COMBINED PARALLEL SEISMIC AND CONE PENETROMETER TESTING OF EXISTING BRIDGE FOUNDATIONS AND LEVEE SHEET PILES FOR LENGTH AND CAPACITY EVALUATIONS

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Abstract

The use of the Parallel Seismic (PS) test method has been well documented and has been shown to be effective for foundation length evaluation when used with a cased borehole adjacent to the foundation being evaluated. In addition, the use of the Cone Penetrometer Test (CPT) to evaluate soil properties without a borehole has also been well documented. Recent research, hardware development, and field testing have been conducted on a system which combines the two methods to allow fast and economical evaluation of both soil properties and foundation depth without requiring a drill rig. The combined system collects both PS and CPT data in one or two probe penetrations into the soil. The combined system can be used with a smaller, relatively low clearance CPT rig which is self-propelled and designed for use on rough site conditions. Thus, access is possible to bridge foundations that could not be tested with conventional means. The paper presents details of the principles and operations of the combined system, as well as field test data from driven pile bridge foundations as well as steel sheet piles under levee walls in New Orleans.

Introduction

Determining the true tip depth and foundation geometry for bridge foundations without documentation is becoming an increasingly important task for the nondestructive testing community. These unknown foundations are found under a wide variety of structures, ranging from bridges to antenna towers to buildings. For most of these foundations, the lack of any information is not a major concern if the structure has been performing adequately for a period of years. However, a variety of situations can arise which can suddenly make knowing the foundation depth and geometry be of prime importance. The most common situation that arises is a planned change in loading of the foundation element. For antenna towers, this situation occurs when new or heavier antenna elements must be added to the tower. For bridge foundations, this can be due to adding lanes to an existing bridge or reusing foundations for a totally new superstructure. The need for foundation information can also be driven by scour safety analyses for bridges, to verify that the predicted or historic scour depths will not undermine the foundations during a major flood event or high tides.

Regardless of the actual reason for needing information on foundation depth and type, there is a clear requirement for reliable, fast, and cost-effective test techniques to allow this determination. There are several methods that can be used for unknown foundation evaluation, with the specific utility of each method usually dependent on the actual foundation to be tested. These methods include electromagnetic methods such as surface and borehole based Ground Penetrating Radar and borehole based Induction Field, as well as various stress-wave based test methods such as surface Sonic Echo, Impulse Response, Ultraseismic (US) methods as well as the borehole-based Parallel Seismic method. Previous research conducted for the National Highway Cooperative Research Program (NCHRP) by Olson Engineering (1,2) has shown that of the methods available, the Parallel Seismic (PS) test method is the most versatile and reliable. This method can be applied to a wide variety of foundation types and almost any foundation depth, and does not require direct physical access to the foundation being tested. The most significant limitation to wider application of the PS method is that it typically requires a cased borehole be placed in the ground next to the foundation in question using a truck-mounted drill rig.

As stated above, the biggest limitation to the wider application of the PS test method is the requirement for a cased borehole next to the foundation element. Recent research and development has resulted in a system that uses a cone probe system to simplify the borehole installation or eliminate it altogether. The newly developed system can be used to either install a small-diameter casing for PS testing, or can be used with an instrumented cone probe to allow collection of PS data without a borehole at all. For sites with stiffer soils, the cone probe rig can be used to install a cased borehole using hollow steel casing and a vibratory hammer. This casing can then be used to quickly perform a PS test using "conventional" methods, but still without requiring the use of a large truck-mounted drill rig. Sites with softer soil profiles can be tested with just an instrumented cone probe as the PS receiver. These two options are discussed below, after a brief summary of how the PS test method is used.

Parallel Seismic Test Method

The Parallel Seismic (PS) test is normally performed by impacting an exposed foundation top or side, or impacting a part of the structure above the foundation (such as a pile cap or column). The impacts can be either vertical or horizontal, and are typically done with an instrumented impulse hammer to generate compressional waves. Testing can also be done with a non-instrumented hammer, using an accelerometer mounted nearby for the trigger source. These waves travel down the foundation and couple into the surrounding soil as shown in Figure 1. The coupled compressional waves are then picked up in the soil by a nearby hydrophone or geophone receiver. This receiver is typically suspended in a water-filled cased borehole, but can also be near the tip of an instrumented cone probe pushed into the ground. The impact data is collected at a series of multiple receiver depths and stored. This data is then used to create a plot of receiver signal arrival time versus depth, from which the analysis is performed.

