A Mini Project report

on

METHODS OF EVALUATION OF FOUNDATION DEPTH USING NON-DESTRUCTIVE TECHNIQUES: A COMPARATIVE STUDY

Submitted in partial fulfilment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

CIVIL ENGINEERING

(With specialization in Geotechnical Engineering)

Under

ASSAM SCIENCE AND TECHNOLOGY UNIVERSITY

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CANDIDATE DECLARATION

I hereby declare that the work presented in this report entitled **"METHODS OF EVALUATION OF FOUNDATION DEPTH USING NON-DESTRUCTIVE TECHNIQUES: A COMPARATIVE STUDY"**, in the partial fulfilment of the requirement for the award of the degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science and Technology University, is a work carried out in the said college under the supervision of Dr. Abinash Mahanta, Associate Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati- 13, Assam. Whatever I have presented in this report has not been submitted by me for the award of any other degree or diploma.

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CERTIFICATE OF SUPERVISION

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ABSTRACT

The evaluation of foundation depth is essential for structural assessment and retrofitting, particularly for existing infrastructure with limited design records. Non-destructive testing (NDT) methods offer a non-invasive approach to determine foundation depth, providing critical data without damaging the structure. This study focuses on a comparative analysis of three NDT techniques: Sonic Echo/Impulse Response Test, 2D Resistivity Imaging Survey, and Parallel Seismic Method. Each method's effectiveness is assessed based on factors such as accuracy, reliability, ease of application, and suitability under varying soil and foundation conditions.

The Sonic Echo/Impulse Response Test is evaluated for its ability to detect depth and anomalies through stress wave reflections. The 2D Resistivity Imaging Survey is analyzed for its potential to map subsurface conditions based on electrical resistivity variations. The Parallel Seismic Method is examined for its precision in determining foundation depth, especially in cases of buried or inaccessible foundations.

The results of this study provide insights into the relative strengths and limitations of these techniques, offering a comprehensive comparison to guide the selection of appropriate methods for specific scenarios. This comparative analysis aims to assist practitioners in optimizing NDT applications for foundation depth evaluation, contributing to efficient structural assessments and retrofitting strategies.

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CHAPTER 1

INTRODUCTION

The precise evaluation of the depth and condition of existing bridge foundations is crucial for managing infrastructure, especially as older bridges encounter increased pressures from greater traffic loads and environmental factors. Gaining insights into foundation properties is vital for maintaining structural safety, planning retrofitting strategies, and prolonging the lifespan of bridges. Traditional methods for assessing foundations, often involving destructive approaches, present challenges such as high expenses, disruptions to operations, and possible damage to the structure. These drawbacks have led to the innovation and use of non-destructive testing (NDT) techniques.

NDT methods have become an indispensable tool in modern engineering, offering efficient, accurate, and minimally invasive solutions for assessing foundation depth and integrity. Olson and Yu (2019) highlight the critical role of NDT methods in evaluating inaccessible or submerged foundations, where traditional techniques are impractical. Juang et al. (2020) emphasize that advanced seismic and geophysical approaches can overcome the complexities of heterogeneous subsurface conditions, providing reliable insights into foundation characteristics. Additionally, Li et al. (2022) illustrate the effectiveness of electromagnetic methods combined with geophysical surveys in improving accuracy, particularly for reinforced concrete foundations.

As infrastructure deteriorates and the need for retrofitting increases, the significance of non-invasive methods is becoming more apparent. The combination of different NDT approaches has improved the capability to evaluate foundation depth and integrity while reducing operational interruptions. These advancements enable safer, more economical, and eco-friendly assessment and upkeep of infrastructure. Ongoing research aims to enhance these methods, confirming their suitability for various geotechnical and structural situations.

1.1 Non-Destructive Techniques

I. Sonic Echo/Impulse Response Test
II. Seismic Wave Reflection Survey
III. Parallel Seismic Method
IV. Induction Field Method

V. Dynamic Foundation Response Method
VI. Resistivity Imaging Method

1.2 Evaluation of Depth of foundation

1.2.1 Methodology and technique employed

In this project 3 techniques have been used, namely

I. Sonic Echo/Impulse Response Test
II. 2D Resistivity Imaging Survey
III. Parallel Seismic Method

1.2.2 Analysis and Results

The sonic echo/impulse response test can be used to evaluate the integrity and length of newly constructed piles. It can be used to detect defects, soil inclusions and pile necking, diameter increases (bulging) as well as approximate pile lengths.

The Resistivity Imaging Test is a non-destructive method to determine the depth and geometry of foundations by measuring subsurface electrical resistivity.

The Parallel Seismic (PS) method is a borehole test method for determining depths of foundations.

1.3 Project Objective

The results obtained from the three techniques are compared and the most effective and most economical technique to determine the depth has been suggested.

CHAPTER 2

THEORITICAL BACKGROUND

2.1 WHY NON-DESTRUCTIVE TESTING?

Today a lot of bridges are in a great need of restauration or reconstruction due to the aging infrastructure. The Eurocodes are primarily focusing on the design of the new structures and not as much of the rules for assessing and gearing up existing structures. (Holický et al., 2013)

By using existing structures, a lot of money and time to the community can be saved instead of building only new bridges. Assessment of existing structures is, therefore, an important topic for the people working in construction in industrial countries. Existing structures do not always and/or completely fulfil the requirements of the current standards. To assess an existing structure overlapping knowledge of the framework for the design of new structures needs to be present to really get a good result. The assessment should focus on doing minimal construction interventions on the existing structures and the civil engineers and the owner's needs new guidance for performing the assessment. (Holický et al., 2013) The field of civil engineering are not as innovative as other engineering and science fields.

Despite this, we now live in a world where innovation is more important than ever considering the incoming future. The maintenance and improvement of existing infrastructure lacks investment and around the world you find failing infrastructure that are a risk to the society in many ways. With the increased population and the climate changes a lot of necessary changes needs to be done in the future and the governments are struggling a lot to fund and mandate the future. (Autodesk, n.d.)

New trends in the field of civil engineering and the construction industry show that sustainability and resiliency are becoming requirements instead of desirable characteristics. Innovative projects have already shown that focusing on sustainability and resiliency doesn't have to compromise with the environment or the budget. The owners are also beginning to consider the full lifespan cost of the projects instead of only focusing on the solely first cost. (Autodesk, n.d.)

2.1 WHAT IS NON-DESTRUCTIVE TESTING?

Assessment of existing structures with non-destructive testing has become more common the last decades. (Breysse et al., 2012) When assessing a damaged structure, the following scheme should be followed:

1. Visual inspection: it is always useful to make an initial visual inspection to get a hang of the condition of the structure. Any defects should be noted and after that a decision of the severity of the defect should be decided.

2. Explanation of observed phenomena, to better understand the defect and the present condition of the structure, a simulation of the observed behaviour of the structure should be done in a model. If a divergence between calculations and observations is discovered, one might look for errors in construction, design errors etc.

3. Reliability assessment, when a structure is in its present state given the present information, the reliability of the structure should be estimated. If the result shows that the reliability is enough, the assessment can be satisfying, and no further action must take place.

4. Additional information, if the assessment in step 3 is not satisfying enough, additional information should be gathered to get to the final decision. This can be done using more advanced structural models, additional inspections and measurements.

5. Final decision, if the structures' reliability is still too low, you might decide to: - accept the present situation based on economic reasons - reduce the load on the structure - repair or demolish the structure (Holický et al., 2012)

A lot of research has been done with the goal to develop techniques and data processing for doing NDT. Some standards have been developed for different techniques, but the general opinion is that the quality of the assessment is limited by; systematic interferences with the environment, the testing method, random interference, human factors and data interpretation. A big problem is to evaluate and find the correlating values of the non-destructive measurements. The lack of internationally acknowledged standards is a significant limitation as well. Concrete is a very variable material that can cause a lot of mistakes in the investigation process just by being as it is. (Breysse et al., 2012)

Choosing between all the different techniques when an NDT process is going to be started is difficult. It takes a lot of experience and knowledge of the available instruments and the results you can expect from the different alternatives. (Breysse et al., 2012).

2.2 NON-DESTRUCTIVE EVALUATION (NDE) TECHNIQUES

The NDE techniques used in this project are:

I. Sonic Echo/Impulse Response Test
II. 2D Resistivity Imaging Survey
III. Parallel Seismic Method

2.3 SONIC ECHO/IMPULSE RESPONSE TEST (SE/IR)

Sonic Echo/Impulse Response tests are performed to evaluate the integrity and determine the length of deep foundations. SE/IR tests can be performed on drilled shafts and driven or auger-cast piles. The test can also be performed on shallow wall structures such as an abutment or a wall pier of a bridge provided the top of the wall is accessible.

Fig 2.1: Pile Integrity Test Equipment

(Source: https://olsoninstruments.com/wp-content/uploads/seir_field1.jpg)

Sonic Echo/Impulse Response tests can be performed on both concrete and wood foundations. Round steel pile foundations (pipe piles) can also be tested, but H-type piles generally cannot be tested. This is because damping of the signal energy in H-piles is often much greater than that of concrete and wood due to the large surface areas and small cross-sectional areas of these piles.

Analysis of the Sonic Echo data is performed in the time domain while analysis of the Impulse Response data is performed in the frequency domain. In both tests, the reflection of compressional waves (fastest of all wave types) from the bottom of the tested structural element or from a discontinuity such as a crack, soil intrusion, or diameter change (bulb or neck) is measured. In simple terms, the generated wave from an impulse hammer travel down in a shaft or a pile until a change in impedance is encountered, where the wave reflects back and is measured by a receiver placed next to the impact point.

