 feet are commonly used in order to provide more accuracy. For foundation evaluations, shorter levels that range in length from 2 to 4 feet that are more convenient to handle and transport are commonly used.

Figure 2.1.1 Carpenter level showing body, insert, vial, and cutouts

In recent years digital levels, a type of carpenter level, have become available. Digital levels replace the vial display with a digital numeric display, usually in degrees from level or plumb. Digital levels sense the direction of gravity with an accelerometer, and can display results in degrees, percent grade, or rise/run.

Digital levels are especially useful when surfaces that are far from level or plumb are to be measured for quantitative deviation from plumb and level. Vial levels are accurate when used to determine small deviations from plumb and level, but are not useful by themselves to quantify larger deviations from plumb and level. A vial level may be used in conjunction with a measuring tape to measure slope, and although this method introduces several sources of possible errors, it uses inexpensive and readily available tools.

General Applications

Carpenter levels have the following uses during the inspection of structures:

1. Could be used on floors to confirm the findings of other foundation elevation survey instruments.
2. Could be used on walls and horizontal surfaces (i.e. countertops, doorframes, and window sills) to correlate with foundation elevation survey. Ambiguities in the survey may exist if it is not clear whether non-level floors are the result of foundation movement or initial construction condition. Ambiguities may also exist if foundation deflections are small and damages are either not present or present and non-indicative.
3. Used to evaluate if adjustments have been made to the levelness of finished components, such as countertops, doorframes, and window sills, to compensate for slope of the floor at the time of installation.

Some Considerations

1. An advantage of vial levels is the analog display which experienced handlers can quickly interpret.
2. The slope direction may be difficult to ascertain with digital levels.
3. Carpenter levels are relatively fragile, and can be damaged, broken, or rendered inaccurate by rough handling or drops.
4. Carpenter levels should be periodically inspected for accuracy by placing them on both a horizontal level surface and a vertically plumb surface. Rotate the level 180 degrees in the plane of the surface in order to ensure that the levelness indications in both positions agree.
5. Digital levels are typically more expensive and require batteries.
6. Digital levels are affected by environmental temperature limitations.
7. Typically longer levels provide higher accuracy depending on the flatness of the surface.

Relative Cost

Purchase: $-$$

Additional Resources

None found.

2.2 CHAIN DRAGGING

General Description and Applications

Chain Dragging (Figure 2.2.1) is a qualitative test method used to estimate location and extent of delaminations in a concrete slab. Variations in the sound from reverberations that are produced by rattling the chain over the concrete surface indicate anomalies in the continuity of the underlying material. Depending of the size of the area to be tested, a trolley with a series of chains in an overlapping pattern may be used. A separate chain is used to test local areas to better evaluate specific suspect locations. Typically chain link diameter size varies between 1/2 inch and 3/4 inch.

Some Considerations

1. The equipment is easy to use and relatively portable.
2. Different chain sizes may be used to investigate different depths of delamination.
3. The test can be used to survey large areas quickly.
4. The results may need to be verified with other test methods.
5. The results do not provide quantitative data, so the depth of defects is unknown.
6. The test is relatively inexpensive, does not require special equipment or specific expertise, and is non-invasive.

Figure 2.2.1 Testing for delamination using Chain Dragging

Relative Cost

Purchase: $

Additional Resources

ASTM D4580 *Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding*

2.3 CHLORIDE ION CONTENT TESTING

General Description

Chlorides in concrete can be determined by total, water-soluble, or acid-soluble chloride techniques. Methods of sampling and testing are described in AASHTO T260 (acid-soluble), AASHTO T260 and ASTM C1218 (water-soluble), and ASTM C1152 (acid-soluble).

Total chloride is not commonly measured (not all chlorides present in concrete contribute to corrosion), although Wiss Janney, Elsner Associates (WJE) has developed a laboratory technique to measure total chloride by fusing a concrete sample with calcium oxide. This total chloride technique will measure all chloride in the aggregates and any organic chloride present. Acid-soluble techniques normally measure most chloride ions in the paste and aggregates. However, in certain specialty concretes, the acid-soluble chloride may only be a small portion of the total chloride, depending on the particle size or the presence of chloride containing polymers or insoluble chloride salts. The water-soluble technique measures chlorides made available by a certain grinding and extraction procedure and may represent the chloride presently available for corrosion. However, the water-soluble techinque does not measure certain acid-soluble chlorides that may become water-soluble in the future due to carbonation or sulfate ingress.

General Applications

It is common to analyze for chlorides in concrete at the level of the steel reinforcement to determine whether the "chloride threshold" (refer to discussion in the next paragraph) for active corrosion has been reached. The test for acid-soluble chloride content is typically used because the titration endpoint is distinct and the threshold value for initiation of corrosion is well-established.

An extensive corrosion study funded by the Ontario Ministry of Transportation studied the corrosion threshold limit for admixed chloride, that is, when chloride-containing admixtures are mixed into the fresh concrete. This research concluded that corrosion would start when the admixed calcium chloride dihydrate percent by weight of portland cement was between 0.2 and 0.4 percent. This amount of admixed chloride was found by test to be equivalent to about 0.014 to 0.022 percent water-soluble ion by weight of concrete. These water-soluble threshold limits to start corrosion activity are similar to the 0.025 to 0.040 percent corrosion threshold acid soluble chloride ion levels by weight of concrete measured during time-to-corrosion laboratory tests by WJE. Considerable research has been done relating to acid-soluble chloride contents, and have shown the corrosion threshold value of black mild reinforcing steel in concrete to be near 1.0 lbs of admixed calcium chloride dihydrate/cu yd of portland cement, or 0.20 admixed calcium chloride dihydrate percent by weight of portland cement.

Some Considerations

1. ASTM and AASHTO methods are available to determine water-soluble chloride and acid-soluble chloride in concrete.
2. Water-soluble chloride, as determined by these methods, may approximate corrosive chloride at the moment, but may either underestimate it due to any organic chloride or overestimate it due to fine pulverization of the aggregate, liberating chloride that might never migrate to the steel reinforcement within concrete. Water-soluble chloride determinations do not reveal potential future problems due to liberation of chloride from other sources and movement of chloride ions within the concrete.
3. Acid-soluble chloride procedures liberate innocuous chloride bound up within aggregates.
4. The scientists performing Chloride Ion Testing need to be aware of the limitations of the ASTM and AASHTO test methods and mention these limitations when reporting results.
5. The scientists performing the testing should also be aware of pitfalls in chloride analyses such as interferences from bromide, iron, or sulfide. Some of these interferences are not currently provided for in the AASHTO or ASTM methods and most testing laboratories do not recognize them.
6. Concrete samples should be obtained in the vicinity of steel reinforcement.
7. Determining the chloride ion content at different levels within the full thickness of the foundation element may be desired in order to evaluate the progression of chloride ion penetration from the surface of the concrete to the steel reinforcement.

Relative Cost

Professional Services: $$-$$$

Additional Resources

ASTM C09.69 Miscellaneous Tests Subcommittee of Technical Committee C09 on Concrete and Concrete Aggregates ASTM C114 *Standard Test Methods for Chemical Analysis of Hydraulic Cement*
ASTM C1152 *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*
ASTM C1218 *Standard Test Method for Water-Soluble Chloride in Mortar and Concrete*
AASHTO T-260 *Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials*

2.4 CONCRETE CORES

General Description

Existing concrete members, structures, and foundation elements may be evaluated by drilling, extracting, and testing concrete core samples. The cores are typically 4 inches in diameter, but other sizes may be used. Concrete core samples are typically transported to a testing laboratory where various tests can be performed to determine a variety of concrete properties. Due to the variability of concrete properties, it is desirable to obtain several core samples at strategically selected locations so that the concrete properties may be obtained based on statistical analysis of the test samples data.

General Applications

Concrete core samples (Figure 2.4.1) are most often used to determine the compressive strength of the existing concrete by performing a laboratory compression test of the core sample. The cored specimens may also be used for other laboratory tests such as petrography, hardness, moisture content, permeability, aggregate soundness, and member thickness.

The core samples may be the primary method of testing or they may be part of a larger testing program that involves many other types of tests. The concrete may need to be tested for a variety of reasons. The structure may be showing signs of distress, damage, deterioration, or some other type of change that makes the concrete strength suspect. Other circumstances that may warrant Concrete Core Sample Testing is a change in usage or occupancy of the structure, a suspicion of a defective design or deficient construction, or simply to evaluate a foundation when the original design criteria are not known.

Figure 2.4.1 Concrete Core Sample

Some Considerations

1. The test typically requires patching the concrete core holes to restore the concrete to its original condition.
2. The concrete patch usually has a different appearance that may be aesthetically objectionable.
3. The test results are not known immediately when the core samples are extracted. The total lead time to deliver the samples to the laboratory, to perform the tests, to evaluate and summarize the test results in a written report, and to deliver the report could take weeks.
4. The laboratory test methods usually provide a direct measurement of the concrete properties (e.g. compressive strength). Applicable adjustment factors have to be applied to the test results.
5. The results of compressive strength laboratory tests are usually very reliable, particularly when a large number of concrete core samples are tested.
6. Core samples are most easily obtained from the top horizontal surface of concrete slabs, paving, grade beams, or other concrete members. Coring into vertical concrete surfaces such as walls is more difficult.
7. The location of the core samples is limited by the ability of the core drilling equipment to drill into the member, and the accessibility of getting the drilling equipment and the equipment operator to the location where the coring is to be done.
8. Temporary anchoring of the core drilling equipment is usually required.
9. Some cutting and patching of architectural materials and finishes may be required to obtain core samples from above-grade concrete elements, and some soil excavation, pavement cutting and patching, or tunneling may be required to obtain core samples from concrete foundation elements located below grade.
10. Concrete reinforcing may be inadvertently cut during the coring process. In order to avoid cutting the reinforcement, it should be located prior to coring.
11. Usually coring drilling equipment requires a source of water to core.
12. ACI-214R includes adjustment factors for compressive strength test values of concrete core samples that need to be considered.

Relative Cost

Contractor services for core drilling $$-$$$

Additional Resources

ACI 214.4R *Guide to Obtaining Cores and Interpreting Compressive Strength Results*

2.5 CONCRETE SCREWDRIVER TEST

General Description

The Concrete Screwdriver Test (Figure 2.5.1) is a crude method of testing for concrete that is significantly lower (typically half or more) than the required compressive strength. A slotted screwdriver is used in an attempt to score the concrete surface. If the metal blade rides over the concrete surface without loosening any particles and leaves no more than a shiny mark, the surface is sound. If the surface of the concrete is gouged by the slotted screwdriver, then the compressive strength of the concrete may be less than that specified in the drawings and specifications. The edge of a steel file or the blade of a pocket knife may also be used in lieu of a screwdriver blade. Concrete cores (refer to Section 2.4) can be obtained in order to perform laboratory testing to more accurately determine the concrete compressive strength.

Figure 2.5.1 Concrete Screwdriver Test on a Slab Surface

General Applications

The Concrete Screwdriver Test is used to evaluate concrete relative hardness and durability.

Some Considerations

1. Surface hardeners may affect the results of the test.
2. The test may damage the surface of the concrete.
3. The test results are known instantly.
4. The method is not exact science, it is a qualitative method.

5. The method is just a preliminary method of determining if low concrete compressive strength exists.

Relative Cost

Purchase $

Additional Resources

NACE Publication 6G191 (withdrawn), *Surface Preparation of Contaminated Concrete for Corrosion Control*

2.6 GEOTECHNICAL

General Description

A geotechnical investigation (soil report) identifies and classifies the engineering properties of the soil. Geotechnical Testing consists of obtaining field soil samples and performing field and laboratory tests to evaluate physical and engineering properties of soils. The investigation should be made by a company specializing in soil sampling and testing. A geotechnical investigation is limited to testing specific points (one-dimensional) of a site using borings. Considerably more information can be obtained if the geotechnical investigation is supplemented with geophysical testing, which can provide data in two and three dimensions.

General Applications

Typical Geotechnical Testing for a forensic investigation of foundation performance can determine the cause of the unexpected foundation movement, the direction of the foundation movement, and the amount of movement that can still be expected to occur. Results of a geotechnical investigation are typically provided in a written report and may also include, if needed, recommended depth of repair piles or piers, recommended depth of moisture barriers, recommended depth and extent of root barriers, guidelines to attain slope stability, etc.

If an original design soil report is available, the data can be correlated with the elevation and distress surveys to determine the type and extent of foundation movement. It can also be correlated with current soil conditions such as moisture content.

In the greater Houston area, sampling of soils for existing foundations is usually performed by boring holes twenty feet or more in depth. A testing laboratory will classify the soil types, measure the soil strengths, report the Atterberg limits including the plasticity index (PI), the moisture content, the ground water level, compaction, shear strength, clay content, active zone depth, swell potential from swell test, and other geotechnical information. Potential Vertical Movement (PVM) analysis utilizing soil suction can be used to quantify the amount of potential future movement. For a guideline on minimum requirements for geotechnical testing, see document FPA-SC-04, *Recommended Practice for Geotechnical Explorations and Reports*, which is freely available at http://www.foundationperformance.org/committee_papers.cfm.

Some Considerations

1. Care should be taken to locate and avoid existing underground utilities and other obstructions.
2. Typically there is a time lag between field testing and written report.
3. Borings should be located to provide useful information. Typical locations would include at least one boring under the foundation and several others adjacent to the foundation in order to compare the moisture content, amount and type of fill (if any), and soil characteristics.
4. If a deep boring is desired, the testing company will likely require access for a truck-mounted drill rig (Fig. 2.6.1).
5. In active soils (i.e., clay soils that expand/contract with increasing/decreasing moisture content) with mature vegetation, one boring should be 25 feet deep or deeper in order to estimate the active zone depth. Other borings may be shallower.
6. If paving or other exposed concrete is cored, it is typically patched after sampling, but the patch appearance usually does not match the existing concrete. Interior borings should be located to minimize damage to floor coverings such as tile and hardwoods, if possible.
7. If groundwater is encountered during sampling operations, a monitoring well (e.g. piezometer) may be installed in one or more boreholes to allow monitoring of groundwater level over time. Groundwater in a piezometer can be tested to evaluate its chemical composition.
8. Geophysical testing may be performed in conjunction with the Geotechnical Testing using Ground Penetrating Radar (Section 2.7) or Resistivity Testing (Section 2.23). These types of tests are non-destructive and can electronically provide two or three dimensional graphic depictions of subsurface anomalies and soil conditions.
9. Borings provide data only at locations sampled.
10. In cases where abnormal foundation movement is ongoing or expected to continue, a fixed external benchmark may be installed in one of the deeper bore holes after the drilling operation is complete to allow for more precise monitoring of the foundation’s movement (Fig. 2.6.2).

Figure 2.6.1 Geotechnical Soil sampling using a truck-mounted drill rig

Figure 2.6.2 Example of a 35-ft deep benchmark

Relative Cost

Professional Services: $$-$$$$

Additional Resources

ANSI/IEEE Std 81 *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System*
ASTM D422 *Standard Test Method for Particle-Size Analysis of Soils*
ASTM D698 *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*
ASTM D1140 *Standard Test Methods for Amount of Material in Soils Finer than No. 200 (75-µm) Sieve*
ASTM D2166 *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*
ASTM D2487 *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*
ASTM D4318 *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*
ASTM D4546 *Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils*
ASTM D4643 *Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating*
ASTM D5298 *Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper*
ASTM D6913 *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*
ASTM D6432 *Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation*
ASTM G57 *Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*
ASTM WK11776 *New Test Methods for Determining Particle Size Distribution of Soil Using Hydrometer (Sedimentation) or Combined Hydrometer and Sieve Analysis Procedures*
FPA-SC-04 *Recommended Practice for Geotechnical Explorations and Reports*

2.7 GROUND PENETRATING RADAR (GPR)

General Description

The Ground-Penetrating Radar technique is a nondestructive testing technique, which involves using electromagnetic waves to assess the internal characteristics of a material. For concrete or cementitious materials such as concrete foundations, GPR is used almost exclusively in the reflection mode, where transmitting and receiving antennas placed a small fixed distance apart traverse the inspected surface. The transmitting antenna (Figure 2.7.1) sends a diverging short pulse of energy between 1 and 3 nanosecond (ns) duration. The receiving antenna collects the energy reflected from dielectric interfaces between materials of differing dielectric properties, and is then processed by the radar unit and displayed on the screen. The reflected energy is recorded as a pattern as shown in Figure 2.7.2. From these patterns the experienced operator and interpreter is able to deduce useful information.

In general, GPR detects the arrival time and energy level of a reflected electromagnetic pulse. Since electromagnetic wave propagation is affected by changes in dielectric properties, variations in the condition and configuration of a structure will cause changes in the signal. Information is obtained by observing the return time, amplitude, shape, and polarity of the signal. In concrete foundations, GPR is commonly used to find voids, honeycombing, location of embedded steel anchors and reinforcing bars, etc.

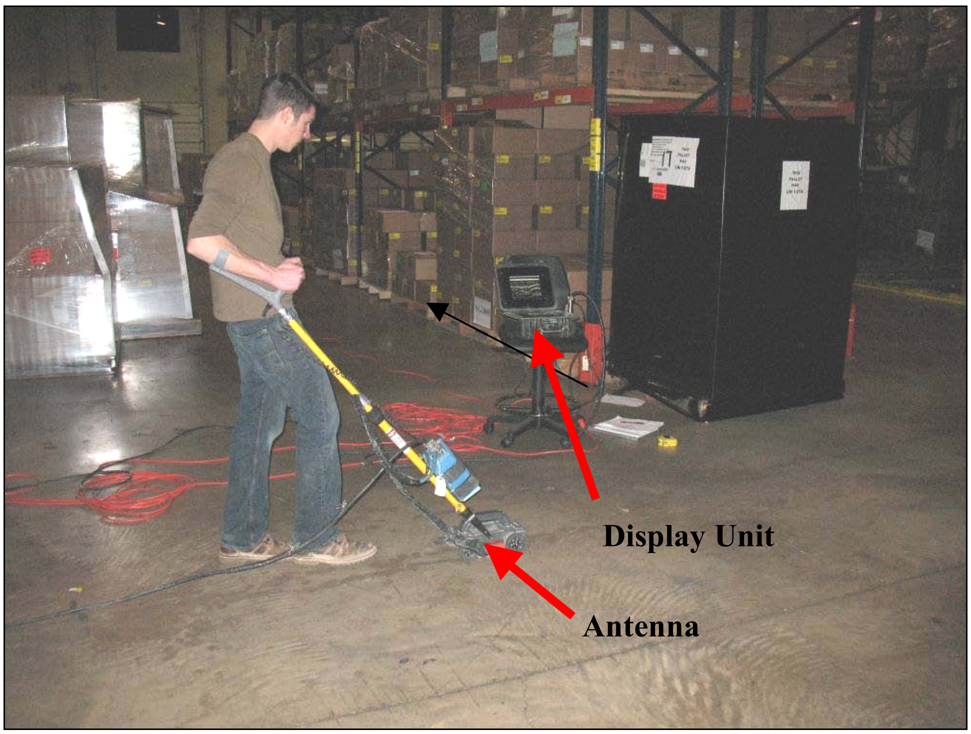
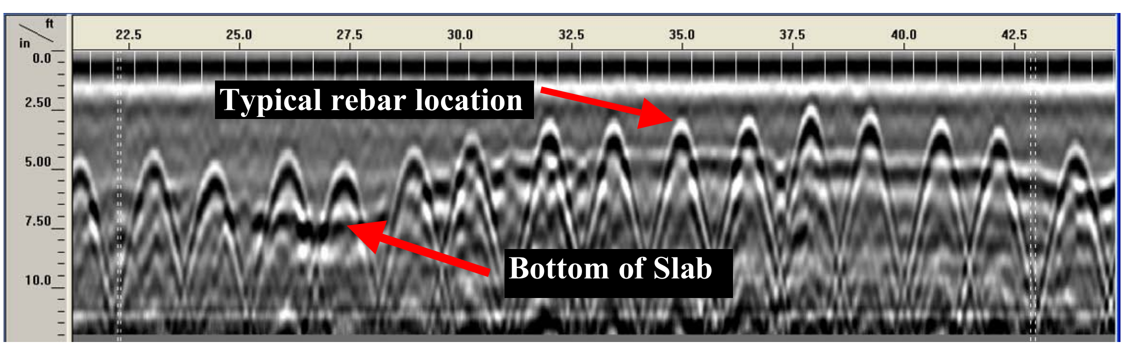
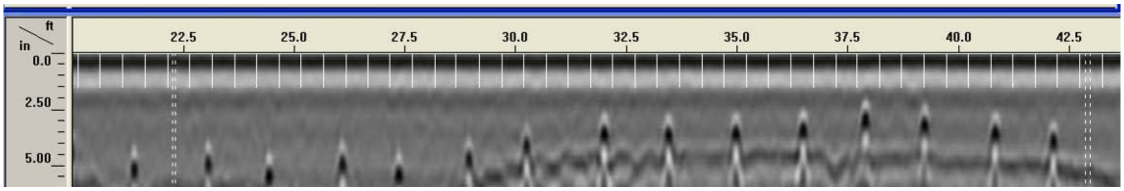


Figure 2.7.1 GPR Testing of a slab-on-ground



(a) Raw data



(b) Post-processed data

Figure 2.7.2 Typical GPR data images from a reinforced concrete slab-on-ground

General Applications

In the context of foundation investigations, GPR includes examining concrete to determine the location, depth, and spacing of reinforcing steel such as rebar, mesh, and pre-stressed strands, and metallic and non-metallic pipes, conduits, utility lines, location of internal flaws such as voids, delaminations, honeycombs, and to estimate the thickness of concrete members. Other applications include examining soil to determine location of soil strata, moisture variations, utility lines, and buried vaults.

Some Considerations

1. The GPR test method allows assessment of larger areas than other methods, which could lead to time and cost savings.
2. The equipment is relatively portable.
3. Access to only one side of the structure is required.
4. Provides the ability to collect and digitize large amounts of data.
5. Different frequency antennas provide the capability to evaluate different depths of penetration with different levels of accuracy.
6. Ability to penetrate across air interfaces.
7. Requires data interpretation and analysis, which typically requires an experienced operator.
8. Relatively expensive equipment.
9. Exact size of subsurface anomalies may be difficult to determine.
10. Variable moisture conditions could affect results.
11. Resolution decreases with depth.
12. Delaminations are very difficult to identify.
13. Presence of metal fibers in concrete mix or closely spaced reinforcement could prevent penetration of the GPR signal beyond the fibers or reinforcement.

Relative Cost

Purchase: $$$$
Rent: $$

Additional Resources

ACI 228.2R *Nondestructive Test Methods for Evaluation of Concrete in Structures*
ASTM D6432 *Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation*

2.8 GROUND PROBING

General Description

A commonly available ground probe for use in the evaluation of foundations is the plumber's probe. This device is "T"-shaped and is commonly available at plumbing supply houses or hardware supply stores. The stem of the plumber's probe is typically a steel rod measuring 3/8 inch diameter by 4 or 5 feet long. At the lower end of the rod should be a conical-shaped upset tip used to break the skin friction along the stem, making probing to 5 feet possible in many soil conditions.

General Applications

a) *Depth of perimeter grade beams*: by probing on a slight batter about a foot away from the perimeter grade beam, the bottom outside corner of the concrete can be located as the probe is pushed below and is then pulled back until the upset tip catches the bottom of the concrete. Using trigonometry, the tester can then determine the depth of the grade beam (Figure 2.8.1).

Figure 2.8.1 Ground Probing at a perimeter grade beam

b) *Soil type and color*: Because the upset tip of the probe will catch soil and return it to the surface during pull-out (see right tip in Figure 2.8.2), the test can allow visual classification of the soil type.

c) *Soil moisture condition*: There are indications of soil moisture conditions as the probe is extracted. In addition to the obvious visual indications, the tester can often hear a sucking sound when pulling the probe from a clayey soil that is well above its optimum moisture content.

d) *Relative soil shear strength*: The tester can determine relative soil shear strength at various locations around the site by simply pushing the probe into the soil with similar effort at each location.

Figure 2.8.2 Ground Probe tips with upset tip with the clay return (arrow)

Some Considerations

1. This test works best in clayey or silty soils. This test may not work well in dense soils.
2. In performing the relative soil shear strength test, because of the upset tip, the standard plumber's probe may plunge too easily in most soils. Better accuracy can be attained by removal of the upset tip (Figure 2.8.2). In so doing, the stem length can be reduced to 4 feet or less to facilitate vertical probing with a uniform effort. The removal of the upset tip will greatly increase the effort needed for a given penetration so that relative penetrations between 1 inch and several feet can be attained in varying soil conditions.
3. During probing, the tester needs to "feel" for underground pipes and other materials before applying too much effort that could cause a leak or other damage. To avoid injury where electrical conduit is buried, consider using a non-metallic probe or a metal probe with insulated handles.
4. While the plumber's probe gives a quick indication of grade beam depths around foundation, it is always more accurate to excavate a test pit and perform actual depth measurements where suspected deficiencies are found.

Relative Cost

Purchase: $-$$

Additional Resources

None found.

2.9 HALF-CELL POTENTIAL (HCP)

General Description

The Half-Cell Potential (HCP) testing (Figure 2.9.1) is a nondestructive test method used to investigate the corrosion probability of the reinforcing steel in concrete foundations. Potential readings measure the electrical activity of the corrosion process. Corrosion occurs simultaneously at the anode and cathode areas of the steel when iron ions are released at the anode areas into the concrete to react and form deposits at the cathode areas.

The HCP method requires that the positive terminal of a high impedance voltmeter be in contact with the steel reinforcement and another point of contact between the negative terminal of the voltmeter and the reference electrode (RE). The RE consists of a copper electrode enclosed in a plastic housing and surrounded by a saturated copper sulfate solution. The end of the cell consists of a porous disk through which the copper sulfate solution can make electrical contact with the concrete surface. The most widely used half-cell RE is the copper-copper sulfate electrode (CSE).

HCP readings are typically collected on a grid pattern laid over the concrete surface of the test areas. Reinforcing steel potentials are then measured with respect to a small reference CSE. The size of the grid system can vary from 6 inches by 6 inches to 3 feet by 3 feet depending on the size of test area.

Conventionally, HCP data is interpreted using the Numeric Magnitude Technique specified in Appendix X1 of ASTM C876. According to the criteria, "*if potentials over an area are more positive than –0.200 V vs. CSE, there is a greater than 90 percent probability that no reinforcing steel corrosion is occurring in that area at the time of measurement. If potentials over an area are more negative than –0.350 V vs. CSE, there is a greater than 90 percent probability that reinforcing steel corrosion is occurring in that area at the time of measurement. If potentials over an area are in the range of –0.200 to –0.350 V vs. CSE, corrosion activity of the reinforcing steel in that area is uncertain*."

Since many factors such as concrete resistivity, temperature, carbonation, oxygen content, type of steel, presence of coating, and degree of water saturation (moisture content) can influence the potential readings, interpretation of the HCP data in this study should not be made solely by the ASTM criteria discussed above. Instead, ASTM C876 indicates that measured potentials should be used to generate equipotential contour maps (Figure 2.9.2), in which each color corresponds to a certain range of potential readings. As HCP becomes more negative, the contour plot has a darker red color in that area. On the other hand, as the potential becomes more positive, the corresponding area shows a greener color. In general, relative variation of potentials within a test area and the spacing between the contour lines can indicate areas of concern for corrosion. Intensive red color compared to surrounding green areas may indicate an actively corroding area and narrower spacing (steeper gradient) of equipotential contour lines may indicate higher corrosion rates. HCP data is also typically presented as a cumulative frequency distribution (Figure 2.9.3) plot to determine the distribution of the data and the location where corrosion activity may be occurring.