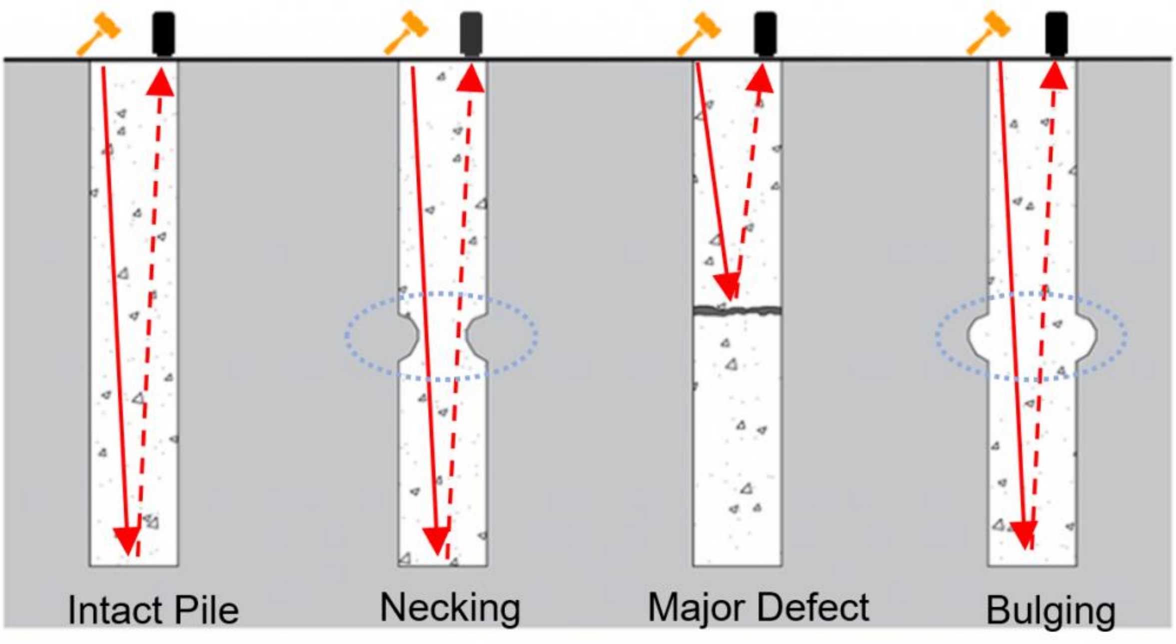

Fig 2.2: Defects in Pile (Echo sonic Test)

(Source: https://www.geotech.hr/wp-content/uploads/2018/08/defekti_pilota-1024x553.png)

2.3.1 Access

For drilled shafts and piles, the best results from SE/IR tests are obtained if the top of the drilled shaft or the pile is exposed for receiver attachment and hammer hitting. If the top is not exposed, then the SE/IR tests are performed on the side, which requires at least the upper 1-2 feet of the shaft to be exposed. For wall-like shallow structures, the top of an abutment or a pier should be exposed for SE/IR testing.

2.3.2 Collection of Data

In an SE/IR test, the foundation top is struck by a hammer and the response of the foundation is monitored by a receiver. An Olson Instruments Freedom Data PC Sonic Echo/Impulse Response (SE/IR-1) system (shown below) records the hammer input and the receiver output. SE tests are typically performed with different frequency filtering to optimize reflections coming from the bottom of the foundation and to reduce the effect of surface waves or reflections from a discontinuity at a shallow depth where the frequencies associated with these two conditions are high. In IR tests, the transfer and coherence functions are automatically calculated by the digital analyser after transforming the time records of the hammer and the receiver to the frequency domain.

Fig 2.3: OLSON Instrument for Pile Integrity Test (Source: https://olsonengineering.com/)

2.3.3 Processing Techniques Sonic Echo/ Impulse Response

To help interpret SE/IR data, some processing techniques can be applied to enhance weak echoes. First, the SE signals are integrated from acceleration to velocity and exponentially amplified to enhance weak reflections and to compensate for acoustic energy damping. Another processing technique for SE data is the Cepstrum technique in which an autocorrelation function is calculated to help determine better the time separation between two echoes. In simple cases, the SE data can be used to obtain an image of the shaft through a process called impedance imaging.

2.3.4 Interpretation of Data

The Sonic Echo data is used to determine the depth of the foundation based on the time separation between the first arrival and the first reflection events or between any two consecutive reflection events (tP) according to the following equation:

$$D = VP \text{ x } tP / 2$$

where D is the reflector depth and VP is the velocity of compressional waves. A reflector can be the bottom of the foundation or any discontinuity along the embedded part of the foundation. Also, the Sonic Echo data can be used to determine the existence of a bulb or a neck in a shaft or the end conditions of the shaft based on the polarity of the reflection events. The Impulse Response data is also used to determine the depth of reflectors according to the following equation:

$$D = VP / (2 \text{ x } \_f)$$

Where, _f is the distance between two peaks in the transfer function plot (velocity/force versus frequency) or between zero frequency and first peak for soft bottom conditions.

In addition, the IR data provides information about the dynamic stiffness of the foundation. This value can be used to predict foundation behaviour under working loads or correlated with the results of load tests to more accurately predict foundation settlement.

2.3.5 Effectiveness

The SE/IR method works best for columnar type foundations such as piles and drilled shafts. Reflection events are clearest if there is nothing on top of the foundations (such as a column).

In cases where the superstructure is in place, the SE/IR data becomes more difficult to interpret because of the many reflecting boundaries and 2 or more receivers should be used to rack reflections. Typically, SE/IR tests are performed on shafts or piles of length to diameter ratios of up to 20:1. Higher ratios (30:1 or greater) are possible in softer soils. SE/IR tests are accurate to within 5% in the determination of the depth of the foundation provided an independent measurement of the wave velocity used in the depth calculation is made. In case the wave velocity is assumed based on the material type, SE/IR tests are normally accurate to within about 10%.

2.4 RESISTIVITY IMAGING SURVEY AS PER IS 15736

2.4.1 Applications:

1. Determining the depth and extent of unknown foundations.
2. Investigating subsurface conditions, such as soil stratification, voids, and groundwater levels.
3. Assessing foundation integrity for retrofitting or reconstruction projects.
4. Profiling large areas to identify hidden or buried foundations.
5. Complementary technique in geotechnical site characterization.

2.4.2 Access Requirements:

1. **Surface Accessibility:**
   - Requires access to the ground surface around the foundation for electrode placement.
   - Limited by obstructions like pavements, buildings, or utilities.
2. **Electrode Deployment:**
   - Electrodes need to be spaced appropriately based on the expected depth of the foundation.
   - Minimum area clearance is essential to maintain the accuracy of the resistivity profile.

2.4.3 Process:

1. **Site Preparation:**
   - Clear the area around the foundation to ensure unobstructed electrode placement.

- Determine survey line length and electrode spacing based on anticipated foundation depth and site conditions.

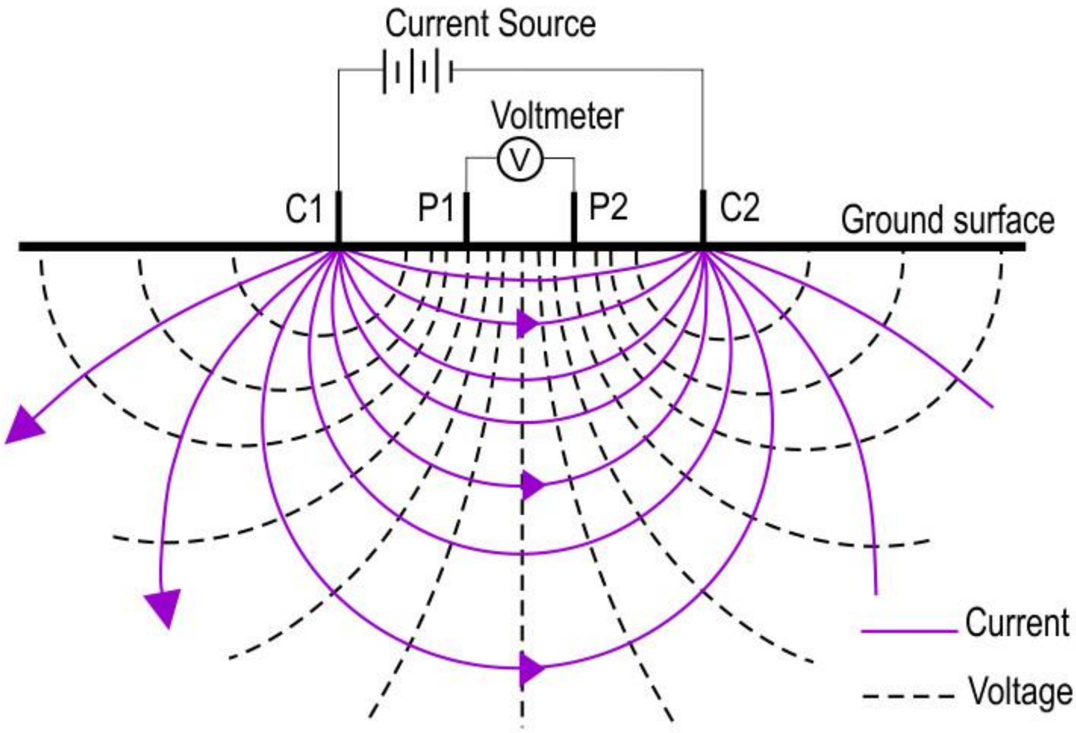

Fig 2.4: Equipotential Lines And Current Flow Lines For Four Electrode Array (Source: GEOLOGICAL EXPLORATION BY GEOPHYSICAL METHOD (ELECTRICAL RESISTIVITY) —CODE OF PRACTICE IS 15736:2007)

2. **Data Acquisition:**
   - Insert electrodes into the ground along a linear or grid pattern.
   - Inject electrical current into the ground using a resistivity meter and record potential differences.
   - Vary electrode configurations (e.g., Wenner, Schlumberger, or dipole-dipole) for deeper or more focused profiling.
3. **Data Processing:**
   - Process raw resistivity data to generate 2D or 3D resistivity profiles.

- Apply corrections for noise and edge effects.

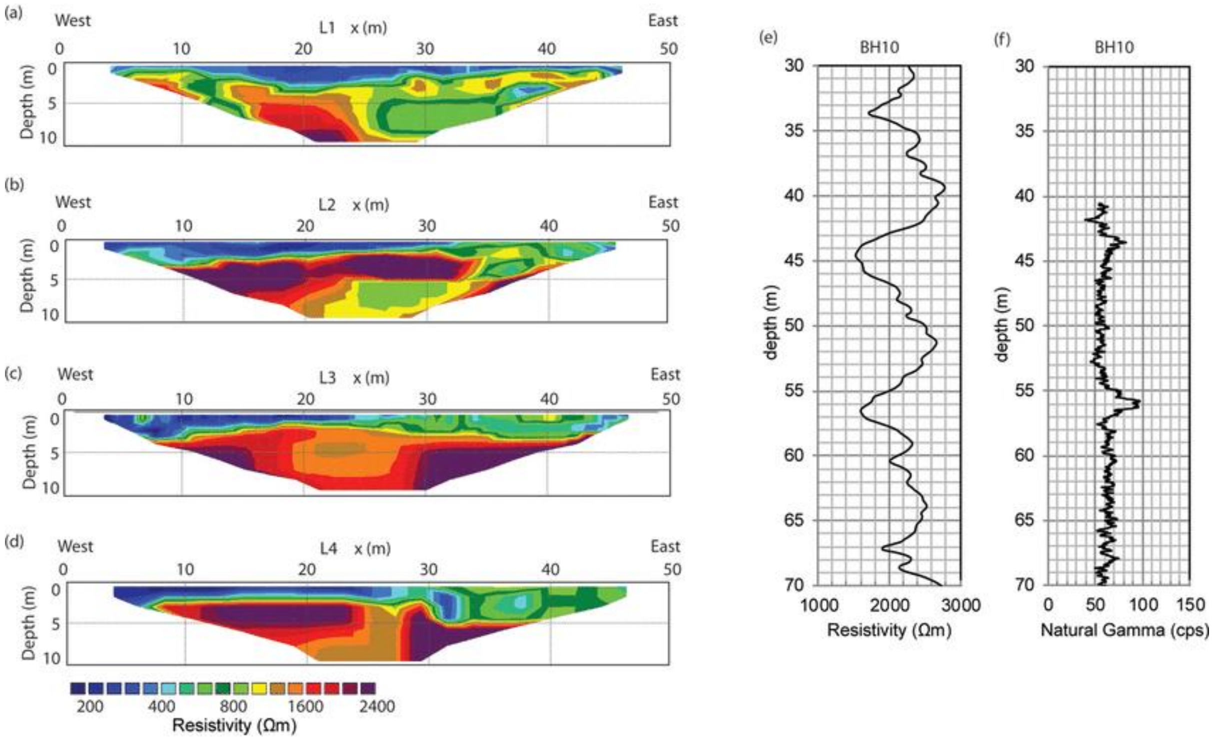

Fig 2.5: Electrical Resistivity Tomography Profiles (Source:https://www.researchgate.net/publication/322277080/figure/fig3/AS:583923440566272@1516229605682/Four-electrical-resistivity-tomography-profiles-a-d-completed-at-the-site-with-2-m.png)