Figure 2.9.1 Copper-copper sulfate cell

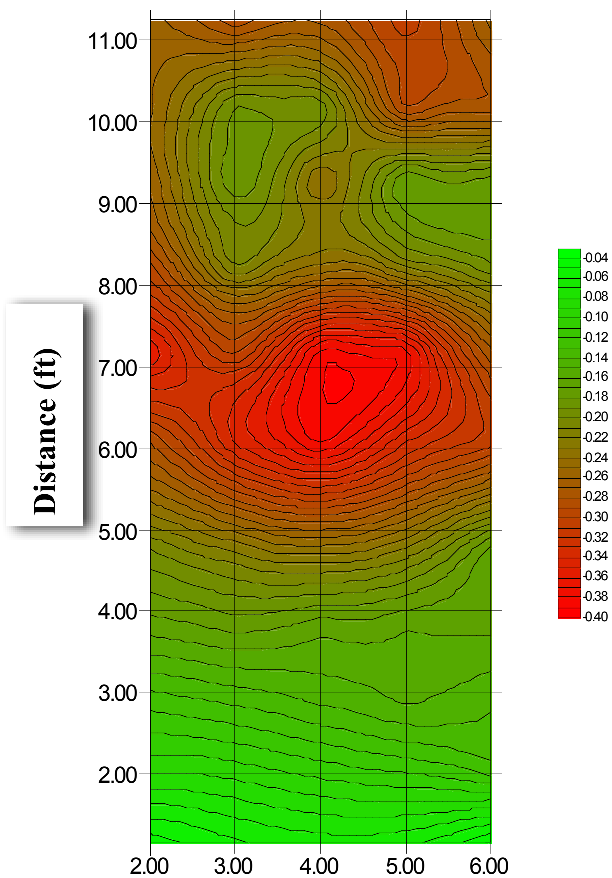


Figure 2.9.2 Half-cell Potential contour map

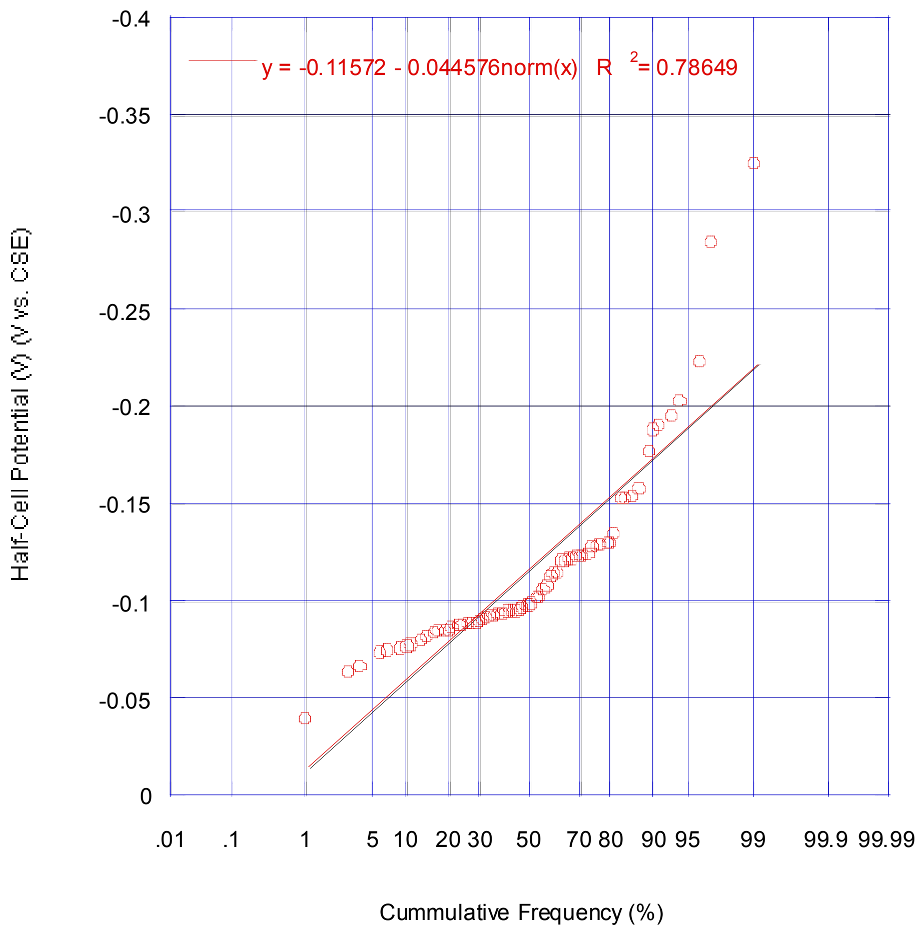


Figure 2.9.3 Cumulative frequency distribution plot

General Applications

HCP testing is used to investigate the corrosion probability, at the time of testing, of reinforcing steel embedded in concrete foundation and structures.

Some Considerations

1. The positive terminal of a high impedance voltmeter needs be in contact with the steel reinforcement, which usually requires drilling into the concrete structure being tested.
2. The location of steel reinforcement needs to be indentified at a minimum of two locations with an applicable method.
3. Connectivity, via electrical conductivity, of steel reinforcement needs to be verified.
4. The equipment is portable.
5. Access to only one side of the structure is required.
6. Provides the ability to collect and digitize large amounts of data.

7. Many factors could affect the results of this method such as concrete resistivity, temperature, carbonation, oxygen content, type of steel, presence of coating, and degree of water saturation (moisture content).
8. Accuracy decreases with depth of steel reinforcement.

Relative Cost

Purchase: $$

Additional Resources

ASTM C876 *Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*

2.10 HAMMER SOUNDING

General Description and Applications

Hammer Sounding (Figure 2.10.1) consists of striking the bare surface of a concrete foundation with a hammer in order to evaluate the presence of delamination and voids. Variations of the sound from the hammer striking the concrete surface are used to qualitatively determine the possible presence of delamination and voids in concrete. Typically hammer sounding is used to delineate the boundaries of delamination and voids in a concrete slab-on-ground.

Figure 2.10.1 Hammer Sounding Test on a Concrete Slab

Some Considerations

1. The equipment is easy to use and portable.
2. Different size hammers could be used to investigate different depths of delamination.
3. The test is not efficient to survey large areas.
4. The results may need to be verified with other methods.
5. The results do not provide quantitative data, so the depth of defects is unknown.
6. The test is relatively inexpensive, does not require special equipment or specific equipment training, and is non-invasive.

Relative Cost

Purchase: $

Additional Resources

NACE Publication 6G191 (withdrawn), *Surface Preparation of Contaminated Concrete for Corrosion Control*

2.11 IMPACT ECHO

General Description

The Impact-Echo (IE) method involves introducing mechanical energy, in the form of a brief impact, to the structure. When a material, such as concrete, is subject to a surface impact, stress waves propagate through the material at a finite speed. The velocity of these waves is a characteristic of the material through which the waves propagate. Typically, the higher the velocity the more dense the concrete.

In isotropic solids, elastic theory indicates propagation of three types of waves: primary or P-waves, secondary or S-waves (shear waves), and surface or R-waves (Raleigh waves). The P-waves are those in which particle motion is parallel to the direction of impact. S-waves are those in which particle motion is normal to the direction of impact. The R-waves propagate along the free surface of the material and decay exponentially with depth from the surface.

When a concrete surface is impacted, a transducer acoustically mounted on the same surface receives the primary or P-wave energy reflections from discontinuities within the panel. Therefore, with the knowledge of the propagation velocity through the material, the amplitude spectrum can be evaluated to determine the location of discontinuity or flaws within the concrete.

Figure 2.11.1 is a typical IE spectral plot obtained from a test point indicating a shallow delamination. A low frequency, high amplitude response is typical of this condition. Figure 2.11.2 is a typical IE spectral plot obtained from a solid response.

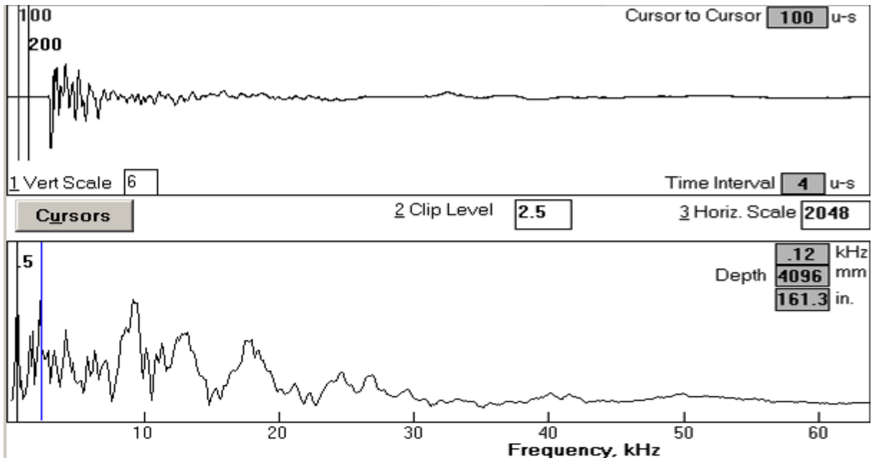


Figure 2.11.1 IE Test Result from a concrete shallow delamination

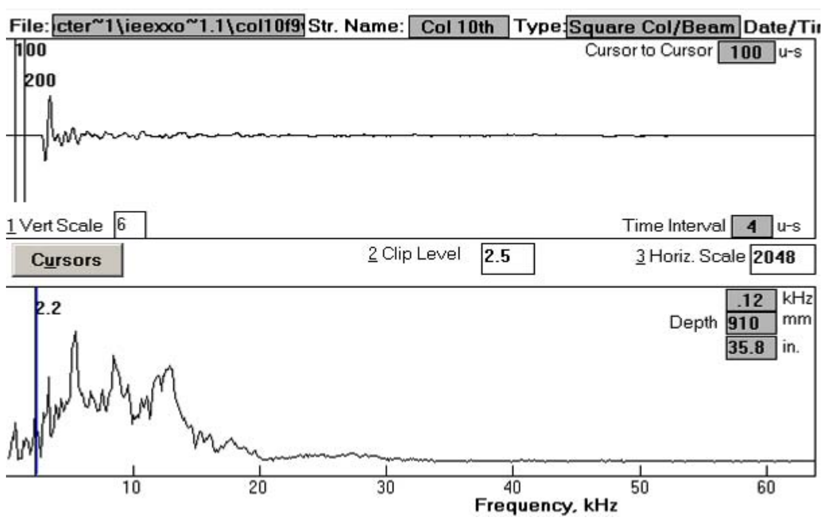


Figure 2.11.2 IE Test Result from a solid concrete section

General Applications

Impact-Echo Testing is a nondestructive testing technique used to evaluate the quality of the concrete by detecting internal flaws, including delamination, honeycombs, voids, etc. Impact-Echo could also be used to determine the presence and extent of voids underneath a slab-on-ground.

Some Considerations

1. The equipment is relatively portable.

2. Access to only one side of the structure is required.
3. Provides the ability to collect and digitize large amounts of data.
4. Field data acquisition is obtained and processed within a few seconds.
5. Requires data interpretation and analysis, which typically requires an experienced operator.
6. Relatively expensive equipment.
7. Exact size of subsurface anomalies may be difficult to determine.

Relative Cost

Purchase: $$$
Rent: $$

Additional Resources

ACI 228.2R *Nondestructive Test Methods for Evaluation of Concrete in Structures*

2.12 INSPECTION OPENINGS AND EXCAVATIONS

General Description and Applications

Inspection Openings and Excavations consist of exposing a portion of a foundation element in order to obtain visual evidence of as-built conditions. Inspection Openings and Excavations are typically performed to verify or calibrate other test methods in order to increase reliability of test results.

Inspection Openings
Inspection Openings consist of partial concrete removal to determine size and placement of steel reinforcement, depth of steel reinforcement, presence of vapor retarder/barrier below the slab, and concrete thickness. Inspection Openings include test cuts, concrete cores (see Section 2.4), and concrete drilling. Depending on the depth of the inspection opening through the concrete, localized soil conditions may be exposed for observation.

Excavations
Excavations (Figure 2.12.1) consist of temporary removal of soil at the outside of the foundation perimeter. Excavations are typically used to determine dimensional properties and conditions of foundation structural elements. Excavations include the following:

- Soil removal next to a grade beam to determine dimensional properties and conditions of grade beam
- Tunneling to evaluate presence and condition of plumbing and dimensions of interior grade beams and depth, straightness, and continuity of leveling piles
- Pit excavation and drilling through soil adjacent to pier to evaluate drilled pier and under-reamed bell dimensions

- Augered excavations to determine free water elevations and condition of fill

Figure 2.12.1 Excavation at Foundation Edge Showing High Water Table

Some Considerations

1. Measures should be taken to eliminate the possibility of damaging utility lines during the inspection opening and excavation process.
2. Care should be exercised during the process of making inspection openings in a concrete slab in order to minimize the possibility of damaging steel reinforcement, especially post-tensioned cables, and other embedded items.
3. Measures to dewater excavations should be considered.
4. This test method is intrusive and limited to isolated areas of the structural element being evaluated.
5. Visual evidence of non-exposed existing conditions can be obtained with this method.
6. Depending on the extent of the inspection opening and excavation, this method could be expensive.
7. Typically requires the use of a contractor.
8. Applicable local and federal safety regulations may need to be considered in order to implement this test method. As previously indicated, safety issues associated with this or any test methods are not covered in this paper.

9. The concrete patch usually has a different appearance that may be aesthetically objectionable.

Relative Cost

Contractor's services: $-$$$

Additional Resources

None found.

2.13 LASER LEVEL

General Description

A Laser Level, also called a laser plane level, is a line of sight apparatus used to measure elevation differentials between two points in a three dimensional space. The apparatus consists of a laser producing head supported on a tripod at a stationary position (base station), and a traveling vertical pole indicating the relative vertical displacement from the laser head. The laser head can consist of a laser pointed horizontally rotating on a spindle, or a vertical beam striking an inclined rotating mirror surface. In either case, the laser head produces a laser beam that rotates in the horizontal plane to produce a laser plane. The laser plane is made level by the use of thumbscrews in the instrument base centering bubbles within spirit vials. The laser plane may also be self-leveling. The pole can either consist of a visually graduated rod, or a laser sensor which translates vertically on the rod and emits a signal when the sensor is aligned with the laser beam. The laser sensor has visual displays and audible outputs indicating too-low, too-high (Figure 2.13.1), and on-level.

Figure 2.13.1 Laser Level

General Applications

1. Laser Level systems are used to measure floor elevations.
2. Laser plane level systems are the sensory basis for the process of land laser leveling, which controls land leveling machinery, bringing grades to level or with slight grades for drainage.

Some Considerations

1. Laser level systems that do not use a sensor, but use the laser beam to mark the visually graduated scale on the rod, are limited by ambient lighting conditions. Their use is practically limited to short distances indoors.
2. Laser level systems that use laser sensors can have a range as long as 1600 feet.
3. Vial leveling systems require a protocol for calibration and setup on station. Operator error can occur.
4. Laser level systems which are self-leveling can reach accuracies of 1/16 inch in 100 feet.
5. Laser level systems can be operated by one person.
6. Laser level systems have their greatest advantage in open sites, where line-of-sight is not limited.
7. Laser level systems results can incur errors when performing floor elevations in typical residential and other low-rise buildings, where some floor areas are not within line-of-sight. When line-of-sight is not possible with one position of the base station, movement of the base station is required. This requires tying-in the two readings at the "turn" (set-up), and manually offsetting the readings obtained at the new base station position. Manually offsetting the sensor output can induce errors.
8. Elevation survey should be noted for steps and changes in floor coverings.
9. There are numerous texts detailing the methods and protocols of good surveying practice and the proper usage of these instruments. As in all test methods that attempt to define relational positions of various points, thorough and complete note taking is essential to minimize error.
10. As with any precision instrument care in handling is paramount.

Relative Cost

Purchase: $$$

Additional Resources

None found.

2.14 MANOMETER

General Description

A Manometer is an instrument that utilizes pressure differential of a liquid or gas in a system to measure relative elevations between two points within a three dimensional space. Three types of manometers are currently commercially available. All three systems are predicated on the property of a liquid within a system to equalize pressure within the liquid in the system at any given elevation.

The first system is an open system and generally consists of a clear flexible hose or tubing attached on both ends to rods with integral measuring scales. Visual readings are taken at both locations and the difference in readings is the elevation differential between the two points. This type of system is an open system, i.e. both ends of the line must be open to the local atmospheric pressure within the area being surveyed. Some systems incorporate a reservoir at one end of the system.

The second system is a closed, liquid-only system (Figure 2.14.1). This system contains a liquid in a tube, typically a clear flexible hose or tubing with a tinted liquid. A flexible-wall reservoir is located on one end of the tubing (the base unit) and an electronic pressure-sensing device (sensing unit) is located at the other end. A digital display is integral with the sensing unit and provides a reading of the elevation of the point at the sensing unit relative to the base unit, based on the pressure differential between the base and sensing unit.

The third type is a closed liquid/gas system (Figure 2.14.2). The flexible hose or tubing is opaque and contains two inner channels. One channel contains a liquid and the other contains an inert gas. Pressure differential is measured in the sensing unit at one end of the hose or tubing and is displayed as an elevation of the point at the sensing unit relative to the base unit, based on the pressure differential between the base and sensing unit.

Figure 2.14.1 Closed Liquid-Only Manometer

Figure 2.14.2 Closed Liquid/Gas System Manometer

General Applications

Elevations at selected locations on a floor or floor slab surface can be measured utilizing any of the systems discussed above. Elevations can be taken relative to an assumed elevation on the surface or a selected point external to the surface being considered. Elevations obtained can be utilized to produce floor elevation contour maps.

Some Considerations

1. The closed liquid/gas system is most sensitive to environmental and temperature differentials. The closed liquid/gas system utilized should be allowed to stabilize with the localized ambient temperature prior to use. A minimum of 20 minutes should be allowed for stabilization.
2. Readings taken at the sensing unit in one temperature environment when the base unit is in a different environment should be made as quickly as possible to avoid temperature induced error.
3. In exterior environments, wind may also adversely affect readings.
4. Manometers require hose or tubing to connect the sensing and reservoir units. The composition, sizing and connections vary from system to system and manufacturer to manufacturer.
5. Care should be taken to avoid excessive stress on the hose or tubing to minimize the likelihood of damaged hose or tubing.
6. The liquids used in the systems may contain hazardous materials or dyes and may damage property if spilled or leaked.
7. Some systems may require re-calibration if the instrument undergoes a large enough temperature differential.
8. All systems can be operated in a manner similar to an optical leveling system and readings of elevation obtained can be used to compute elevations of points over a range of elevations.
9. The mathematics required to compute elevations is straightforward; however, care should be taken to understand the relationship between the base and sensing units for the system utilized.
10. Elevation survey should be noted for steps and changes in floor coverings.
11. Open systems typically utilize dyed water to aid in reading the elevations.
12. Open systems are subject to spillage accidents.
13. The closed, liquid-only system frequently requires the addition of fluids.

Relative Cost

Purchase: $$-$$$

Additional Resources

None found.

2.15 METAL DETECTOR

General Description

Metal Detectors are instruments that apply a low frequency alternating magnetic field to the concrete foundation. The alternating magnetic field is altered if steel reinforcement is present. Metal Detectors measure the change in magnetic field intensity, which provides information regarding the presence and location of steel reinforcement in a concrete foundation. Metal Detectors are typically hand held (Figure 2.15.1). The output is typically an audible and/or visual signal.

General Applications

Metal Detectors are used to identify the presence and general location of steel reinforcement embedded in concrete foundations. Metal Detectors are also used to evaluate the presence of reinforcement in flat work and dowels at joints.

Figure 2.15.1 Metal Detector

Some Considerations

1. The equipment is portable.
2. Access to only one side of the structure is required.
3. Able to penetrate across air or other material interfaces (i.e. placement of the metal detector on the concrete surface is not required).

4. Does not require data interpretation and analysis.
5. Signal decreases with depth of penetration. Typically 4 to 6 inches is the limitation in depth of penetration.
6. Depth and size of steel reinforcement cannot be evaluated with metal detectors.
7. Areas with congested reinforcement prevent an accurate signal.
8. Metal Detectors respond to any electrically conductive materials, which could impact the interpretation of results.
9. Presence of metal fibers in concrete mix prevents penetration of the metal detector signal.

Relative Cost

Purchase: $-$$

Additional Resources

None found.

2.16 OPTICAL LEVEL

General Description

An Optical Level (Figure 2.16.1) is a line-of-sight instrument used in conjunction with a graduated level rod to measure elevation differentials between two points. The basic instrument consists of a telescope rotating in a horizontal plane with built-in crosshairs that is sighted in on a graduated scale on the level rod. The instrument is typically mounted on a tripod adjusted to allow eye-level access. There are several types of instruments available. The accuracy desired for any series of measurements will typically determine the instrument configuration, functions and cost.

The basis for providing accurate measurements depends upon maintaining the instrument in a level position during all measurements. Newer models are typically self-leveling. Older non-self-leveling instruments require manual leveling typically achieved with thumbscrews in the instrument base and built-in or attached bubble levels. Frequent re-checking of this style of instrument is required throughout the measuring cycle to maintain accuracy.

Self-leveling, or auto-leveling instruments have been available for a number of years. The instrument is adjusted to a near-level position, and internal mechanisms maintain the instrument in a level position. As with the non-self-leveling instrument, care should be taken to avoid disturbing the instrument during use.

Over the last decade digital instruments have been developed. These instruments utilize a bar-coded rod, which is read by the instrument when a switch is activated. Newer models have onboard storage capabilities with several different styles of computer interface for data downloading.

Figure 2.16.1 Self-leveling Optical Level, tripod and 16 foot Collapsible Fiberglas Rod

General Applications

Elevations at selected locations on a floor or floor slab surface can be measured utilizing any of the instruments discussed above. Elevations can be taken relative to an assumed elevation on the surface or a selected point external to the surface being considered. Elevations obtained can be utilized to produce floor elevation contour maps.

Some Considerations

1. The optical level systems results can incur errors when performing floor elevations in typical residential and other low-rise buildings, where some floor areas are not within line-of-sight. When line-of-sight is not possible with one position of the base station, movement of the base station is required. This requires tying-in the two readings at the “turn” (set-up), and manually offsetting the readings obtained at the new base station position. Manually offsetting the sensor output can induce errors.

2. There are numerous texts detailing the methods and protocols of good surveying practice and the proper usage of these instruments. As in all test methods that attempt to define relational positions of various points, thorough and complete note taking is essential to minimize error.

3. The accuracy that can be expected with a moderately priced, non-digital level that is maintained according to the manufacturer’s specifications and used in accordance with generally accepted methods and protocols is on the order of 0.01 feet. Short distance sightings may allow estimation to 0.005 feet. Digital levels can achieve accuracies of up to

0.001 feet, depending upon instrument configuration. Certain non-digital levels can achieve accuracies of up to 0.001 feet by using a Vernier-type scale attached to the level rod.

4. As with any precision instrument care in handling is paramount.
5. Elevation survey should be noted for steps and changes in floor coverings.
6. Vial leveling systems require a protocol for calibration and setup on station. Operator error can occur.
7. Optical level systems require two people.

Relative Cost

Purchase: $$-$$$$
Rent: $$-$$$

Additional Resources

Numerous texts are available covering surveying methods and protocols in-depth.
National Society of Professional Surveyors: http://www.nspsmo.org/

2.17 PETROGRAPHIC EXAMINATIONS

General Description

Petrographic Examinations consists of the examination of concrete samples using chemicals and lighting techniques through a microscope. The objective of the examination is to evaluate the condition of the concrete including defects, visible indicators of deterioration, evidence of unsound or reactive concrete, un-hydrated cement, and carbonation of the concrete and mortar.

This test requires obtaining core samples (Section 2.4) from the structure being evaluated. Petrographic Examination consists of a series of observations that require interpretation to draw conclusions regarding the quality of the concrete sample being observed. The first step in a Petrographic Examination is to visually examine the concrete core sample as received, and then the sample is fractured and examined (Figure 2.17.1).

Figure 2.17.1 Freshly fractured concrete pile specimen. Note sand pocket (arrow)

Next, a lapped (polished) thin cross-section of the sample is prepared to accentuate the appearances of the paste, aggregate, and air voids. The lapped specimen and freshly fractured surfaces of the specimen are examined visually and stereo-microscopically up to 100X. Petrographic Examination could also involve the evaluation of powder mounts of cement paste. A powder mount is prepared by scratching away very small portions of the paste and mounting them on a glass microscope and slide in optical immersion oil. The powder mount is examined using a polarized/transmitted-light microscope at magnifications up to approximately 500X.

General Applications

In general, Petrographic Examination is used to evaluate the quality and soundness of concrete at selected locations. More specifically, Petrographic Examination used to determine the cement content, percent of entrained air, and degree of concrete consolidation. The examination may also determine the aggregate type and whether it is acid soluble, the extent of hydration, the condition of the sample, whether deposits or contaminants are present, and if there is micro-cracking.

Petrographic Examination is also commonly used to evaluate the presence of detrimental chemical reactions such as delayed ettringite formation (DEF) and alkaline silica reaction (ASR) in hardened concrete. DEF is described as an internal sulfate attack in hardened concrete due to different factors including curing, composition, and exposure. Sulfate reacts with calcium and aluminum in the cement paste leading to expansion of the cement paste. Due to this expansion, gaps formed around aggregates. The gaps become partially or completely filled with ettringite. ASR is a heterogeneous chemical reaction that takes place in aggregate particles between the alkaline pore solution of the cement paste and silica in the aggregate particles. The reaction products occupy more space than the original silica so the surface reaction sites are put under pressure, which could be greater than the tensile capacity of the aggregate particles in the concrete leading to cracking.

Figures 2.17.2 through 2.17.9 show examples of concrete deficiencies that were determined by petrographic examinations.

Coarse Aggregate Segregation

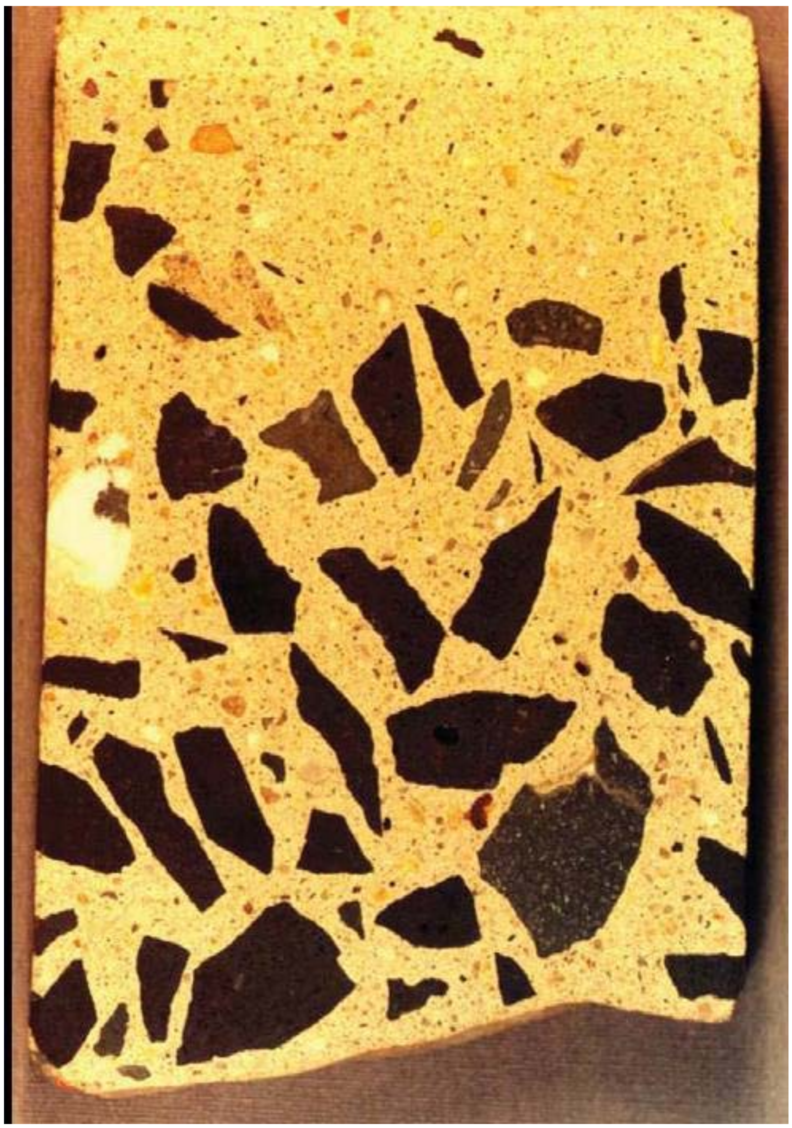


Figure 2.17.2 Severe segregation of coarse aggregate. The lighter colored layer of cementitious matrix near the top represents a zone of very high water-cementitious ratio

Air Voids

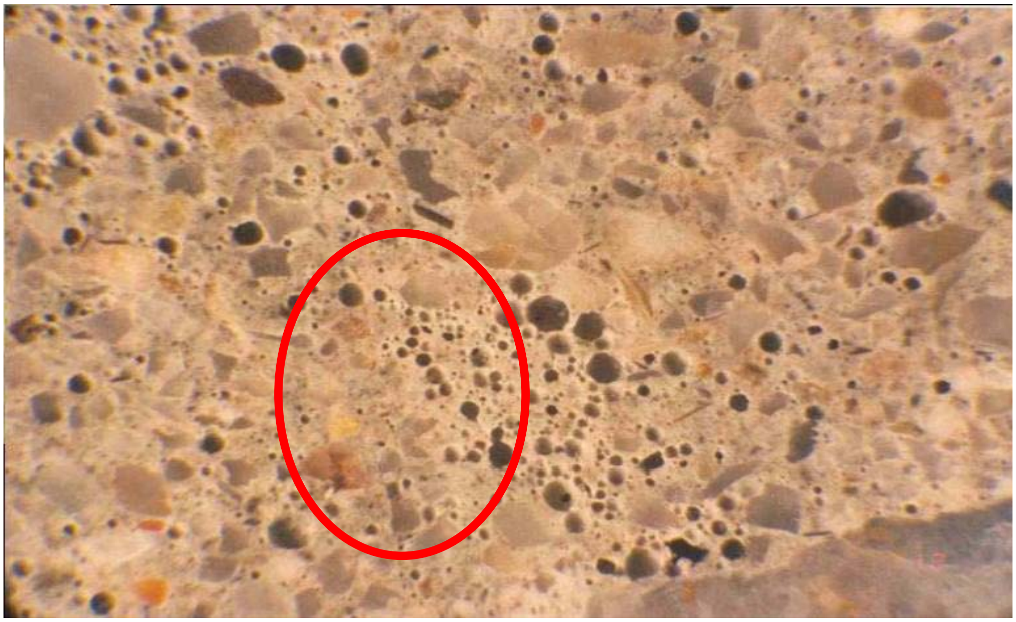


Figure 2.17.3 Air void cluster (oval)

Poor Curing

Figure 2.17.4 Poor curing caused by a "Leisegang Ring" type feature in concrete (arrows)