2.4.4 Interpretation of Data:

1. **Resistivity Contrast Analysis:**
    - High-resistivity zones typically indicate the presence of foundation material (e.g., concrete or stone).
    - Low-resistivity zones may signify soil, voids, or water.
2. **Depth Estimation:**
    - Foundation depth is inferred from the base of the high-resistivity anomaly.
    - Software modelling helps identify boundaries and estimate depths accurately.

3. **Verification:**
    - Cross-validate findings with other methods like Sonic Echo or Parallel Seismic Tests for improved reliability.

2.5 PARALLEL SEISMIC METHOD

The Parallel Seismic (PS) method is applied to determine the lengths of deep foundations where foundation tops are not accessible, or when the piles are too long and slender (such as H piles or driven piles) to be tested by Impact Echo techniques. In addition, the PS method can provide information about the soil below the foundation bottom.

2.5.1 Applications

The PS investigation can be performed on foundations made of

- Concrete
- Wood
- Masonry
- Steel

Soil quality below the foundation can also be determined by the PS tests.

Fig 2.6: Parallel Seismic Test Equipment Setup (Source: https://th.bing.com/th/id/R.9e116bda4d568cacd5ad04543c5cc6e1?rik=j8mXr6TOi%2btvkQ&riu=http%3a%2f%2folsoninstruments.com%2fwp-content%2fuploads%2fps_field1.jpg&ehk=UJU7Jb76%2bScVcEJh5eG08YJTgCuQsgxp409VusPyf44%3d&risl=&pid=ImgRaw&r=0)

2.5.2 How It Works

Parallel Seismic involves hitting any part of the structure that is connected to the foundation (or hitting the foundation itself, if accessible) and receiving compressional and/or shear waves travelling down the foundation by a hydrophone or a geophone receiver.

The PS investigation is performed at 30-60cm vertical receiver intervals in the borehole. The field setup for PS investigation is

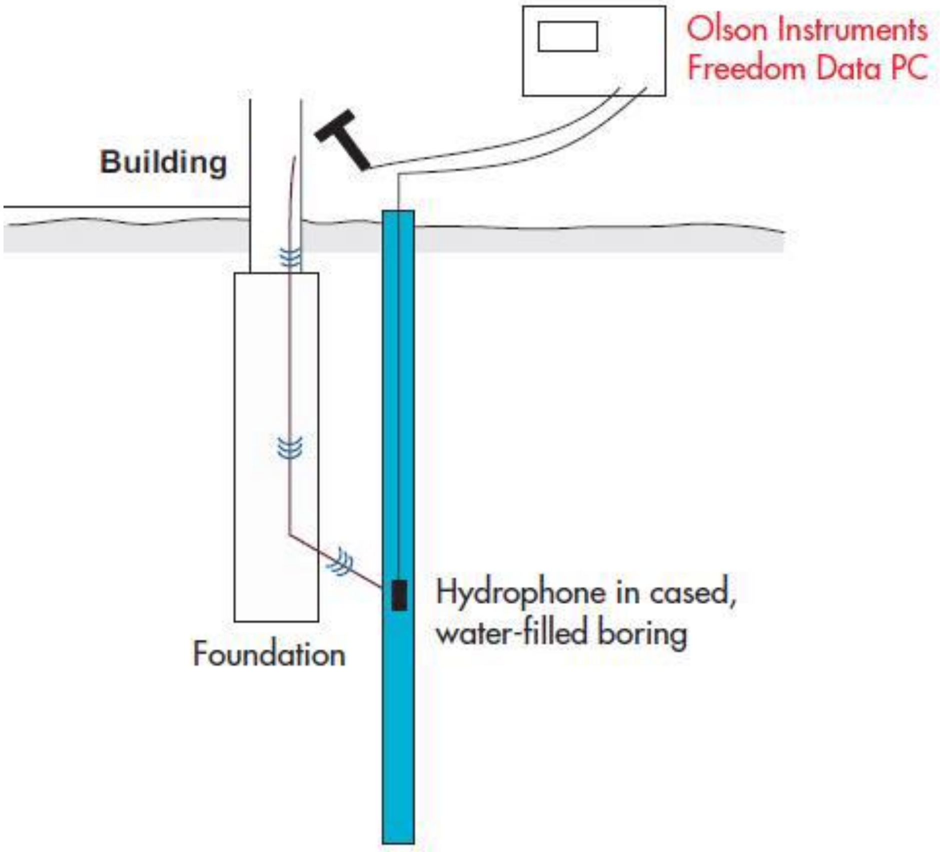

Fig. 2.7: Field Setup for Parallel Seismic Test

(Source:https://www.researchgate.net/publication/337784083/figure/fig3/AS:833052695609344@1575626648084/Schematic-of-parallel-seismic-test.ppm)

2.5.3 Access

Some portion of the structure that is connected to the foundation must be exposed for the hammer impacts. A borehole is required. Typically, a 5-10-centimeter diameter hole is drilled as close as possible to the foundation (within 1.5 meters preferred). The borehole should extend at least 3 to 4.5 meters below the expected bottom of the foundation. In case of hydrophone use, the hole must be cased, capped at the bottom and the casing and hole filled with water. For geophone use, the hole must usually be cased and grouted to prevent the soil from caving in during testing.

2.5.4 Processing Techniques

Some geophysical processing techniques can be used to help optimise the Parallel Seismic data. These techniques include Auto Gain Control (AGC) and filtering to enhance weak events. IX Foundation, a seismic analysis and display program, allows the full range of data to be viewed at one time. This improves the ability to identify the bottom of the foundation being investigated.

1. Data PC

2. Impulse hammer

3. Hydrophone

4. Reel of cable

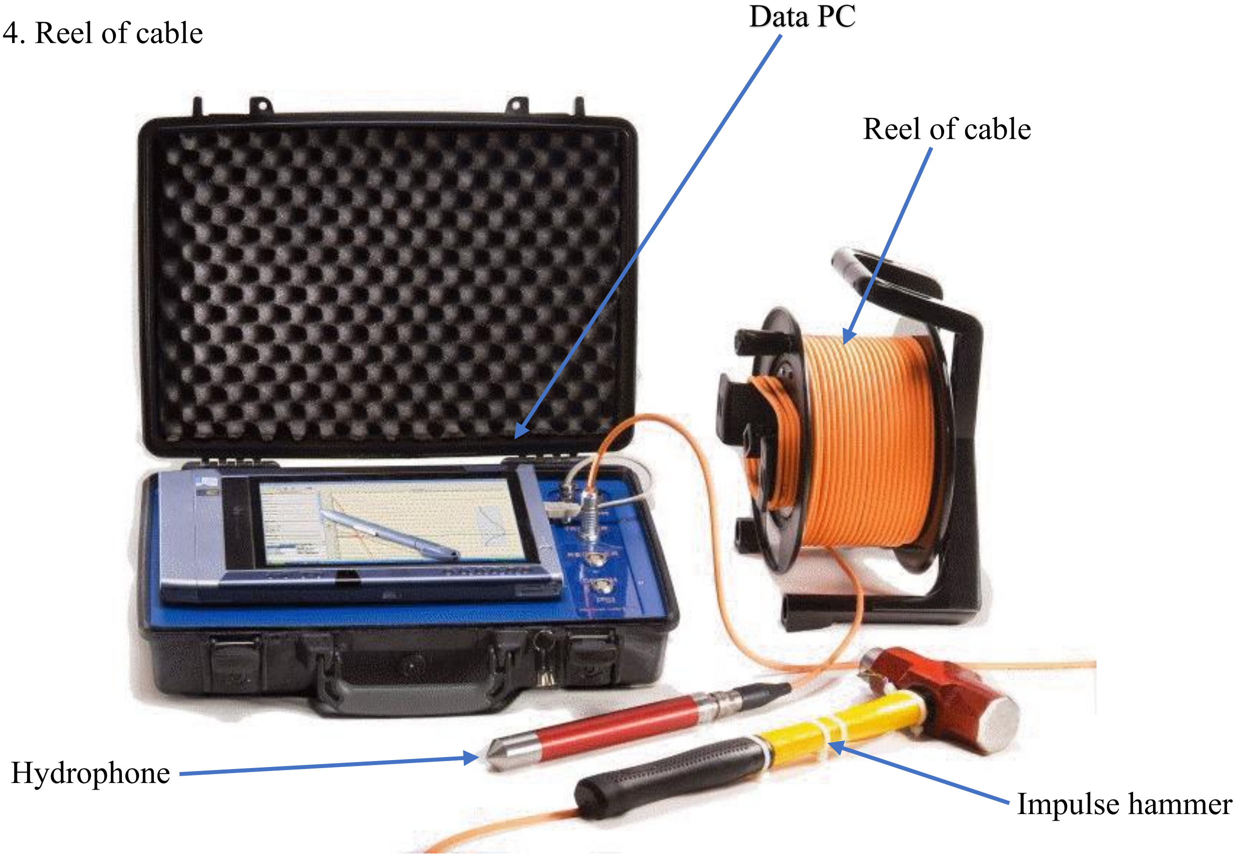

Fig 2.8: Parallel Seismic Test Equipment (Source: https://onestoptesting.co.uk/wp-content/uploads/2016/05/PSI_System.jpg)

2.5.5 Interpretation of Data

The use of seismic analysis software, such as IX Foundation, allows f5 or determination of approximate pile length easily. The diffraction, or change in slope, that occurs in the data as a result of the pile tip acting as a point diffractor and a reflector is shown in Figure 1. The software is capable of determining velocity based on the slope of the line and where the two lines of the differing slopes intersect a depth is determined.