Water-cementitious Ratio

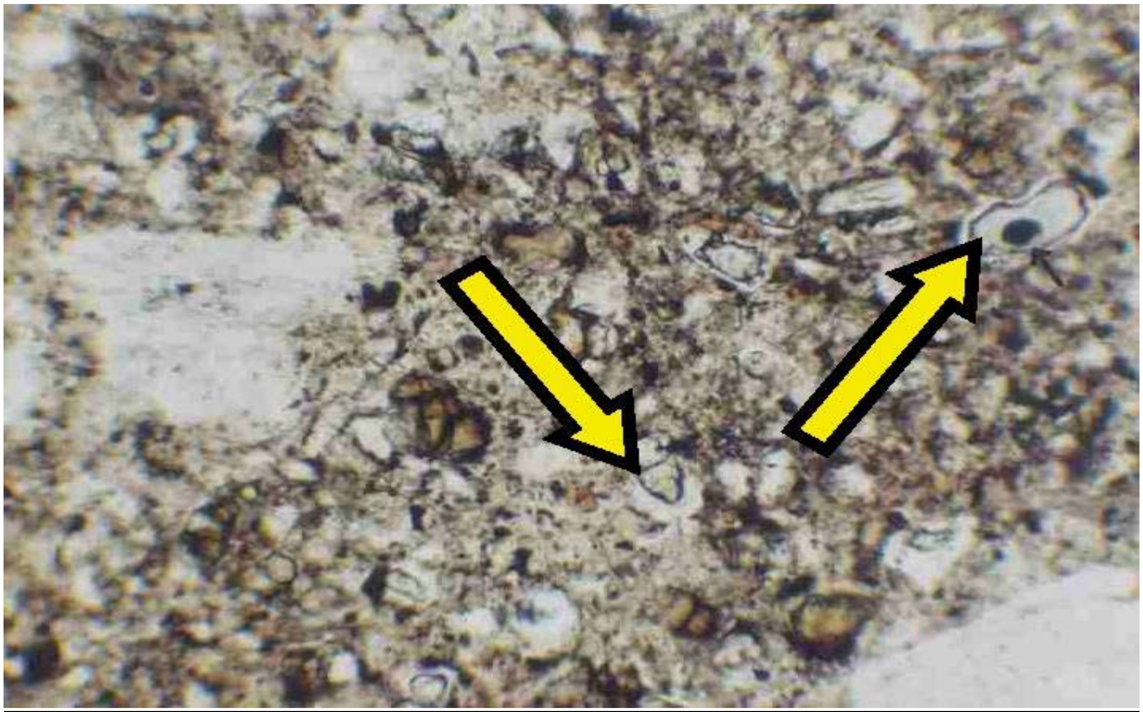


Figure 2.17.5 Very low water to cement ratio (arrows)

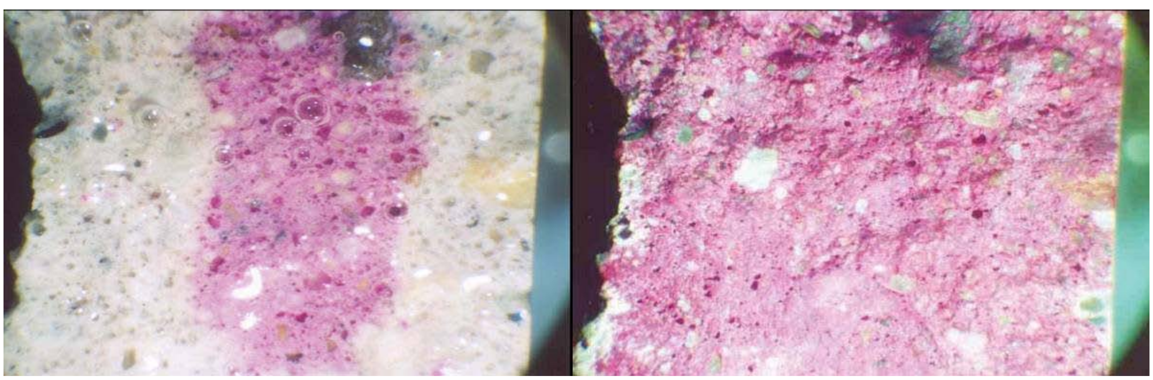
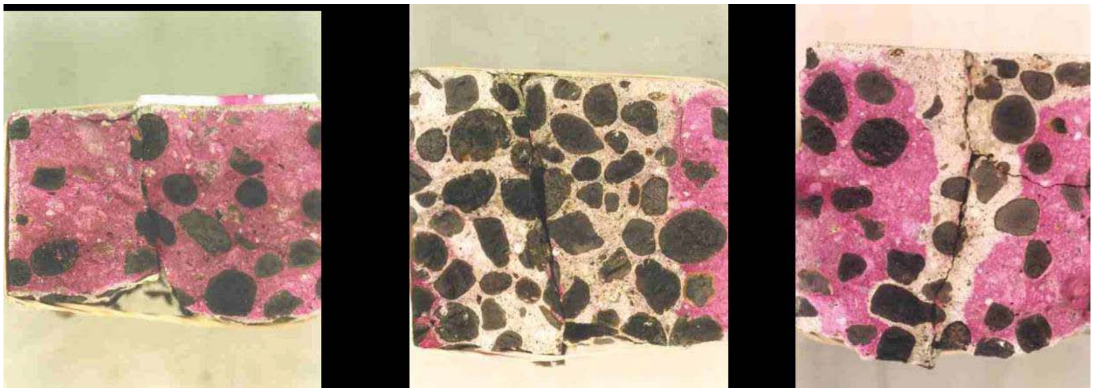


Figure 2.17.6 Carbonation pattern indicates high water cement ratio

Age of Cracks



(a) (b) (c)

Figure 2.17.7 Age of crack based on carbonation (unstained) pattern. (a) Young crack, (b) Old crack, (c) Moving crack

Types of Cracks

Figure 2.17.8 Typical plastic shrinkage cracking

Figure 2.17.9 Severe drying shrinkage cracking

Some Considerations

1. This test method is limited to small areas of the structural element being evaluated. In other words the test method is limited to the samples obtained from the structure being analyzed.
2. Typically, concrete coring is required to obtain samples for Petrographic Examination.
3. Petrographic Examination is typically performed in the lab with high magnification microscopes, but can also be performed in the field with field microscopes. However, the magnification of field microscopes is limited.
4. Treatment of samples during and after collection is important in order to maintain the condition of the collected sample as close as possible to actual field conditions during handling.
5. Background information regarding the as-built conditions and in some cases the design intent of the concrete structure being evaluated may be required in order to properly interpret results.
6. Location of sample(s) being evaluated should be documented.
7. Petrographic Examination requires data interpretation and analysis following standard techniques described in several ASTM standards. This requires the involvement of an experienced petrographer.
8. Water-cementitious ratio can only be evaluated qualitatively. In other words, water cementitious ratio cannot be determined petrographically; samples can only be compared relative to one another.

Relative Cost

Professional Services: $$ - $$$$ (cost will vary depending on number of samples required to be analyzed and extent of petrographic examination).

Additional Resources

FHWA-HRT-04-150 *Petrographic Methods of Examining Hardened Concrete: A Petrographic Manual* by the US Department of Transportation Federal Highway Administration
ASTM C295 *Standard Guide for Petrographic Examination of Aggregates for Concrete*
ASTM C457 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*
ASTM C823 *Standard Practice for Examination and Sampling of Hardened Concrete in Constructions*
ASTM C856 *Standard Practice for Petrographic Examination of Hardened Concrete*
ASTM C1260 - *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)*
ASTM C1293 *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*

2.18 PLUMBING LEAK DETECTION

General Description

Plumbing Tests, also called Leak Detection Tests, are employed when a supply and/or sanitary leak is suspected beneath a foundation. Common plumbing leak tests include:

- Pressure test for supply lines and sprinkler lines.
- Hydrostatic, isolation, flow, and video tests for sanitary system and storm water drain lines.

Air conditioning condensate lines are visually evaluated

To test the supply system, the occupants are instructed to not use any water during the test and the water supplies to toilets, icemakers and other automatic watering devices are shut off. The water meter is read. If after an allotted time, typically 30 minutes, the meter reading does not change, then there is no supply leak. An alternative method to testing the supply system is to shut-off the main supply valve or a building shut-off valve and to place a pressure gage at a hose bib and monitor pressure drop over time.

Prior to the hydrostatic test being performed, the occupants are instructed to not use any water during the test. Water supplies to toilets and any automatic watering devices are shut off. The air conditioner/dehumidifier should also be shut off if the condensate drains into the sanitary system.

To perform a hydrostatic test on the sanitary system, a plumber fills the plumbing system to floor level and if the water surface level remains constant for approximately 30 minutes, no leaks are present. To test the system, a rubber bladder (Figure 2.18.1) is inserted at the sanitary system's exit, normally at the cleanout, and inflated to block the exit of any water from the plumbing system. Typically monitoring is performed from an interior drain such as a toilet floor flange or another floor drain to allow observations of the level of water in the system. Water is run in a sink or shower until the system is full, and the water level is marked or recorded. After the allotted time has elapsed, the ending water level is compared to the initial level. If there is no change, then there is no leak in the system. If there is a change, and there was no malfunction with the rubber bladder, then a leak is present somewhere in the system.

Figure 2.18.1 Leak Test apparatus including pump, hose, and rubber bladders

In the hydrostatic test method described above, the rubber bladder, also called the test ball, is placed between the house and the cleanout riser. This allows for monitoring for leakage past the ball from the vantage of the riser, but requires filling and monitoring from a fixture inside of the house.

An alternative hydrostatic test method is to place the test ball between the riser and the sewer system; this allows filling and monitoring from the cleanout riser, but does not allow for monitoring any leakage past the bladder. If the alternative hydrostatic test shows no change in water level, then the results can be readily accepted. If the test shows a leak, then leakage past the bladder must be considered as a source of leakage.

If the hydrostatic test detects the presence of a leak in the sanitary system, the next step is to isolate the leak. The plumber will use two or more rubber bladders to block a section of the sanitary system. The blocked section is filled with water and checked for leaks in much the same manner as the sanitary system hydrostatic test. This is continued throughout the system until the leak(s) is isolated. Once the leak is isolated, a camera may be inserted in the system to locate and document the leak.

Finally, a flow test may be employed to estimate the amount of water lost through the leak(s) during normal household usage. A known volume of water is poured into the system, making sure that it passes through the leaking section(s) and the water is captured at the exit and measured. The volume of water lost to the leak(s) is the difference between the initial and final water volumes. Based on the test results, the water loss on a daily basis can be estimated.

General Applications

A supply line test is generally performed in conjunction with a sanitary system Leak Detection Test. Both tests are often performed to confirm or rule out foundation movement due to below slab water leaks. A supply line test may also be warranted when unusually high water bills are received or when a leak is suspected for another reason.

Tracing of air conditioning condensate lines are used to determine possible impact on the foundation.

Some Considerations

1. Testing should be performed by a qualified plumber.
2. Supply line test is typically used for below slab plumbing. Typically, an above slab supply plumbing leak is readily apparent.
3. Some owners may consider the removal and replacement of the toilet to be destructive.
4. When toilet is removed, the wax ring will likely need to be replaced.
5. A hydrostatic test does not determine the quantity of water leaking from the system, only whether or not the system is leaking under hydrostatic conditions. A flow test can estimate the quantity of water loss under normal flow conditions.
6. A belly in the sanitary sewer line may result in a gain or a loss of water during the flow test. Several flow tests should be performed in order to characterize the leak.
7. A flow test performed immediately after a leak detection test may not be accurate because the voids around the leak may be charged with water from the leak detection test.
8. Sanitary system leaks may be caused by root intrusions, collapsed pipe, or broken or cracked pipe.
9. A video of the sanitary system can identify the location of bellies in the pipe. Video tests may also help determine cause, location, and condition of leaks. If pipe breaks are not significant in size, the video may not detect the defect in the pipe.
10. Trace condensate line to determine if it discharges into the sanitary sewer system. If so, the air conditioning system should be turned off during hydrostatic and flow tests.
11. Leak testing is often performed before a foundation is lifted and should always be performed after lifting to insure the lifting process did not break any pipes.

Relative Cost

Professional Services: $$ - $$$

Additional Resources

None found.

2.19 POST-TENSION LIFT-OFF

General Description

Post-Tension Lift-Off testing (Figure 2.19.1) consists of gripping and pulling the exposed end of the tendon in order to release the wedges of the tendon anchor and measure the effective force in the tendon. A calibrated hydraulic ram and pressure gages are used to measure the force in the tendon.

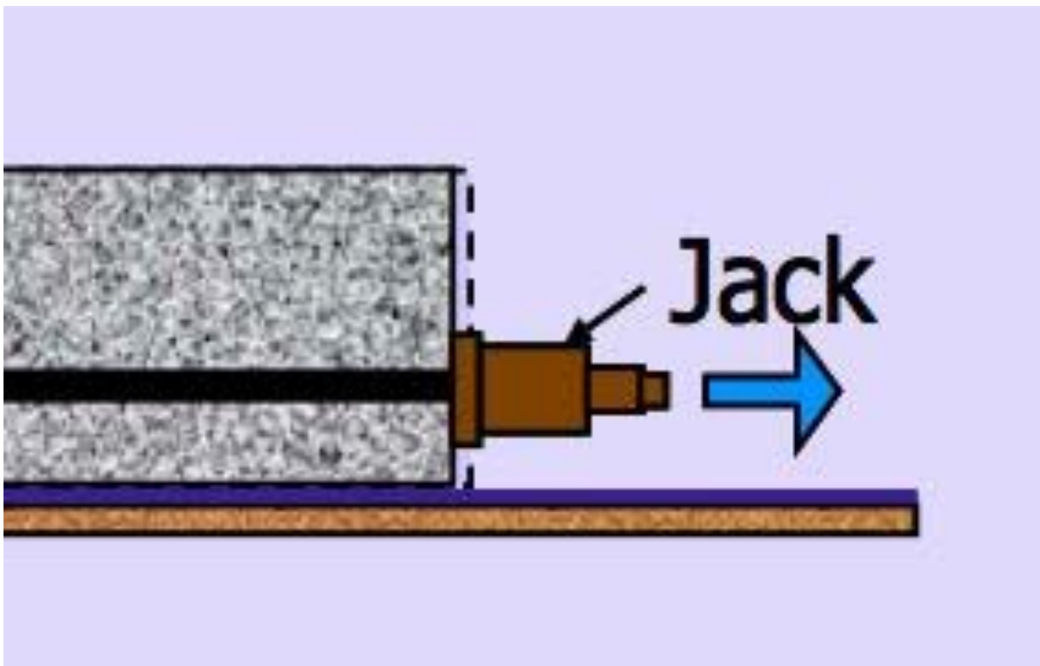


Figure 2.19.1 Jack pulling post-tensioned tendon end during lift-off

General Applications

This test is used to measure the effective tendon tension force in un-bonded post-tensioned tendons.

Some Considerations

1. Failure of post-tensioned strands could occur during testing, possible causing the dead end of the tendon to become a projectile.
2. The exposed tendon anchor and strand tail should be evaluated for deteriorated conditions including corrosion and sufficient length of tendon tail prior to testing.
3. Specialized equipment and tools are required to accommodate different tendon anchorage conditions and properly grip the tail end of the tendon.

4. Testing equipment should have current calibration per equipment manufacturer's written instructions.
5. This test should only be performed by properly trained personnel.
6. The test provides a quantitative result.
7. Access to a tendon live end is required in order to perform the test. Possible access issues include interference from adjacent structures, flatwork, decks, landscaping, and obstructions to test equipment. Access to the dead end should be evaluated in case strand failure occurs and strand replacement is required.
8. The grout at tendon's anchor pocket, where the test is to be performed, may need to be removed if the tendon anchor is not exposed. After the testing is completed, the pockets should be grouted with non-shrink grout.

Relative Cost

Professional service: $$-$$$

Additional Resources

ICRI Guideline No. 03736 *Guide for the Evaluation of Unbonded Post-tensioned Concrete Structures*

2.20 POST-TENSIONED TENDON SCREWDRIVER PENETRATION

General Description

The Post-Tensioned Tendon Screwdriver Penetration Test (Figure 2.20.1) is a test that may help to determine whether a post-tensioned tendon (Figure 2.20.2) has been stressed, cut, or broken. Concrete is removed to expose a portion of the tendon within the concrete structure a sufficient distance away from the corresponding anchors such that the integrity of the anchor support is not compromised. If the tendon is unbonded, the sheathing is removed.