2.5.6 Effectiveness

The PS method is more accurate and more versatile than other non-destructive surface techniques for determination of unknown foundation depths. The accuracy of the method depends on the variability of the velocity of the surrounding soil and the spacing between the borehole and the foundation element.

Depths are normally determined to within 5% accuracy or better. A borehole is typically needed for Parallel Seismic tests, which adds to the cost of the investigation (unless borings are also needed for other geotechnical purposes). The borehole should be within 1.5m of the foundation, which sometimes cannot be achieved due to field constraints. Note that for very uniform soils (such as saturated sands), a successful test can be performed with up to 4.5-6m spacing between the source and the borehole.

As the borehole moves away from the foundation, interpretation of the PS data becomes more difficult and the uncertainty in the tip depth determination becomes greater.

CHAPTER 3

TEST PROCEDURE

3.1 SONIC ECHO/IMPULSE RESPONSE (SE/IR) TEST

Test Procedure:

3.1.1 Pre-Test Preparations

3.1.1.1 Review of Documentation:

- **Collect Site Information:** Gather details about pile types, dimensions, reinforcement, layout, installation records, subsurface profiles, concrete density, and strength.

3.1.1.2 Equipment Setup:

- **Impact Device:** Use a small metal or hard rubber hammer to impart low-strain impacts.

- **Transducer/Accelerometer:** Attach a suitable device to the pile head to measure particle velocity.

- **Data Acquisition System:** Ensure the system can record and analyse the reflected stress waves.

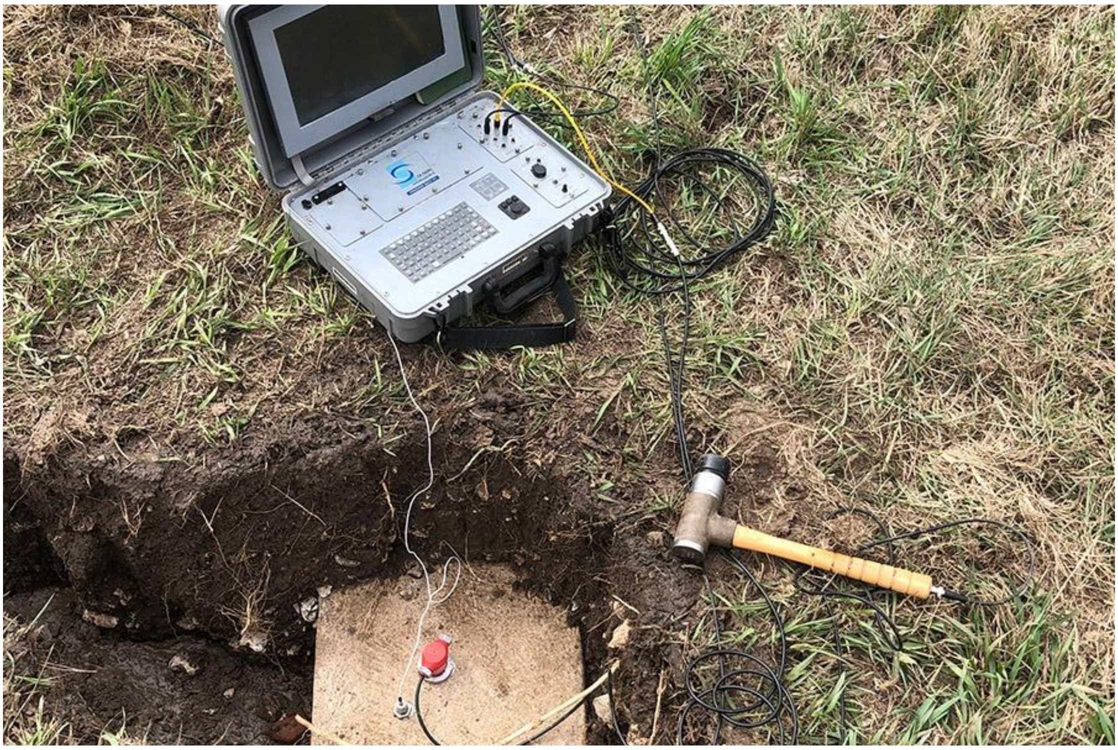

Fig 3.1: Pile Integrity Test Instrument Setup (Source: https://olsoninstruments.com/wp-content/uploads/seir_field2.jpg)

3.1.1.3 Site Inspection:

- **Access and Cleanliness:** Ensure the pile head is accessible and free from debris or laitance to facilitate accurate measurements.

3.1.2 Testing Procedure

3.1.2.1 Impact Application:

- **Hammer Strike:** Deliver a light tap on the pile head using the hammer. The impact generates a stress wave that travels down the pile shaft.

3.1.2.2 Signal Acquisition:

- **Data Recording:** The transducer captures the reflected stress waves, which are then recorded by the data acquisition system. Multiple recordings should be taken to ensure repeatability and accuracy.

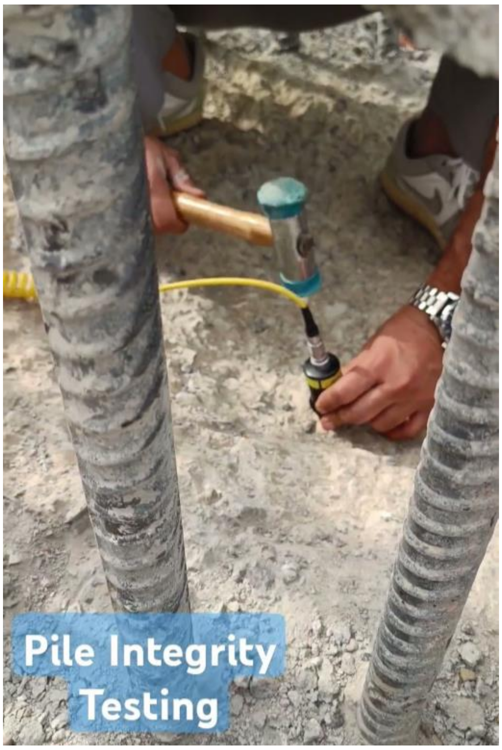

Fig 3.2: Hammer Strike on the pile

3.1.2.3 Multiple Test Points:

- **Large Diameter Piles:** For piles with large diameters, conduct tests at 5-6 locations on the pile head to assess the entire cross-section.

3.1.3 Data Analysis

3.1.3.1 Signal Interpretation:

- **Primary and Secondary Reflections:** Analyse the captured signals to identify primary reflections from the pile toe and secondary reflections from any imperfections or discontinuities within the pile shaft.

3.1.3.2 Velocity Determination:

- **Stress Wave Velocity:** Use known values of stress wave velocity for the specific concrete grade (typically between 3000-4000 m/s for M15-M25 concrete) to assist in depth calculations.

3.1.4 Depth Calculation:

- **Formula Application:** Calculate the pile length (L) using the formula:

L=V×T2L = \frac{V \times T}{2}L=2V×T

where:

  - VVV = Stress wave velocity (m/s)
  - TTT = Time interval between the initial impact and the reflected wave (s)

3.1.5 Interpretation of Results

3.1.5.1 Integrity Assessment:

- **Defect Identification:** Identify any anomalies such as cracks, voids, soil intrusions, or changes in cross-sectional area based on the presence of secondary reflections.

3.1.5.2 Comparison with Design Parameters:

- **Length Verification:** Compare the calculated pile length with design specifications to confirm compliance.

3.1.6 Reporting

3.1.6.1 Documentation:

- **Test Details:** Include information on equipment used, test methodology, site conditions, and any deviations from standard procedures.
- **Findings:** Provide a comprehensive analysis of the pile integrity, highlighting any defects or concerns.
- **Recommendations:** Suggest further investigations or remedial actions if significant anomalies are detected.

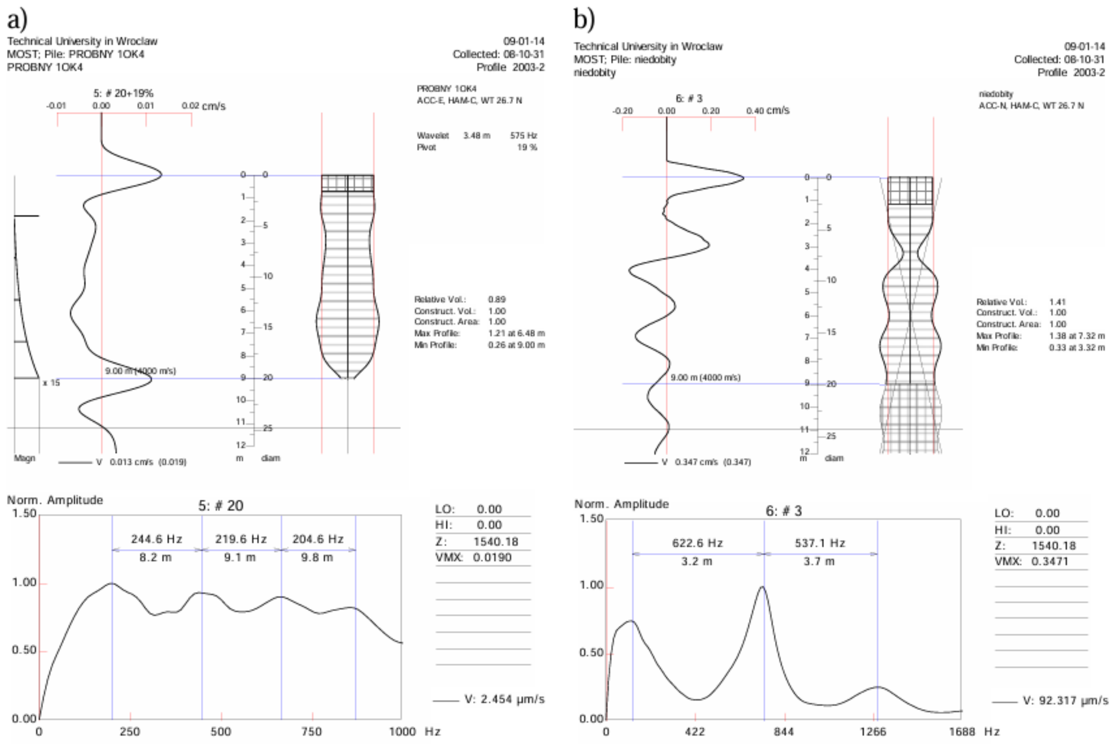

Fig 3.3: The results of the PIT tests for: a) a 9.0-meter long, continuous pile, b) a pile with a cracking at the distance of 3.5 m from the pile's head

3.1.7 Safety and Quality Assurance

3.1.7.1 Personnel Qualifications:

- **Trained Operators:** Ensure that the test is conducted and interpreted by personnel trained and experienced in non-destructive testing methods.

3.1.7.2 Equipment Calibration:

- **Regular Maintenance:** Verify that all equipment is properly calibrated and functioning correctly before conducting the tests.

Adhering to this procedure, as outlined in IS 14893:2001, ensures a systematic approach to evaluating pile integrity using the SE/IR method, providing reliable data for assessing foundation conditions.

3.2 Procedure for Resistivity Imaging Test (As per IS 15736)

The Resistivity Imaging Test is a non-destructive method to determine the depth and geometry of foundations by measuring subsurface electrical resistivity. The procedure outlined here adheres to the guidelines provided in IS 15736. 2D Resistivity Imaging uses an array of electrodes (typically 60) connected by multicore cable to provide a linear depth profile, or pseudo-section, of the variation in resistivity, both, along the survey line and with depth. Switching of the current and potential electrode pairs is done using electrical resistivity imaging system. The spacing between the electrodes is fixed initially and then increased intending to greater depth of investigation.

3.2.1 Equipment

1. **Resistivity Meter:** To measure electrical resistance.
2. **Electrodes:**
   - Current electrodes (C1, C2).
   - Potential electrodes (P1, P2).
3. **Cables and Connectors:** For connecting electrodes and resistivity meter.
4. **Data Logger:** To record resistivity readings.
5. **Power Source:** Battery or generator for field operations.
6. **Survey Accessories:**
   - Measuring tape.
   - Marking stakes.

Fig 3.4: Resistivity Meter

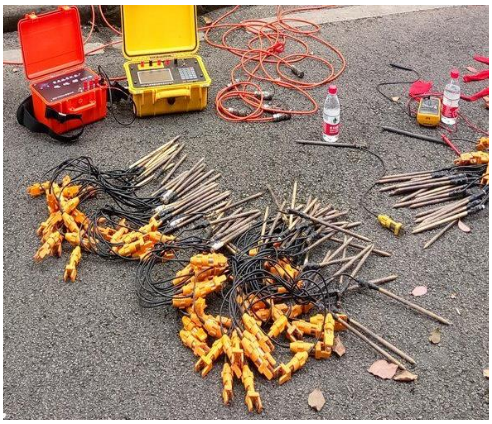

Fig 3.5: Electrodes

Fig 3.6: Cables

Fig 3.7: power Source

Fig 3.8: Measuring Tape

3.2.2 Test Setup

1. **Electrode Layout:**
   - Arrange the electrodes along a straight line parallel to the foundation.
   - Ensure appropriate spacing between electrodes depending on the desired depth of investigation.
   - Use configurations like Wenner or Schlumberger array, as appropriate for site conditions

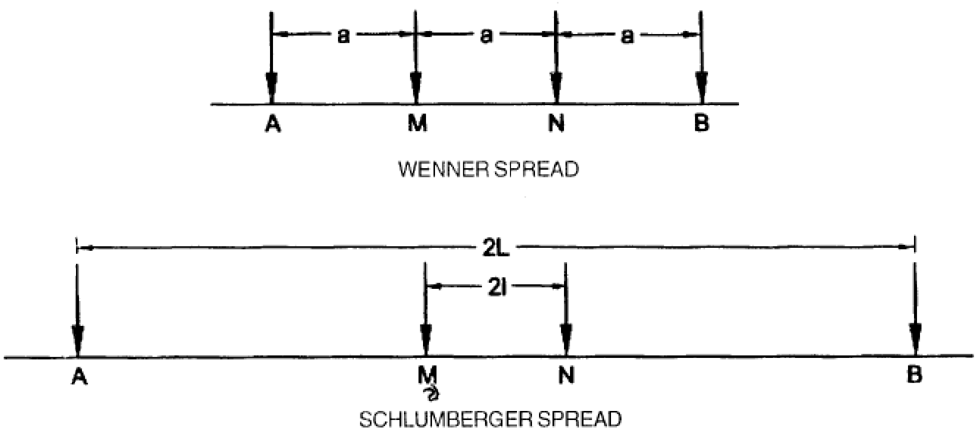

Fig 3.9 A: Standard Electrode Geometries (Source: IS 15736: 2007)

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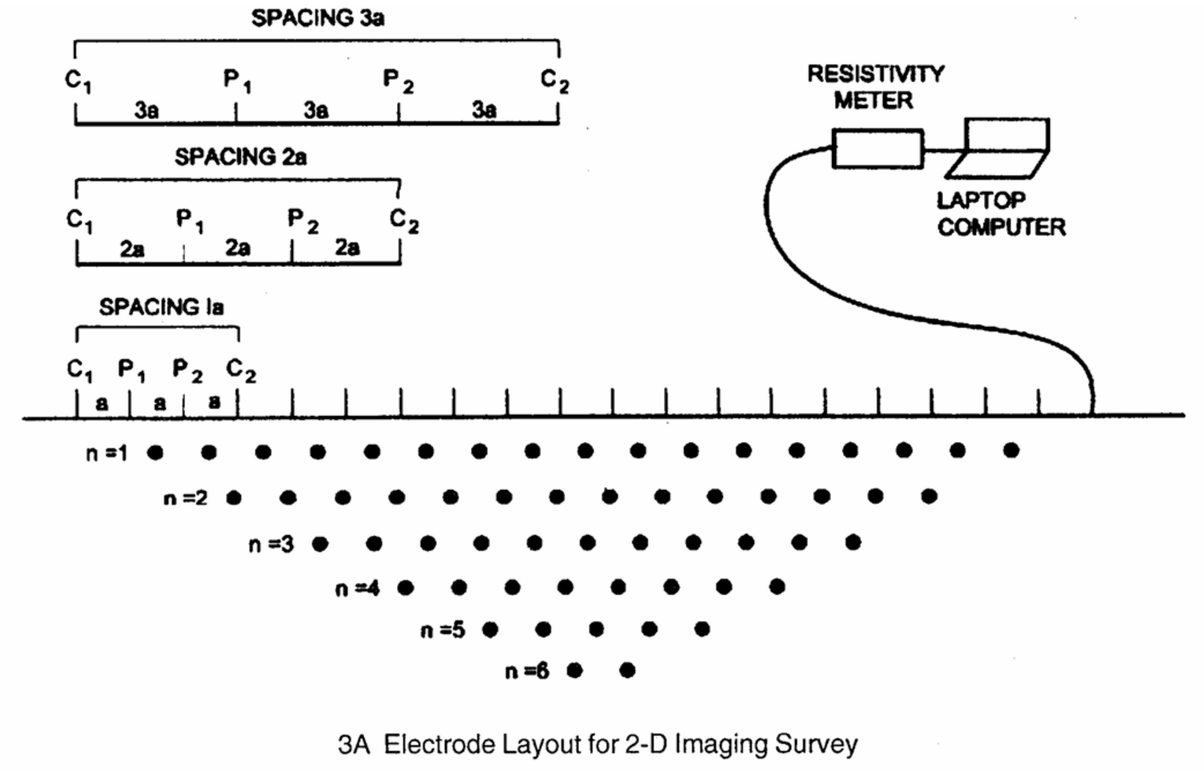

Fig 3.9 B: Layout for 2D Imaging Survey (Source: IS 15736:2007)

2. **Soil Preparation:**
   - Remove debris and ensure good electrical contact between electrodes and soil.
   - Use saline water or bentonite slurry if soil resistivity is very high for better contact.
3. **Instrumentation:**
   - Connect electrodes to the resistivity meter.
   - Calibrate the resistivity meter before beginning measurements.

3.2.3 Testing Procedure

1. **Electrode Spacing Adjustment:**
   - Start with small electrode spacing to measure resistivity at shallow depths.
   - Gradually increase spacing to probe deeper layers.

2. **Data Collection:**
   - Inject current into the ground using the current electrodes (C1, C2 etc).
   - Measure the resulting potential difference using the potential electrodes (P1, P2 etc).
   - Record the resistivity values for each electrode spacing.
3. **Grid Measurement (If needed):**
   - Repeat the test at multiple lines around the foundation to obtain a three-dimensional resistivity profile.
   - Ensure overlapping grids for accurate subsurface imaging.
4. **Data Logging:**
   - Ensure that all readings are logged correctly in the data logger or manual recording sheets.
   - Note environmental and site conditions during testing.

3.2.4 Data Processing

1. **Resistivity Calculation:**
   - Calculate apparent resistivity (ρa\rho_aρa) using the formula: ρa=K×VI\rho_a = K \times \frac{V}{I}ρa=K×IV Where:
     - KKK: Geometric factor based on electrode configuration.
     - VVV: Measured potential difference (volts).
     - III: Injected current (amperes).
2. **Depth Determination:**
   - Use resistivity profiles to identify resistivity contrasts between the foundation material and surrounding soil.
   - The depth to the foundation is determined based on these contrasts.

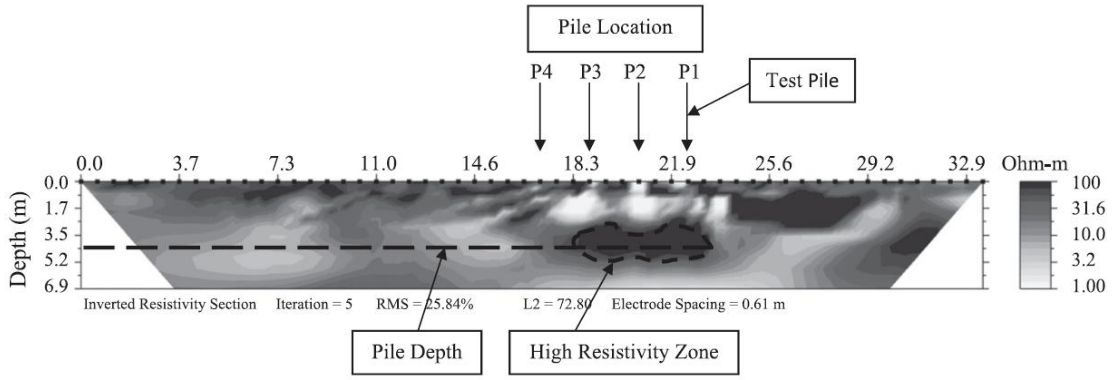

Fig 3.10 : Resistivity profile for depth calculation (M. S. Hossain et al 2013)

3. **Imaging Software:**
    - Process the data using geophysical software to generate resistivity tomograms.
    - Interpret the tomograms to identify the foundation depth and geometry.

3.2.5 Quality Control

1. **Repeat Measurements:**
    - Repeat tests to ensure data reliability.
    - Conduct cross-line surveys for consistency.
2. **Environmental Considerations:**
    - Avoid interference from nearby utilities or metal objects.
    - Conduct tests during optimal weather conditions to reduce noise.
3. **Calibration and Verification:**
    - Periodically calibrate instruments against known standards.
    - Validate results using known foundation depths, if available.