The Screwdriver Penetration Test is performed by attempting to insert the tip of a standard size flat tip screwdriver between the wires of the strand in the post-tensioned tendon. If the tendon had been tensioned and it is uncut and unbroken, it will usually not be possible to separate the wires of the strand. If needed, a hammer may be used to apply an impact force to the screwdriver.

Figure 2.20.1 Post-Tensioned Tendon Screwdriver Penetration Test

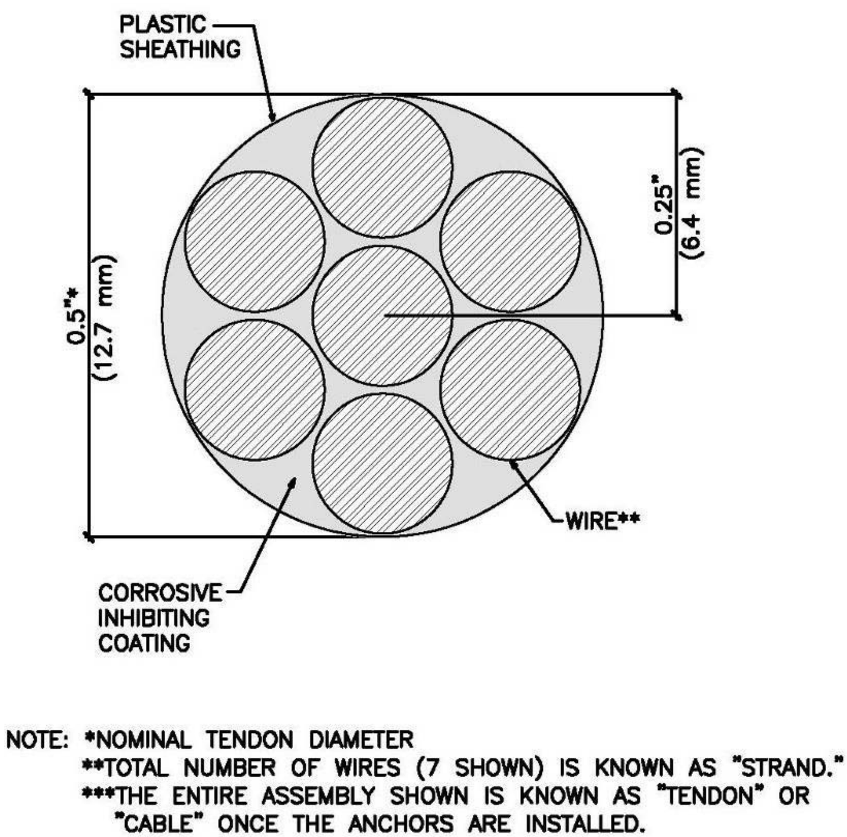


Figure 2.20.2 Cross-section of a 7-wire strand***

General Applications

The Post-Tensioned Tendon Screwdriver Penetration Test may be applied to any post-tensioned reinforced concrete foundation to evaluate the presence of tension in the tendon.

Some Considerations

1. The tendons may be damaged during the process of removing the concrete.
2. Different operators may apply different forces during the test.
3. There are no universally accepted standard specifications for the size or length of the screwdriver.
4. The test is most useful to evaluate if the tendon is un-tensioned. The difference between fully tensioned and partially tensioned tendons cannot be readily evaluated.
5. Patching of the chipped concrete void at the test location is typically required if the surface of the concrete must be restored to its original condition.

Relative Cost

Purchase: $

Additional Resources

ICRI Guideline No. 03736 *Guide for the Evaluation of Unbonded Post-tensioned Concrete Structures*

2.21 REBOUND HAMMER (“SWISS” OR “SCHMIDT” HAMMER)

General Description

Masons and construction workers used to check the soundness of the concrete by striking the surface with a hammer. They used to be able to roughly assess the relative hardness of the concrete on the basis of the more or less metallic sound produced and of the rebounding of the hammer in the hand. The Rebound Hammer is the result of the evolution of this crude test method.

The Rebound Hammer (Figure 2.21.1) is a hand held spring-loaded device used to measure the hardness of concrete as a function of the energy dissipation of the spring-loaded rod after it releases and hits the concrete surface. The Rebound Hammer operates by pressing a hammer rod against the concrete surface to be tested, loading an internal spring. After the spring is set, the rod is released striking the surface of the concrete. The rod reacts and re-transmits the rebound to the mass; and the harder and more compact the concrete, the greater the rebound. During the rebound stroke, the mass moves a pointer indicating the maximum point of return and at the same time a reference value on a scale. The reference value, when translated in a chart provides an approximation of the compressive strength as a function of the impact angle.

Figure 2.21.1 Rebound Hammer Test

General Applications

The Rebound Hammer is a qualitative method used to evaluate the relative hardness of concrete in order to aid in the selection of points where concrete sampling and testing may be warranted.

Some Considerations

1. Test results are available on-site.
2. The method is not a substitute for material sampling and compressive strength testing.
3. The test may leave small indentations on the concrete surface.
4. Can be used with minimum training.
5. Concrete surface preparation may be necessary.
6. Periodic calibration is necessary.

Relative Cost

Purchase: $$

Additional Resources

ASTM C805 *Standard Test Method for Rebound Number of Hardened Concrete*
ACI 228.1R *In-Place Methods to Estimate Concrete Strength*

2.22 REINFORCEMENT LOCATOR (R-METER)

General Description

A reinforcement locator (R-meter) (Figure 2.22.1) measures changes in electric inductance to indicate the presence of underlying ferromagnetic metal. An R-meter measures the intensity of electromagnetic signal in order to locate the steel to a certain level of precision. Some units include a digital display that indicates cover and diameter of steel reinforcing bar (Figure 2.22.2). More sophisticated units provide a three dimensional layout of the reinforcement and concrete coverage.

Figure 2.22.1 R-meter unit

Figure 2.22.2 R-meter unit digital display

General Applications

R-meters are used to determine the location and size of embedded conventional steel reinforcement and post-tensioned tendons. These instruments are also used to determine the concrete cover over steel reinforcement.

Some Considerations

1. The equipment is portable and typically battery powered.
2. Access to only one side of the structure is required.
3. Able to penetrate across air or other material interfaces (i.e. placement of the meter on the concrete surface is not required).
4. Does not require data interpretation and analysis. Units with digital display provide the output directly.
5. Signal decreases with depth. Typically 4 to 6 inches is the limitation in depth of penetration.
6. Areas with congested reinforcement prevent accurate signal.
7. Presence of metal fibers in concrete mix could prevent penetration of the R-meter signal.

Relative Cost

Purchase: $$ - $$$$$
Rent: $ - $$

Additional Resources

ACI 228.2R *Nondestructive Test Methods for Evaluation of Concrete in Structures*

2.23 RESISTIVITY

General Description

The Electrical Resistivity Field Testing technique is a type of geophysical testing that was first used in the 1920s by the Schlumberger brothers for logging wells. This early one-dimensional method for determining soil and rock composition has since been extended to two and three dimensions and is now used for investigation of ground composition near the surface and around and below foundations.

Obtaining the resistivity survey involves inducing an electrical current (usually from a 12-volt automobile battery) into the soil surface via two probes functioning as current electrodes (one positive, one negative) and utilizing other probes in between that function as potential electrodes to measure voltage drop due to the resistance of the soil medium. Probes in a liner array (Figure 2.23.1) may be spaced along a straight line at a predetermined spacing, for example, every five feet.

With the collected resistivity data (in ohms) algorithms are used to compute resistivity and provide two-dimensional graphical plots of apparent resistance (in ohm-meters) to depths of soil that may be 50 ft. or more. The longer the probe line the deeper the depth of measured resistivity. Three-dimensional plots may be obtained by using multiple probe lines that form a two-dimensional array on the ground surface.

Figure 2.23.1 Reading data from a line of resistivity probes

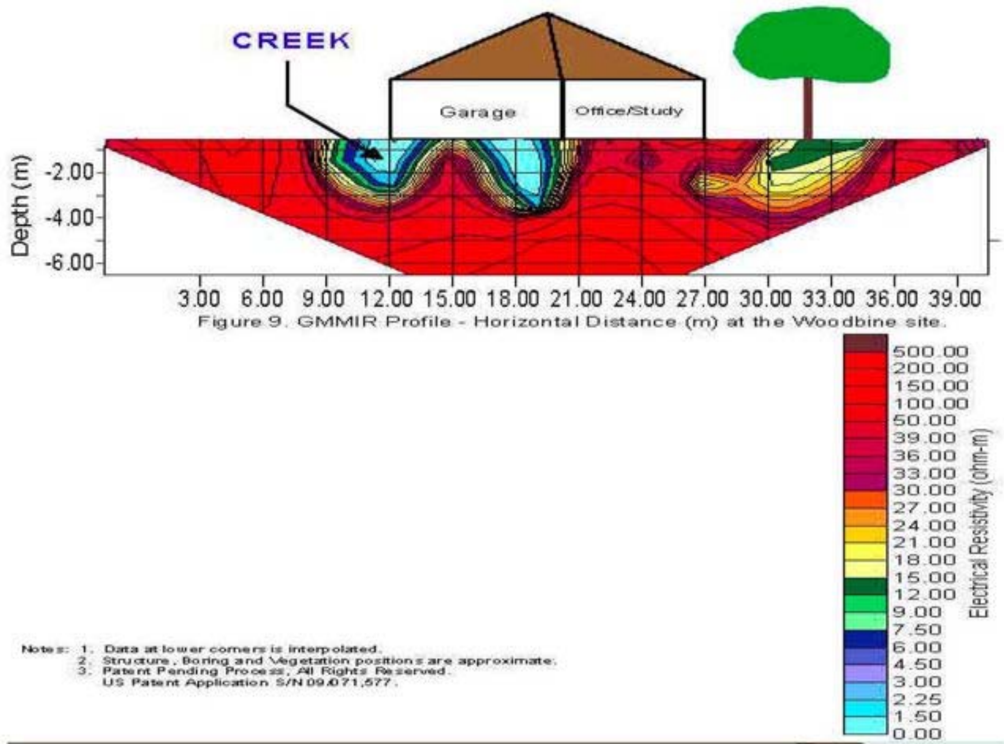


Figure 2.23.2 Two-dimensional resistivity profile, from 10 Dec 08 FPA slide presentation by John Bryant, PhD, P.G., P.E., where high (red) values indicate dry soil and low (blue) values indicate excessive ground moisture, such as the pre-existing creek shown

In order to increase the reliability of the results, Resistivity Testing should be coupled with geotechnical testing. Soil boring samples are retrieved in line with or near the resistivity lines and individually resistivity-tested in the lab. This geotechnical data set can then be correlated with more extensive data retrieved by the resistivity surveys conducted.

General Applications

Resistivity Testing has applications for remote sensing of composition, condition, and anomalies below grade. In evaluating existing foundations, Resistivity Testing is commonly used to determine underground effects of plumbing leaks, poor drainage, and the location of pre-existing ponds, lakes, streams, etc. Resistivity Testing is also used to detect pre-existing foundations, pipe locations, caverns and other voids, landfills, soil strata variations, tree root zones, and accumulation of ground water.

The output from Resistivity Testing can contain useful images that pinpoint and identify underground anomalies via graphical plots of apparent resistance (Figure 2.23.2). Since groundwater is highly conductive, resistivity testing can be useful in locating underground water sources or pockets. Because root-affected zones and some underground structures such as concrete footings or metal pipes have different conductivity, resistivity testing can also delineate and locate these anomalies.

Some Considerations

1. Test results are quickly obtained and available on-site to allow confirmation of results.
2. The field equipment for the resistivity survey is portable, can be hand carried, and used inside buildings.
3. Resistivity surveys are non-destructive when applied on grade outside and along foundations; however these surveys require the drilling of small (about 0.5”) diameter holes through concrete flatwork or foundation slabs and flooring materials, which then require patching. If the floor finish is carpet, it should be rolled back during testing.
4. Technicians with some training can collect data. However, proper interpretation of the data requires a geotechnical and geophysical background.
5. The electrical resistivity survey is not a substitute for geotechnical testing and should be correlated with laboratory Resistivity Tests and standard geotechnical testing of soil borings retrieved in line with or near the lines of resistivity data collection in order to pair the site specific soil conditions with correspondence resistance measurements.
6. Two-dimensional Resistivity Testing is usually adequate in cases where the foundation footprint can be surrounded by lines of resistivity. Three-dimensional images contain hidden information that may require many 2-D slices during post-processing in order to adequately evaluate the data.
7. Personnel and pets should be kept clear of the probes while current is flowing and data collection is in process.

8. For small residential lots, data collection depths of 25 feet are usually attainable. However deeper penetrations are achieved where the resistivity lines can be increased in length. The greatest depths are attained near the center of the arrays, so the arrays must extend well beyond the area of interest, as only surface information will be attained near the array endpoints.
9. While the usual linear array for 2-D resistivity surveying consists of ground penetrating probes during data collection, it is possible to rent linear arrays that can be dragged along the ground surface manually or by vehicle.

Relative Cost

Professional Services: $$$$-$$$$$

Additional Resources

ASTM D1125 *Standard Test Methods for Electrical Conductivity and Resistivity of Water*
ASTM G57 *Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*
ASTM G187 *Standard Test Method for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method*
M. H. Loke, Ph.D., *Electrical Imaging Surveys for Environmental and Engineering Studies; A Practical Guide to 2-D and 3-D Surveys, 1999*
M. H. Loke, Ph.D., *Tutorial: 2-D and 3-D Electrical Imaging Surveys, 2010* (Course Notes)
ANSI/IEEE 81 *Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System*

2.24 ULTRASONIC-PULSE VELOCITY

General Description

The Ultrasonic Pulse Velocity (UPV) Test consists of using a pair of electro-acoustical transducers to emit a stress pulse of compressive waves through mature concrete from the transmitting lead to the receiving lead and determining their travel time for a known path distance (Figure 2.24.1). The wave speed of the ultrasonic-pulse indicates the relative quality of the concrete member with wave speeds of less than 12000 ft/s (3660 m/s) indicating poor quality concrete. Factors that affect the pulse velocity include: aggregate type, aggregate content, moisture content, and reinforcement.

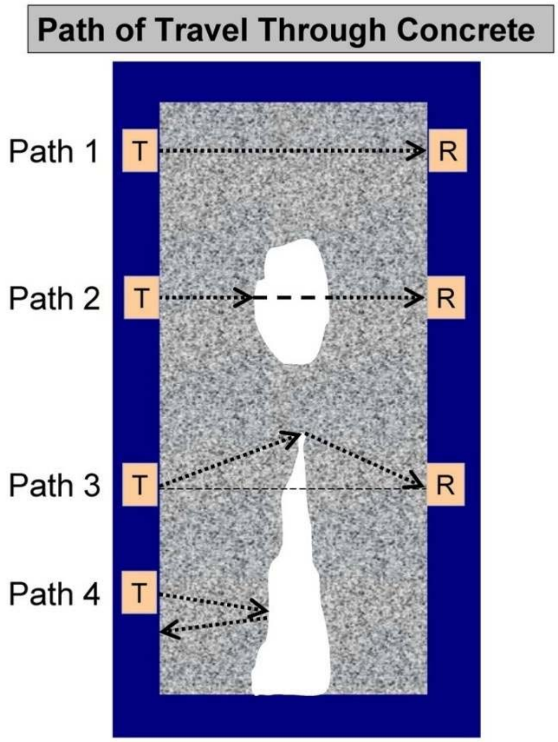


Figure 2.24.1 UPV path of travel through mature concrete

The electro-acoustical transducers are held in contact with opposite ends of the concrete member with a coupling agent that will allow transmission of the ultrasonic-pulse through the interface. Lower frequency electro-acoustical transducers (around 20 kHz) should be used for longer path lengths where more variation in UPV could occur, while higher frequency transducers (50 - 100 kHz) are better suited to obtaining more accuracy in shorter path distances. The acoustic coupling will have an effect on the signal strength of the transducers, so care must be taken to ensure that the coupling agent does not inhibit the transfer of the ultrasonic-pulse. Using technology that is currently available, the test can be performed on members measuring 2 inches (0.05 meters) to 50 feet (15 meters) in length.

General Applications

The UPV method is a qualitative test that helps to determine the relative quality of concrete. The UPV method can be used to assess relative uniformity of a concrete member or to detect damage such as internal cracking, delaminations, voids, and honeycomb.

Some Considerations

1. Access to both sides of the concrete member is required to perform the test; therefore, the test is typically used on elevated concrete structures.
2. The equipment is easy to use and relatively compact and portable.
3. The results should be verified with other methods.

4. The results do not provide quantitative data, so the depth of defects is unknown.
5. The test requires that the precise path distance is known and that the smallest dimension of the member is greater than the ultrasonic-pulse wavelength (pulse velocity divided by the ultrasonic pulse frequency).
6. The test is affected by the degree of saturation of the concrete member as water increases the UPV.
7. The test is affected by the presence and amount of steel reinforcement, with pulse velocities being higher in heavily reinforced concrete versus plain concrete, which will affect the interpretation of results.
8. Variations from typical UPV must be interpreted to determine condition of concrete, which requires some experience.
9. The two transducers must be prevented from coming in close contact with each other when measurements are being taken to avoid having the receiver lead pick up unwanted direct signals from the transmitter lead, which will result in an incorrect display of the wave transit time.
10. A 2-D map or 3-D rendering can be generated of a foundation element to visualize the internal damage by conducting extensive UPV testing and exporting the test data from the testing instrument to appropriate software.

Relative Cost

Purchase: $$$-$$$$
Rent: $ - $$

Additional Resources

ASTM C597 *Standard Test Method for Pulse Velocity through Concrete*
ASTM E494 *Standard Practice for Measuring Ultrasonic Velocity in Materials*
ACI 228.1R *In-Place Methods to Estimate Concrete Strength*
ACI 228.2R *Nondestructive Test Methods for Evaluation of Concrete in Structures*

2.25 VAPOR TRANSMISSION

General Description

Vapor Transmission Test (Figure 2.25.1) consists of measuring the vapor emission rate (VER) through a slab-on-ground. The rate of vapor emission is measured by using anhydrous calcium chloride in powder form placed over an exposed area of the slab covered with a plastic cover. Vapor emission can be measured qualitatively or quantitatively.

Qualitative Approach: The qualitative approach consists of visually inspecting the condition of the anhydrous calcium chloride after 60 to 72 hours of being placed over the slab-on-ground and covered with the plastic cover. Moisture emission will cause the anhydrous calcium chloride to darken or gel under small moisture emission. The anhydrous calcium chloride will liquefy if the moisture emission is significant.

Quantitative Approach: this approach consists of placing a weighted amount of anhydrous calcium chloride into a plastic container over a measured exposed area of a slab-on-ground covered by a plastic and covered for a defined time period between 60 to 72 hours. The weight of the anhydrous calcium chloride and the plastic container is to be weighed to the nearest centigram (0.01 gram) before and after the test is performed. The difference in the container weight is defined as the “weight gain”. The vapor emission rate in pounds per 1,000 square foot area per 24 hours is measured by the following formula:

$$VER = \frac{1{,}000\ sq.ft.x\ weight\ gain\ (grams)\ x\ 24\ hours}{Area\ of\ test\ (sq.ft.)x\ Exposure\ time(hours)\ x\ 454\ grams\ per\ pound}$$

Figure 2.25.1 Vapor Drive Test Kit over a exposed area of a concrete slab-on-ground

General Applications

This test method is typically used to determine the adequacy of a slab-on-ground to receive a finish floor system that is sensitive to vapor emission. This test method could also be used to evaluate the effectiveness of a slab vapor retarder/barrier. Acceptable vapor emission rates will vary depending of the type of floor system. A typical acceptable vapor emission rate for many floor systems is a VER of 3 pounds of moisture per 1,000 square foot area in a 24 hour period.

Some Considerations

1. The plastic container with the anhydrous calcium chloride including the tape used to seal the container must be weighed to the nearest 0.01 grams before and after the test.
2. The test surface must be prepared properly by removing dirt, debris, coatings, and/or residue of adhesive material that may have been used in a floor system previously present.
3. Exercise caution not to spill any amount of the anhydrous calcium chloride after the test is complete. If this situation is presented, the test results are not valid if the quantitative approach is used to evaluate VER.
4. The plastic cover must be sealed tight against the concrete surface in order to eliminate moisture from escaping the test area. The surface area delineated by the plastic cover shall be accurately measured. Typically the plastic cover including the surface area delineated by the cover is provided by the test vapor emission test kit manufacturer.
5. A caution sign should be placed over the test areas during testing in order to minimize the possibility of disturbing the test units. This is especially important if the test is performed in occupied spaces.
6. A representative number of tests should be performed. A suggested general guideline on the number of required test per square foot area is as follows:
    a. 2 tests for areas up to 500 sq. ft.
    b. 3 tests for areas ranging between 501 and 1,000 sq. ft
    c. 4 test for areas ranging between 1,001 and 5,000 sq. ft.
    d. 1 additional test for each additional 5,000 sq. ft
7. Avoid placing test units within 5 feet of slab edges.
8. Testing should be performed under the same climate controlled conditions that the flooring would be exposed to during normal service.

Relative Cost

Purchase: $-$$

Additional Resources

ASTM F1869 *Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride.*

2.26 VISUAL

General Description

Visual Observation is the oldest evaluation method, and remains the primary choice of nondestructive methods. Visual Observation is often the first method used in the evaluation of existing foundations. Many indicators of foundation performance and the causes of foundation behavior can be identified through visual methods. Using Visual Observation as a first step allows the investigator to identify the potential problem(s) in order to, select the types and extent of further investigation. Visual indicators can always be documented through photography. Visual indicators are often supplemented with measurements.

General Applications

The following include some of the general applications of this method.

a) *Damages*: Damages observed can be classified as one of two types: characteristic and non-characteristic. Characteristic damages are those expected and usually found in the context of foundation movement. Non-characteristic damages are those not caused by foundation movement (refer to FPA-SC-03 *Distress Phenomena Often Mistakenly Attributed To Foundation Movement* for additional information). Characteristic damages can be classified into one of two types, indicative and non-indicative. Indicative damages contain some information (in the eye of an experienced engineer) about the direction or severity of movement. Non-indicative damages do not aid the practitioner in the evaluation of the foundation. An engineer, then, will only use characteristic indicative damages as a basis for his opinions.

    i) *Cracks at openings*: These occur at windows and doorways, on the exterior and interior surfaces of the building. In the analysis of these cracks, it is helpful to remember that the framing tends to distort into a parallelogram during movement. Cracks at windows are usually accompanied by separations of the window from the finish materials.

    ii) *Exterior trim separations*: On exterior walls, trim separates from the finish (e.g. brick or stone veneer) when foundation movement occurs. Trim separations can occur by the veneer pushing against the trim which will cause a separation at the miter at the corners, indicating a local drop. Trim separations can occur by the veneer pulling away from the trim, which will cause a gap along the length of the trim, indicating a local rise.

    iii) *Expansion joints*: Expansion joints should also be examined for differential foundation movement.

    iv) *Interior separations*: Separations can occur between interior surfaces, such as wall to ceiling, or between components and surfaces, such as cabinet separation from the wall. These damages often accompany foundation movement but may not indicate the nature of the movement.

    v) *Severe damages*: Severe damages usually accompany a high magnitude of foundation movement, and may compromise the ability of the structure to perform its intended function. Examples include cracks through concrete grade beams, framing separations, and other damage phenomena not normally seen in investigations of moderate foundation movement.

vi) *Slab cracks*: Cracks are attributed to concrete shrinkage, foundation movement, and/or other factors. Documentation of crack location, size, and pattern could aid in the determination of the possible cause of cracking.

vii) *Squareness of openings*: Window and door frame fit and function problems are usually accompanied by cracks at these locations. Considering the fit of the door within the jamb gives an indication of the movement across the width of the door.

b) *Crawlspace*: Crawlspace should be visually investigated for the possibility of drainage of yard water into the crawlspace, the drainage of water from the crawlspace, depressions, sump pumps, swales, ventilation, etc. Visually evaluate exposed piers as to whether bearing is at the surface or below, the size of the piers, and the floor area supported by each. Measurements can compliment this investigation.

c) *Drainage*: It is accepted that proper drainage is important to the performance of a foundation, and that poor drainage can adversely affect foundation performance. The slope of the grading surface within the influential vicinity of the foundation should be evaluated for its ability to carry water away from the foundation. These areas should be checked for depressions that could hold water. Sidewalks, landscaping, and other features that can impound drainage water should also be visually investigated. Debris, mulch, elevated decks and any other elements that may obscure the actual drainage pattern should be considered.

d) *Excavation near foundation*: The presence of underground tanks or other subterranean objects that require digging to install may undermine the foundation.

e) *Excessive moisture*: Soggy soils, free water in submerged cavities, efflorescence, algae, standing water, and aquatic plants, are signs of excessive moisture.

f) *Exterior building lines*: Distorted exterior building lines may indicate possible foundation movement. Some exterior finish materials, notably brick or lap siding, are usually constructed with linear visual features.

g) *Flatwork*: Horizontal movement of flatwork, called “walking”, may indicate movement due to expansive soils. Vertical movement of flatwork usually indicates soil activity.

h) *Foundation exposure*: Concrete foundations are typically visible at the perimeter. Large exposures may indicate inadequate embedment of the bottom of the perimeter beam, which could allow the support soil to be more sensitive to moisture changes. Foundation exposures may also show post tension system hardware or patches over the hardware, honeycomb pockets, cold joints, exposed reinforcing steel, deterioration, cracks and other anomalies.

i) *Grass and shrubs*: The condition of the grass and shrubs near the foundation is an indicator of the maintenance of moisture near the foundation.

j) *Pools*: Pools present particular threats to foundations. Normally pool decks are sloped for drainage away from the pool, and, if the deck reaches the foundation, this is an area of water loading if this deck runoff is not properly managed. Pools that have been built close to the foundation have the possibility of undermining the support soils for the house foundation. Pool plumbing can have leaks, which can affect both the pool and the house. Visual investigation and distance measurements are useful for the evaluation of deck runoff, but not often useful for pool leak determination.

k) *Previous work*: Signs of previous foundation repair work may include concrete repairs, disturbed soil, or concrete splatter on the side of the building or slab.

l) *Retaining walls and slopes*: Good foundation performance requires that the foundation support soils be structurally stable. Retaining walls near the foundation that are moving away from the foundation may have an effect on the support soils. Slopes near the foundation should be considered for possible effect on the support soils of the foundation.

m) *Roof runoff*: Roofs with valleys may concentrate the roof runoff to locations adjacent to the foundation. The management of this runoff, by gutters or other means, should be visually investigated. If gutters are used, investigate the exits from the system to ensure this water is not presenting a threat to foundation performance.

n) *Soils*: If soils are exposed for Visual Evaluation or exhibit cracking and separation from the foundation, these visual cues can aid in evaluating the moisture-related activity of the soils.

o) *Trees*: Trees and heavy vegetation within the influential distance of a foundation (consider neighboring properties also) should be visually investigated and their size, distance, and species documented. Trees next to a foundation should be investigated for the effect of roots lifting the perimeter beam or withdrawing moisture from the soils below the foundation causing subsidence.

p) *Topography*: The natural topography may affect foundation performance. Some of the natural topographic conditions to observe could include: the tops of hills with possible shallow top soil formations underlain by rock strata, valleys that may have sediments consisting of active soils, wet areas at the base or side of a hill that may indicate the presence of a water table. The man-made development of the topography may also affect foundation performance. Some of the man-made topographic conditions to observe could include: terracing of hillsides exposing various strata at the foundation elevation; areas of cut and fill.

Some Considerations

1. Visual Evaluations are inexpensive, do not require special equipment or specific expertise, and are non-invasive.

2. Visual Evaluations are often not conclusive, but they may be used to direct further investigation.

3. Tilting of the foundation cannot be evaluated by visual damages alone because foundation movement may occur without flexure.

4. Different finish materials will be damaged at different stress intensities; for example, masonry will show distress first, drywall second, and then thin wood paneling. Depending on the finish materials foundation movement may occur without visible damage.

5. The practitioner should be aware of other conditions that mimic damages from foundation flexure, such as roof rafter splaying, improper attachment of attic trusses to walls, and excessive mortar spoils behind masonry veneer. Refer to FPA-SC-03, *Distress Phenomena Often Mistakenly Attributed to Foundation Movement.*

6. Cracks in finish materials may be dynamic and may open and close cyclically. Refer to FPA-SC-12, *Guidelines for Evaluating Foundation Performance by Monitoring*.

7. Damages at the upper floors are usually more severe than damages at the first floor but may not be related to foundation movement. The closer the damage is to the foundation, the more likely that the damage is induced by foundation movement.

8. Failure of retaining walls and slopes may not be a factor in foundation performance if the foundation is supported by underpinning which is able to resist the effects of the slope failure.

9. Determine if primary condensate lines discharge adjacent to the foundation or if the primary condensate line is blocked and the secondary condensate line discharges adjacent to the foundation.

Relative Cost - N/A

Additional Resources

ACI 228.2R *Nondestructive Test Methods for Evaluation of Concrete in Structures*
ACI 201.1R *Guide for Conducting a Visual Inspection of Concrete in Service*
ACI 207.3R *Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions*
ACI 224.1R *Causes, Evaluation, and Repair of Cracks in Concrete Structures*
FPA-SC-03 *Distress Phenomena Often Mistakenly Attributed to Foundation Movement*
FPA-SC-12 *Guideline for Evaluating Foundation Performance by Monitoring*
FPA-SC-13 *Guidelines for the Evaluation of Foundation Movement for Residential and Other Low-Rise Buildings*

3.0 FOUNDATION CHARACTERISTICS AND DEFECTS

This section describes some characteristics and defects that engineers typically encounter in existing foundation evaluation projects. Some of the foundation characteristics and defects listed in the summary table attached to this paper (Appendix A) are not described in this section.