3.2.6 Reporting

1. **Field Observations:**
   - Document site conditions, electrode spacing, and test configurations.
2. **Data Presentation:**
   - Provide resistivity profiles and interpreted tomograms.
   - Clearly mark identified foundation depth and geometry.

3.3 PARALLEL SEISMIC METHOD

Test Procedure:

3.3.1 Pre-Test Preparations:

- **Review Documentation:** Gather all available information about the structure, including design drawings, construction records, and previous inspection reports.
- **Site Inspection:** Assess the site to determine the optimal location for the borehole, ensuring it is as close as possible to the foundation (preferably within 1 to 2 meters) and extends at least 3 to 4.5 meters beyond the expected foundation depth.

3.3.2 Borehole Installation:

- **Drilling:** Drill a vertical borehole parallel to the foundation. The borehole should be cased to prevent collapse and, if using a hydrophone, filled with water to ensure proper acoustic coupling.

Fig 3.11: Borehole for Parallel seismic test setup

(Source:https://th.bing.com/th/id/R.2231679c6f6461a1d042c128aa59faaa?rik=BZpnPIzHDk209A&riu=http%3a%2f%2folsoninstruments.com%2fwp-content%2fuploads%2fps_field4.jpg&ehk=25ipa2BMisXdbMNfd0RUvgsI3laPZl5zAN5Eakpy9Gk%3d&risl=&pid=ImgRaw&r=0)

- **Casing:** Install a plastic or metal casing inside the borehole to maintain its integrity during testing.

3.3.3 Equipment Setup:

- **Seismic Source:** Use a hammer or similar impact device to generate seismic waves by striking the accessible part of the structure connected to the foundation.
- **Receiver:** Lower a hydrophone (in water-filled boreholes) or a geophone (in dry boreholes) into the cased borehole to record seismic waves.
- **Data Acquisition System:** Set up a system capable of recording and analysing the time and amplitude of seismic wave arrivals.

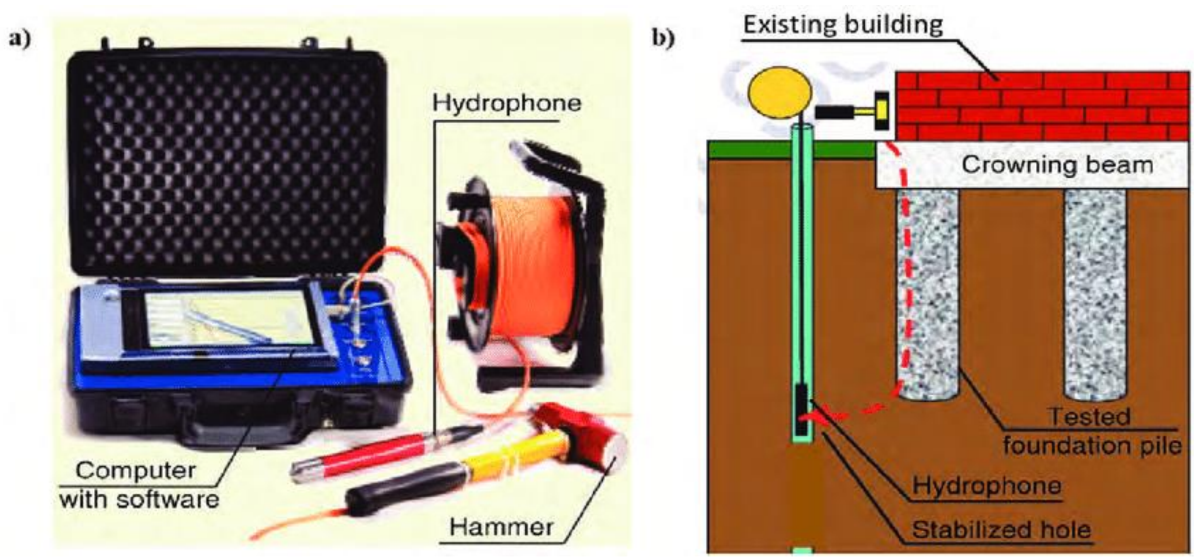

Fig 3.12: a) Equipment for PST b) Setup for data collection

(Source:https://www.researchgate.net/publication/330248171/figure/fig5/AS:713151473516548@1547039969775/The-parallel-seismic-method-according-to-18-a-measurement-set-b-exemplary-test.png)

3.3.4 Data Collection:

- **Impact Generation:** Strike the structure to generate seismic waves. Ensure consistent impacts to produce reliable data.

- **Signal Recording:** Position the receiver at the bottom of the borehole and record the seismic signals. Move the receiver upward in predetermined intervals (e.g., 0.5 to 1 meter), recording signals at each depth until reaching the top of the borehole.

3.3.5 Data Analysis:

- **First Arrival Time Plotting:** Plot the first arrival times of seismic waves against the corresponding depths of the receiver.
- **Velocity Determination:** Identify changes in the slope of the plotted data to distinguish between the higher velocity within the foundation and the lower velocity of the surrounding soil.
- **Foundation Depth Identification:** Determine the foundation depth at the point where there is a significant change in wave velocity, indicated by a change in the slope of the arrival time plot or a notable reduction in signal amplitude.

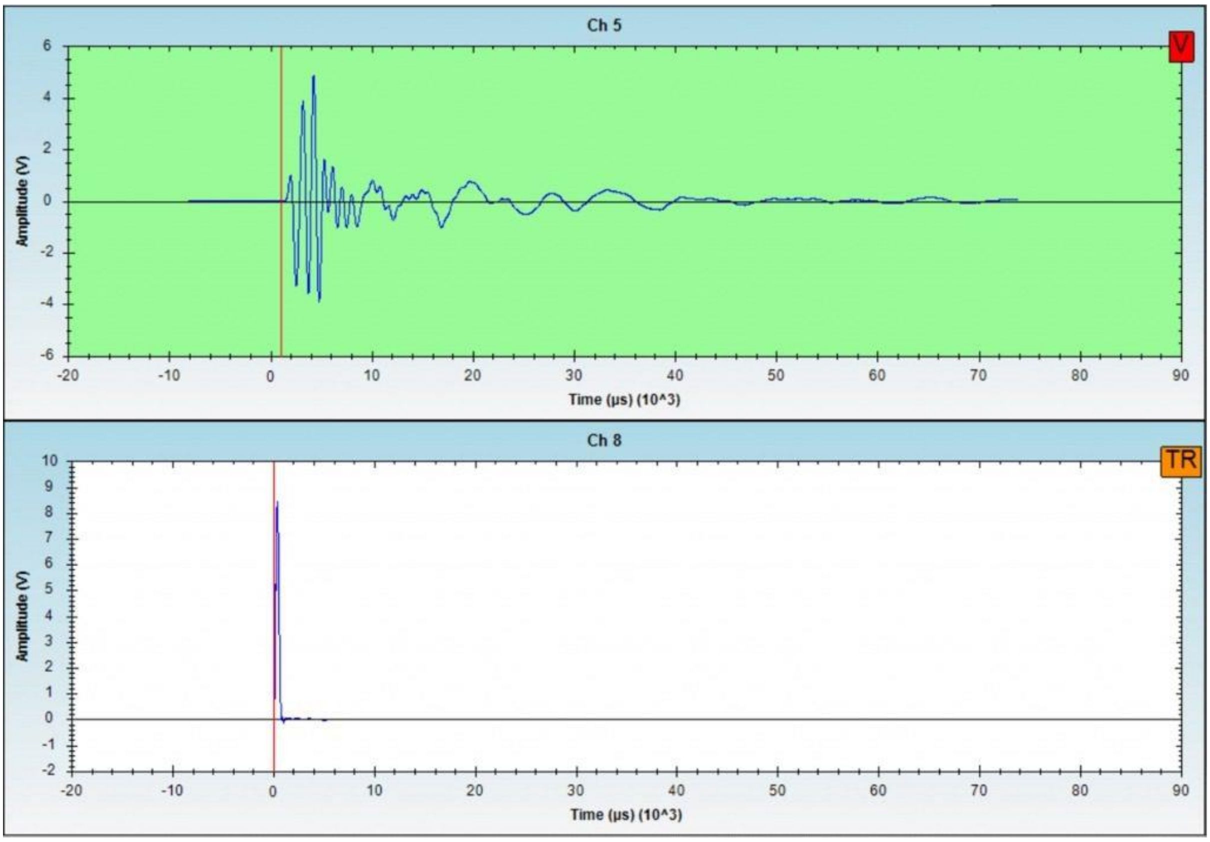

Fig 3.13: First arrival time plotting (Source: https://olsonengineering.com/)

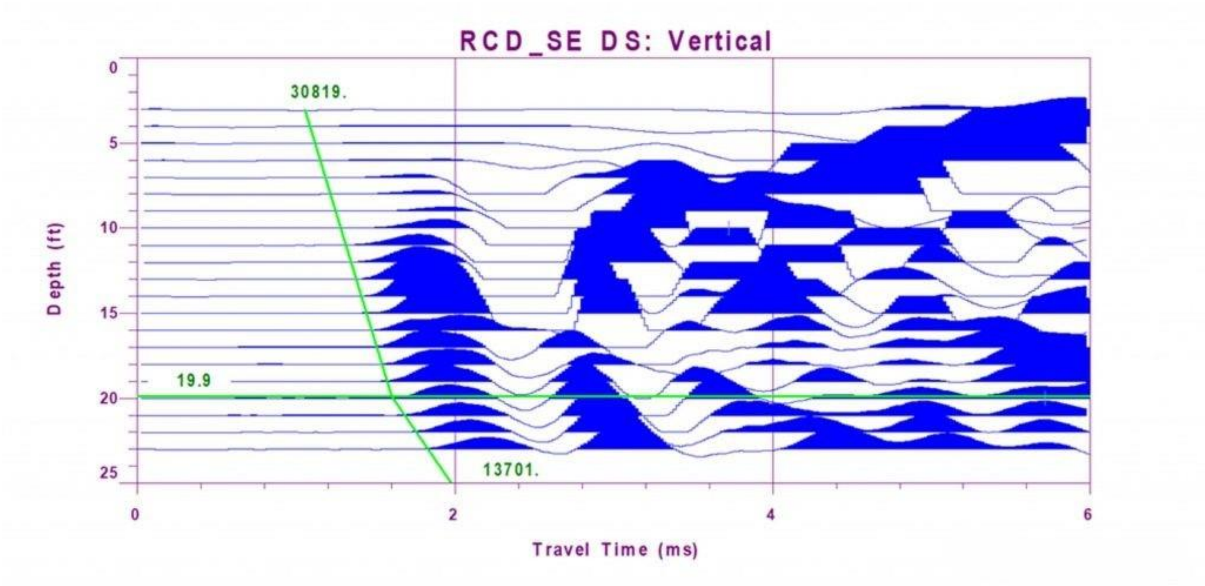

Fig 3.14: Depth identification by change in velocity (Source: https://olsonengineering.com/)