3.1 CONCRETE DIMENSIONAL PROPERTIES

Dimensional properties that engineers routinely measure in order to evaluate existing foundations include the slab thickness, levelness, and flatness, grade beam dimensions, and pier dimensions and depth. These dimensional properties can be determined using some of the test methods described in this paper. Refer to Section 2 and the summary table in the Appendix for information regarding different test methods that apply to concrete dimensional properties.

3.2 CONCRETE DISTRESS

3.2.1 Cracking

Concrete cracking is the partial or complete separation of a concrete element into two or more parts. Typically, concrete cracks are measured in terms of width, length, and type. The different types of cracks found in concrete foundations include craze, D-cracks, diagonal, transverse, longitudinal, hairline, map, pattern, gridline, plastic shrinkage, shrinkage (restraint), random, corner spalls and temperature. Refer to ACI 201.1R *Guide for Conducting a Visual Inspection of Concrete in Service* for additional information regarding concrete cracking.

3.2.2 Delamination

Reinforced concrete delamination is the separation of a reinforced concrete member above and below the location of steel reinforcement. Typically delamination occurs in reinforced concrete foundations that are subjected to reinforcement corrosion or freezing and thawing, which is similar to other types of distress such as spalling, scaling, or peeling except that delamination typically affects large concrete areas. The delamination mechanism typically consists of corrosion of the steel reinforcement, which has greater volume than the steel reinforcement prior to corrosion. This steel reinforcement volumetric increase causes stress on the concrete. This stress overcomes the relatively weak tensile strength of concrete, resulting in a separation of the concrete above and below the reinforcing bars. Refer to ACI 201.1R *Guide for Conducting a Visual Inspection of Concrete in Service* for additional information regarding concrete delamination.

3.2.3 Detrimental Chemical Reactions

Two of the most common detrimental chemical reactions in concrete structures including foundation systems are alkali silica reaction (ASR) and delayed ettringite formation (DEF).

ASR can be a cause of (usually deleterious) expansion in hardened concrete. ASR is caused by a reaction between certain siliceous aggregate types with alkali contained in the portland cement. Release of alkali during cement hydration and its subsequent reaction with siliceous aggregate particles result in formation of an expansive alkali-silica gel. Severe cracking of concrete is often associated with this reaction. However, in cases where the reactive particles are contained in the fine aggregate, expansion of concrete can occur without formation of severe macro-cracking. Since expansion due to ASR results in disruption of the aggregate, cracks that form typically extend outward from the deleterious particle and into the surrounding cementitious matrix. Refer to ASTM C1260 - *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)* and ASTM C1293 *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction* for additional information regarding ASR.

DEF is a hardened concrete internal expansion mechanism caused by the formation of ettringite crystals in the concrete paste after the concrete has attained rigidity. DEF is caused by several factors including high temperatures, presence of excessive amounts of sulfate, and concrete steam curing process.

3.2.4 Honeycombing

Honeycombing is an anomaly that is typically observed on the surface of concrete structures that occurs when the cement paste does not fill the voids between the large aggregate particles. Typically, honeycombing is caused by poor vibration of concrete during placement or by holes or gaps in the formwork not properly placed during construction, which allows cement paste to flow away from large aggregate particles. Honeycombing presents an aesthetic and performance problem to concrete foundations. Durability and concrete strength could be affected by the presence of honeycombing. In some cases honeycombing could be extended deep into the concrete, which could compromise the integrity of steel reinforcement.

The presence and extent of honeycombing on the surface of the concrete can be evaluated visually. The depth of honeycombing cannot be visually determined. Impact echo and GPR are two evaluation methods that could be used to evaluate the depth of honeycombing into concrete members.

3.2.5 Joint Deficiencies

Joint deficiencies are conditions that cause inadequate function of expansion, control, and construction joints. Joint deficiencies include spalls adjacent to a joint, joint fault or separation, joint leakage (liquid migrating through a joint), and joint sealant material failure. Joint deficiencies could be due to inadequate joint profile, spacing, and joint filler. Refer to ACI 201.1R *Guide for Conducting a Visual Inspection of Concrete in Service* for additional information regarding joint deficiencies.

3.2.6 Slab Curling and Warping

Curling is the distortion of the shape of a concrete slab due to temperature and/or moisture content differential between the exposed and non-exposed surfaces of a slab. Warping is a type of curling that consists of the out-of-plane deformation of slab edges. Some of the factors that affect curling and warping are drying shrinkage, wet subgrades without a vapor retarder and severe temperatures changes during the day and night times. Refer to ACI 201.1R *Guide for Conducting a Visual Inspection of Concrete in Service* for additional information regarding concrete slab curling and warping.

3.2.7 Concrete Spalling

A spall is a fragment of concrete that detaches from the concrete structure due to expansion from steel reinforcement corrosion, pressure, fire, or impact. Spall varies in size from a small spall which involves a roughly circular depression not greater than 3/4 inch in depth and 6 inches in any dimension; a large spall, which may be roughly circular or oval or in some cases elongated, is more than 3/4 inch in depth and 6 inches in greatest dimension. Problems associated with spalling concrete include, but are not limited to, strength loss of member, water infiltration, falling hazard, and being aesthetically undesirable.

The primary deterioration in concrete is due to the corrosion of embedded reinforcing steel. When the reinforcing steel corrodes, scale accumulates and expansive stresses are introduced into the concrete, resulting in cracking of the surrounding concrete in a plane parallel to the concrete surface called a delamination, which break away producing spalling.

Other causes for spalling include free-thaw damage, inadequate concrete mix, the bottom of a brick wall bonding to the top of the concrete grade beam, inadequate concrete cover, and cracks in concrete.

3.3 CONCRETE MATERIAL PROPERTIES

Following are brief descriptions of selected concrete material properties:

3.3.1 Air Entrainment

Air entrainment is the creation of small air bubbles in concrete by the addition to the mix of an air entraining agent. The air bubbles are created during mixing of the plastic concrete, and most of them become part of the hardened concrete. The primary purpose of air entrainment is to increase the durability of the hardened concrete, especially in climates subject to freeze-thaw. The air bubbles are typically 0.0004 to 0.02 inches in diameter and are closely spaced. The air bubbles compress to reduce stresses in hardened concrete from freezing. The secondary purpose is to increase workability to minimize the possibility of adding water in the field during construction.

3.3.2 Chloride Content

Chloride content in concrete is the amount of chloride ions in the paste, aggregates, and any organic chloride present. Chloride content is typically analyzed in concrete in order to determine if the chloride threshold for corrosion activity has been reached at the location of steel reinforcement within the concrete structure. Chlorides are induced in concrete during mixing or by external factors such as deicing salts, marine environments, and chemical exposure.

3.3.3 Compressive Strength

Compressive strength is the capacity of a material to withstand axially directed forces in an unconfined environment. When compressive strength is reached, concrete fractures. Design concrete compressive strength typically varies from 2,500 psi to 5,000 psi for most concrete foundations, but in some cases it could be higher than 5,000 psi.

3.3.4 Durability

Durability of concrete is its ability to resist weathering action, chemical attack, and abrasion without significantly affecting the material properties of concrete. The degree of durability depends on environmental exposures and material properties. For example, concrete exposed to seawater will have different durability requirements than an indoor concrete floor. The mix design, placing and curing practices, and environmental exposure will dictate the durability and useful life of a concrete structure.

3.3.5 Hardness

Hardness, in the context of a concrete structure, is the ability of the concrete surface to resist an applied impact load without exhibiting permanent localized deformation. Hardness is also the resistance of the concrete surface to abrasion.

3.3.6 Unit Weight

By definition unit weight is the weight of a material per unit volume. Typically when concrete structures are defined by their unit weight, there are two classifications: normal weight and lightweight. Normal weight concrete has a unit weight of 140 to 150 pounds per cubic foot (pcf), and lightweight concrete has a unit weight that typically ranges between 110 and 120 pcf.

3.3.7 Water/Cementitious Ratio

Water-cementitious ratio is the ratio of weight of water to the weight of cement plus other cementitious material that may be added to the concrete mix. Water-cementitious ratio influences concrete quality and workability. A lower water-cementitious ratio leads to higher strength and durability, but adversely affects workability. A high water-cementitious ratio could lead to excessive shrinkage cracking, better workability, and/or lower concrete strength.

3.4 NON-PRESTRESSED REINFORCEMENT CHARACTERISTICS

Steel reinforcement is used in concrete for crack control due to volumetric changes and to provide resistance to tensile stresses. Most reinforcing steel bars are deformed in order to provide an adequate bond with concrete. The size of reinforcing bars varies between 1/4 inch and 2-1/4 inch diameter, and it is designated by numbers (in eights of an inch) ranging from #2 through #18. Typical yield stress values for reinforcing steel bar are 40 ksi and 60 ksi, but may be greater. Some of the information regarding the as-built conditions of reinforcing steel that engineer are routinely interested in finding during evaluation of existing foundations include depth of cover, location, spacing, size, and presence of corrosion.

3.5 POST-TENSIONED REINFORCEMENT CHARACTERISTICS

An unbonded post-tensioned system consists of a wire strand covered in grease fed through a plastic sheathing and connected to the foundation at anchorage points. The following are brief descriptions of post-tensioned reinforcement system components.

3.5.1 Anchorages

Anchorage is a mechanical device used to connect prestressing strands where the prestressing force on the strand is transferred to the concrete.

3.5.2 Grease

The grease is the material used to provide corrosion protection to the strands and minimize the friction between the strand and the sheathing.

3.5.3 Sheathing

Sheathing is a jacket containing the grease that surrounds the strand. The sheathing isolates the strand from the concrete and provides corrosion protection to the strand.

3.5.4 Strand

A strand is a group of high strength steel wires weaved around a center wire. The typical strand type used in unbounded post-tensioned slab-on-ground systems has a 7-wire strand.

3.5.5 Tendon

Tendon (also referred to as cable) is the entire post-tensioned assembly consisting of the strand, grease, sheathing, and anchorages.

3.5.6 Tendon Profile

The tendon profile is the path of each tendon across the length of a member. The tendon profiles are straight, reversed parabola, partial parabola, and harped parabola.

3.6 SOIL CHARACTERISTICS

The following is a list of some of the typical soil physical and engineering properties associated with some of the test methods used to evaluate existing foundations. The list of properties is not intended to be an exhaustive or an all-inclusive list:

- Consolidation
- Moisture Content
- Plasticity Index
- Soil shear strength
- Soil strata location
- Soil type and color
- Depth of tree roots
- Water table presence/location and ground water

3.7 OTHER CHARACTERISTICS/DISTRESS

3.7.1 Concrete Anomalies

Concrete may contain physical objects, not associated with the concrete mixture, which may affect appearance and performance.

To affect the appearance, these objects must be visible at the surface. Examples of these anomalies are leaves, debris, and soil. Soil can be introduced into the top surface of concrete by the personnel working the concrete. This soil will eventually wash away and leave a void in the surface.

To affect the performance, these objects must be of substantial size and be located in a critical area of the concrete, such as the top or bottom of a grade beam, or at an exterior corner.

3.7.2 Vapor Transmission

Vapor transmission is the movement of moisture vapor through a slab-on-ground emitted from above and below the slab-on-ground. Vapor transmission is measured in terms of vapor emission. Moisture vapor emission is typically expressed as the rate of moisture vapor emission in units of pounds of moisture over a 1,000 square feet area during a 24 hour period.

For new concrete slab-on-ground, vapor emission could be a byproduct of the concrete drying process. For existing slabs-on-ground, the source of vapor emission is from below the slab and could consists of water trapped between the bottom of the slab and the vapor retarder membrane, the lack or presence of holes in the vapor retarder membrane, leaks in water pipe lines below the slab-on-ground, and groundwater. Vapor emission is a concern for floor covering systems. Typically, floor covering manufacturers have maximum moisture vapor emission rate requirements for their floor systems.

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Appendix FPA-SC-02-0 Summary Table

		Characteristics and Deficiencies	2.1 Carpenter Level	2.2 Chain Dragging	2.3 Chloride Ion ContentTesting	2.4 Concrete Cores	2.5 Concrete Screwdriver Test	2.6 Geotechnical	2.7 Ground Penetrating Radar (GPR)	2.8 Ground Probing	2.9 Half-Cell Potential (HCP)	2.10 Hammer Sounding	2.11 Impact Echo	2.12 Inspection Openings and Excavations	2.13 Laser Level	2.14 Manometer	2.15 Metal Detector	2.16 Optical Level	2.17 Petrographic Examination	2.18 Plumbing (Leak Detection)	2.19 Post-Tension Tendon Lift-Off	2.20 Post-Tension Tendon Screw Driver	2.21 Rebound Hammer	2.22 Reinforcement Locator (R-Meter)	2.23 Resistivity	2.24 Ultrasonic-Pulse Velocity	2.25 Vapor Transmission	2.26 Visual
3.1	Concrete Dimensional Properties	Grade beam dimensions								●				●														
		Pier dimensions								●				●														
		Slab levelness and flatness	●												●	●		●										
		Slab thickness				●			●	●				●														
3.2	Concrete Defects	Coarse aggregate segregation				●													●									
		Cracking/types of cracking																	●							●		●
		Delamination		●					●			●	●													●		●
		Detrimental chemical reactions																	●									
		Honeycombing							●				●													●		●
		Joint deficiencies																										●
		Slab curling and warping													●	●		●										●
		Spalling																										●
		Voids underneath slab				●			●				●	●											●			
3.3	Concrete Material Properties	Air entrainment																	●									
		Chloride content			●																							
		Compressive strength				●																	●					
		Durability				●	●																					
		Hardness				●	●																●					
		Unit weight				●																						
		Water/cementitious ratio				●																						
3.4	Non-prestressed Reinforcement Characteristics	Corrosion potential			●						●																	
		Depth/cover							●					●										●				
		Location/spacing							●					●			●							●				
		Size												●										●				
3.5	Post-tensioned Reinforcement Characteristics	Condition of PT tendon												●														
		Condition of PT tendon grease												●														
		Condition of tendon anchors												●							●							
		Tendon location/spacing							●								●							●				●
		Tendon profile							●															●				
		Tendon tension																			●	●						
3.6	Soil Characteristics	Consolidation						●		●																		
		Moisture content						●		●																		
		Plasticity index						●																				
		Soil shear strength						●		●				●														
		Soil strata location						●	●					●											●			
		Soil type and color						●		●				●														●
		Tree roots						●						●											●			
		Water table/Ground water						●						●											●			
3.7	Other	Anomalies				●			●								●								●			●
		Below slab pipe water leaks																		●					●			
		Vapor transmission																									●	
Cost Rating		Rent	-	-	-	-	-	-	$$	-	-	-	$$	-	-	-	-	$$-$$$	-	-	-	-	-	$-$$	-	$-$$	-	NA
		Purchase	$-$$	$	-	-	$	-	$$$$	$-$$	$$	$	$$$	-	$$$	$$-$$$	$-$$	$$-$$$$	-	-	-	$	$$	$$-$$$$$	-	$$$-$$$$	$-$$	
		Professional/Contractor Services	-	-	$$-$$$	$$-$$$	-	$$-$$$$	-	-	-	-	-	$-$$$	-	-	-	-	$$-$$$$	$$-$$$	$$-$$$	-	-	-	$$$$-$$$$$	-	-	