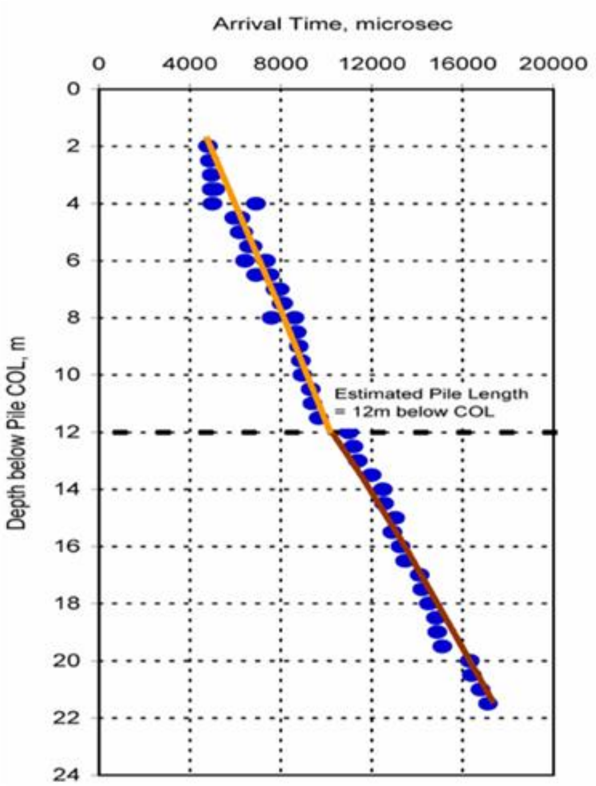

Fig 3.15: Parallel seismic test result (Ravi Sundaram et al, 2015)

3.3.6 Interpretation and Reporting:

- **Depth Confirmation:** Compare the determined foundation depth with existing design documents to verify accuracy.
- **Anomaly Detection:** Analyse data for any irregularities that may indicate defects or changes in the foundation structure.
- **Documentation:** Prepare a comprehensive report detailing the methodology, findings, and any recommendations for further investigation or remedial action.

Project:		Test Date:
Test Unit:		Tester:
Pile No:	Test Device:	Pile Category:
Pile Dia:	Strength Grade:	Measured Depth:
Average Velocity:	Pile Type:	
Integrity Evaluation:		

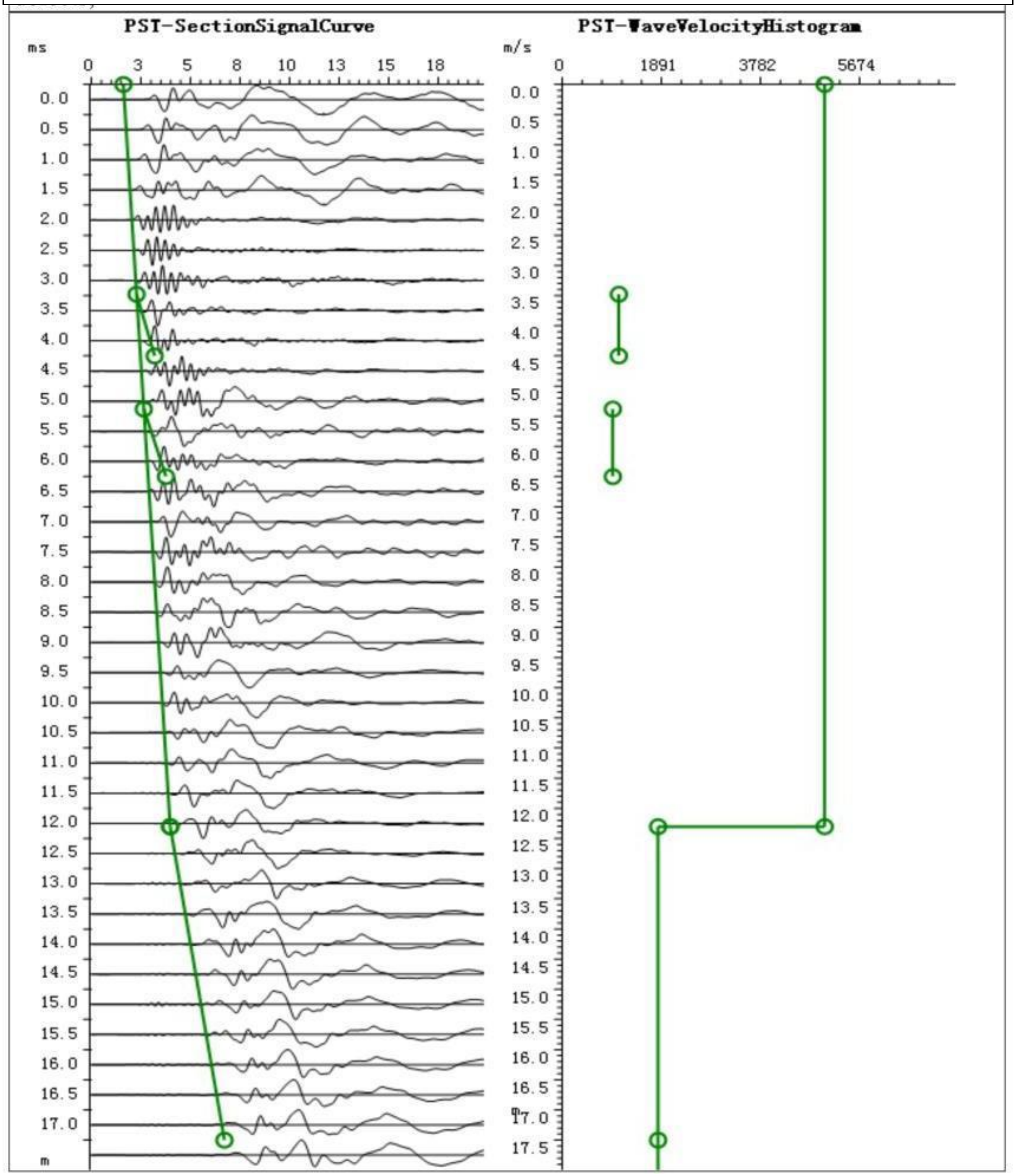

Fig 3.16: Example of an Output report for Parallel Seismic test

3.3.7 Considerations:

- **Borehole Proximity:** The accuracy of the PS test improves with the proximity of the borehole to the foundation. However, practical constraints may limit how close the borehole can be placed.
- **Soil Conditions:** Uniform soil conditions facilitate easier interpretation of results, while heterogeneous soils may complicate data analysis.
- **Equipment Calibration:** Ensure all equipment is properly calibrated and functioning to obtain reliable data.

CHAPTER 4

ADVANTAGES AND LIMITATIONS

4.1 THE SONIC ECHO/IMPULSE RESPONSE (SE/IR) TEST

4.1.1 Advantages

1. **Non-Destructive Nature**:
    - The test does not damage the foundation, making it suitable for evaluating existing structures.
2. **Simplicity and Speed**:
    - The equipment is portable, and the test can be performed quickly, especially on accessible pile heads.
3. **Cost-Effectiveness**:
    - Compared to other non-destructive methods, SE/IR testing is relatively inexpensive and requires minimal equipment.
4. **Pile Integrity Assessment**:
    - Useful for detecting major defects such as cracks, voids, soil inclusions, and changes in cross-section.
5. **Foundation Depth Determination**:
    - Provides an estimate of pile depth by analyzing the time of stress wave reflections.
6. **Wide Application**:
    - Applicable to various foundation types, including cast-in-situ piles, precast piles, and drilled shafts.
7. **Data Repeatability**:
    - The test allows multiple measurements at the same location to improve data accuracy.

8. **Minimal Site Preparation**:
    - Requires only a clean pile head for testing, with no extensive preparation of the surrounding area.

4.1.2 Limitations

1. **Limited to Accessible Pile Heads**:
    - The pile head must be exposed and in good condition, which may not always be feasible in operational structures.
2. **Dependence on Material Homogeneity**:
    - Assumes uniform material properties; heterogeneous piles may produce complex wave reflections that are hard to interpret.
3. **Depth Limitations**:
    - The accuracy of depth measurements decreases for very long piles due to attenuation of stress waves.
4. **Sensitivity to Environmental Noise**:
    - External vibrations or noise can interfere with signal clarity, especially in urban or high-traffic areas.
5. **Interpretation Complexity**:
    - Requires skilled personnel to interpret results, particularly when reflections are weak or anomalies are present.
6. **Detection Resolution**:
    - The test is more suited for detecting major defects and may miss smaller flaws or subtle changes in material properties.
7. **Not Suitable for Embedded Foundations**:
    - Foundations completely buried or with inaccessible heads cannot be tested using this method.

8. **Assumptions of End Reflections**:

    - Relies on clear reflections from the pile toe, which may be disrupted in cases of soft toe material or if the pile base is resting on soft strata.

9. **Requirement for Wave Velocity**:

    - Accurate depth determination depends on knowledge of the wave velocity, which can vary with material and environmental conditions.

4.2 RESISTIVITY IMAGING SURVEY

4.2.1 Advantages

1. **Non-Invasive Technique:**
   - Does not disturb the structure or the surrounding soil, making it ideal for sensitive sites.
2. **Wide Area Coverage:**
   - Capable of profiling large areas to locate foundations and understand subsurface conditions.
3. **Adaptability to Various Materials:**
   - Effective in identifying foundations made of different materials, including concrete, stone, or brick.
4. **Subsurface Profiling:**
   - Provides additional information about soil layers, voids, and groundwater conditions, aiding comprehensive site analysis.
5. **Cost-Effectiveness for Large Sites:**
   - Compared to some methods, it is relatively economical for initial surveys over expansive areas.
6. **Flexibility in Application:**
   - Can be used where direct access to the foundation is unavailable.

4.2.2 Limitations

1. **Sensitivity to Groundwater:**
   - High groundwater levels or highly conductive soils can mask the foundation's presence, reducing accuracy.
2. **Limited Depth Accuracy:**
   - Precision decreases with depth, making it less reliable for very deep foundations.
3. **Time-Consuming Data Collection:**
   - Setting up electrodes and performing the survey can be time-intensive, especially in large or complex sites.
4. **Dependence on Soil Homogeneity:**

- Heterogeneous soil conditions may complicate data interpretation and obscure foundation features.

5. **Interpretation Complexity:**
   - Requires skilled personnel and advanced software for accurate analysis and interpretation of resistivity data.
6. **Edge Effect Issues:**
   - Foundations near the survey boundary may produce distorted resistivity results, leading to errors.
7. **Surface Obstructions:**
   - Presence of pavements, utilities, or other surface-level obstructions may limit the survey's feasibility.

4.3 THE PARALLEL SEISMIC TEST (PST)

4.3.1 Advantages

1. **Non-Destructive Testing**:
   - PST is non-invasive and does not damage the structure or foundation, making it ideal for evaluating existing structures.
2. **Applicability to Inaccessible Foundations**:
   - Can determine the depth of foundations even when the pile or footing top is not exposed, unlike some other methods.
3. **Works in Various Soil Conditions**:
   - Effective in most soil types, including cohesive and granular soils, with minimal interference from surrounding soil characteristics.
4. **Accurate Depth Determination**:
   - Provides precise information about the depth of the foundation by analyzing wave travel time and velocity.
5. **Integrity Assessment**:
   - Can detect changes in material properties, voids, or structural discontinuities along the foundation length.
6. **Minimal Site Disruption**:
   - The test requires only a borehole near the structure and does not disrupt operations or cause major excavation.
7. **Depth Independence**:
   - Capable of testing very deep foundations as long as the borehole extends beyond the foundation's base.
8. **Compatibility with Varied Structures**:
   - Suitable for all types of deep foundations, including piles, caissons, and drilled shafts.

9. **Repeatability**:
    - Allows multiple measurements to verify results, increasing reliability and accuracy.

4.3.2 Limitations

1. **Borehole Requirement**:
    - A borehole must be drilled near the foundation, which can be expensive, time-consuming, and logistically challenging.
2. **Proximity to Foundation**:
    - The accuracy of the test decreases if the borehole is far from the foundation, requiring careful planning for optimal placement.
3. **Dependent on Wave Velocity**:
    - Accurate interpretation requires knowledge of seismic wave velocities for the materials in the foundation and surrounding soil.
4. **Limited to Vertical Foundations**:
    - Best suited for vertical or near-vertical foundations; inclined or battered piles are more challenging to evaluate.
5. **Signal Attenuation**:
    - High levels of noise or attenuation in the signal can complicate data interpretation, particularly in loose or waterlogged soils.
6. **Borehole Integrity**:
    - The borehole must be properly cased and stable; collapsing or poorly constructed boreholes can compromise the results.
7. **Complex Data Interpretation**:
    - Requires skilled operators and advanced equipment for data acquisition and analysis, making it less accessible for small-scale projects.

8. **Cost Consideration**:
    - The need for borehole drilling and specialized equipment makes the test more expensive compared to other non-destructive methods.
9. **Time Intensive**:
    - The process, including borehole drilling and testing, may take significant time, especially in remote or hard-to-access locations.
10. **Environmental Factors**:
    - Groundwater, surrounding infrastructure, and site conditions can affect signal quality and testing accuracy.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 SONIC ECHO/IMPULSE RESPONSE (SE/IR) TEST

5.1.1 Test Results:

1. ***Foundation Depth Detection**:*
    - The SE/IR test effectively determines the depth of shallow foundations, typically up to 20 meters.
    - Reflected wave patterns indicate the end of the foundation, making it possible to measure its depth accurately in accessible conditions.
2. ***Defect Identification**:*
    - The presence of discontinuities, such as cracks or voids, disrupts the stress wave reflections.
    - Test results often show wave attenuation or irregular reflections at defect locations.
3. ***Wave Velocity Variability**:*
    - Variations in wave velocities are commonly observed due to changes in material properties (e.g., concrete degradation) or non-uniform cross-sections.

5.1.2 Discussion:

- The SE/IR test performs well for cylindrical foundations like piles and drilled shafts but struggles with non-uniform or irregular foundations.
- Signal clarity diminishes for foundations embedded in dense soils or where significant defects scatter stress waves.
- The method is limited for deep foundations as reflected signals weaken with depth

5.2 RESULT AND DISCUSSION FOR RESISTIVITY IMAGING SURVEY TO DETERMINE FOUNDATION DEPTH

5.2.1 Results:

1. Resistivity Profile:
   - The survey generated a 2D/3D resistivity profile of the subsurface, highlighting variations in resistivity values.
   - Foundations typically appear as high-resistivity anomalies compared to the surrounding soil.
2. Foundation Depth Identification:
   - The depth of the unknown foundation was inferred from the base of the high-resistivity zone corresponding to the foundation material.
   - Additional layers and features, such as voids or groundwater, were identified in the subsurface profile.
3. Geological Insights:
   - The survey provided details about soil stratification, groundwater levels, and other subsurface features, aiding in a holistic understanding of the site.

5.2.2 Discussion:

1. Accuracy and Resolution:
   - The accuracy of depth determination was influenced by the resistivity contrast between the foundation and the surrounding soil.
   - For shallow and moderate depths, the method performed well; however, for deeper foundations, the resolution decreased, leading to potential uncertainties.
2. Influence of Site Conditions:

    - High groundwater levels and conductive soils reduced the resistivity contrast, making it challenging to distinguish the foundation clearly.
    - Soil heterogeneity and the presence of utilities or debris introduced noise, which required careful filtering during interpretation.
3. Depth Estimation Limitations:
    - For very deep foundations (>20–30 meters), the resistivity imaging survey faced limitations due to reduced signal strength and increased complexity of interpretation.
4. Advantages over Other Methods:
    - The survey provided a non-invasive, wide-area analysis, making it suitable for initial site investigations.
    - Unlike point-based methods like Sonic Echo or Parallel Seismic Tests, resistivity imaging gave insights into the broader subsurface context.
5. Interpretation Challenges:
    - Skilled personnel and advanced modeling software were essential to accurately interpret the resistivity data, especially in complex sites.
    - Edge effects and surface obstructions (e.g., pavements or buildings) occasionally distorted the data, necessitating careful adjustment.

Key Takeaways:

- Resistivity imaging is a powerful tool for identifying the depth of unknown foundations, particularly in sites with moderate depths and minimal interference from groundwater.
- While its resolution decreases with depth and heterogeneous conditions, its ability to provide a wide-area subsurface profile offers distinct advantages in preliminary investigations.
- Combining this method with other techniques, like Sonic Echo or Parallel Seismic Tests, can improve overall accuracy and reliability.

5.3 PARALLEL SEISMIC (PS) TEST

5.3.1 Test Results:

1. **Foundation Depth Measurement**:
   - The PS test provided accurate depth measurements, even for foundations exceeding 30 meters.
   - The transition from the foundation to soil is marked by a noticeable change in seismic wave travel time.
2. **Material Identification**:
   - Variations in seismic wave velocity correlate with different foundation materials, such as concrete, steel, or timber.
   - Results are highly effective in layered or composite foundations.
3. **Subsurface Profiling**:
   - The PS test successfully creates a profile of the subsurface, distinguishing between foundation and surrounding soil.

5.3.2 Discussion:

- The PS test excels in scenarios where direct access to the foundation top is unavailable, such as underwater or buried conditions.
- Test accuracy improves with well-placed boreholes adjacent to the foundation. The depth of penetration depends on the borehole depth and the wave generation source.
- Unlike SE/IR, this method is less affected by dense or heterogeneous soils, making it more versatile for deep foundations.

CHAPTER 6

COMPARATIVE DISCUSSION

Here's a comparative study among Sonic Echo Test, Resistivity Imaging Test, and Parallel Seismic Test for evaluating the depth of unknown foundations:

Aspect	Sonic Echo Test (SET)	Resistivity Imaging Test (RIT)	Parallel Seismic Test (PST)
Principle	Reflection of stress waves from the bottom of the foundation.	Variation in electrical resistivity of subsurface materials.	Travel time of seismic waves through foundation material.
Foundation Material Suitability	Effective for concrete and driven piles; less effective for deteriorated or heavily cracked foundations.	Works for all materials but can be influenced by subsurface conductivity.	Effective for most foundation materials; especially useful for inaccessible foundations.
Accuracy	Limited for complex geometries or deep foundations.	Accuracy decreases with depth and in heterogeneous soils.	High accuracy for depth determination when setup is optimal.
Testing Conditions	Requires a smooth and accessible foundation surface.	Can be applied in open ground; requires electrode deployment.	Needs a borehole close to the foundation.

Setup Complexity	Simple setup; quick to execute.	Moderate setup; requires electrodes and resistivity equipment.	Complex setup; requires borehole and seismic probes.
Cost	Relatively low cost.	Moderate cost; depends on site conditions and survey extent.	Higher cost due to borehole drilling and specialized equipment.
Data Interpretation	Relatively straightforward but requires expertise for anomalies.	Requires geophysical expertise for accurate interpretation.	Requires expertise in wave mechanics and seismic analysis.
Limitations	Cannot detect foundation depth accurately if the material is severely deteriorated or if reflections are masked.	Challenging in areas with high groundwater or conductive materials.	Limited to the borehole's proximity and alignment with the foundation.
Time Efficiency	Fast for small projects.	Moderate to slow, depending on survey area.	Time-intensive due to borehole preparation and data collection.
Applications	Shallow foundations, small bridges, and structures with accessible foundations.	Wide-area subsurface profiling, preliminary investigation.	Deep and inaccessible foundations, bridge retrofitting.

CHAPTER 7

CONCLUSION

This study evaluated the effectiveness of three non-destructive testing (NDT) methods—Sonic Echo/Impulse Response Test, 2D Resistivity Imaging Survey, and Parallel Seismic Method—for determining foundation depth and compared their performance under various conditions. Each method exhibited unique strengths and limitations, highlighting the importance of selecting the appropriate technique based on project-specific requirements.

The **Sonic Echo/Impulse Response Test** proved effective for detecting shallow foundation depths and identifying anomalies such as cracks or voids within the foundation. However, its performance was significantly limited for deep foundations or when applied in complex subsurface environments.

The **2D Resistivity Imaging Survey** offered a geophysical perspective, successfully mapping subsurface conditions and providing estimates of foundation depth, particularly in electrically conductive environments. Despite its broader application range, its accuracy was often affected by the presence of heterogeneous soil conditions and external interferences, such as nearby utilities.

The **Parallel Seismic Method** emerged as the most precise technique for determining the depth of buried or inaccessible foundations. It demonstrated robust performance even in challenging scenarios, such as deep or embedded foundations. However, its implementation required borehole installations and specialized equipment, making it more resource-intensive compared to the other methods.

In conclusion, while each method has its advantages and limitations, no single technique is universally applicable. The choice of method should be guided by factors such as site conditions, foundation accessibility, and project constraints. Combining multiple NDT methods can provide a more comprehensive and reliable assessment, particularly for critical infrastructure. This comparative study offers a valuable framework for practitioners, helping to optimize the application of NDT techniques for foundation depth evaluation and advancing the field of structural and geotechnical assessment.

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