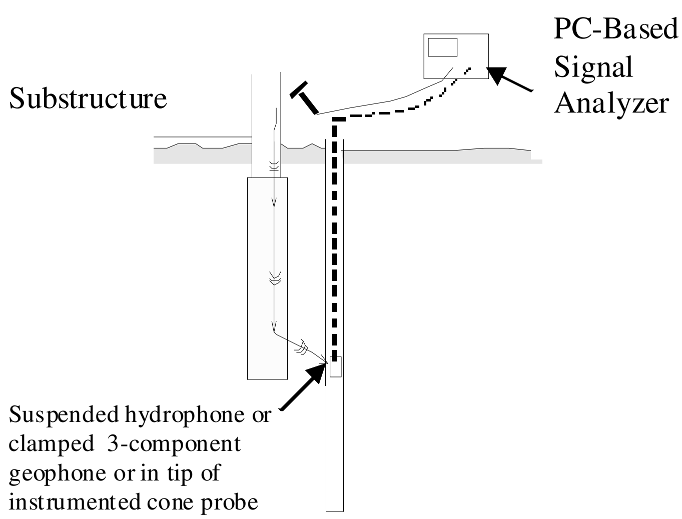

Figure 1: Parallel Seismic (PS) Test Method

Regardless of the type of equipment used to collect the PS data, the tip depth of a foundation is typically indicated by an inflection point in the arrival time versus depth curve, along with a sharp drop in signal amplitude. Diffraction of wave energy from the foundation bottom has also been found to be indicative of foundation tip depth in PS tests as well. Other research at Northwestern University National Geotechnical Site (NGS) has also indicated that the PS method is effective in measuring foundation lengths of inaccessible piles (piles with no access to the pile sides or tops), although this research also pointed out that some care must be taken when using the method under certain soil/rock interface depth versus pile length conditions (4).

Typical Parallel Seismic Test Equipment

The PS test method requires a relatively simple set of equipment to perform. A summary list is presented below:

1. PC based data acquisition system with a sampling rate of at least 100 kiloHertz (10 microseconds/12 bit digital data point) on at least 2 channels (4 channels needed for triaxial geophone) with at least 4096 data points per channel,
2. Signal amplifier(s) for receiver(s). Note: amplifiers can be built into the receivers in some cases.
3. Instrumented impulse hammer or non-instrumented hammer and an accelerometer. Hammers typically weigh 1.4 to 5.5 kg (3 to 12 lb) and must supply an accurate trigger time signal either through the built-in load cell or the nearby accelerometer.
4. Hydrophone or triaxial geophone receivers are required for borehole-based PS tests, while an instrumented cone probe is required for CPT-based tests.

Parallel Seismic Data Interpretation

The Parallel Seismic test is used primarily to determine the depth of unknown foundations, although information as to foundation type can usually be determined by an experienced testing firm based on the foundation velocity, inflection points, etc. The research done for NCHRP 21-5 and 21-5(2) (1,2) resulted in the establishment of several criteria for determining the foundation depths based on Parallel Seismic data as follows:

1. Breaks in the slope of the lines in a plot of depth versus recorded time,
2. Drop in energy amplitude below the bottom of the foundation, and
3. Diffraction of wave energy at the bottom of the foundation.

Example PS Test Data – Concrete Driven Pile Foundation

A PS test was performed on a 29 m (94 ft) deep foundation element supporting a bridge in Baton Rouge, Louisiana. The test was performed by using a CPT rig to install a hollow steel casing into the ground, into which a small diameter (2.5 cm, 1 inch ID) PVC pipe with a slotted bottom was inserted. After insertion of the PVC, the steel casing was removed, leaving the PVC pipe behind. A PS test was then conducted on the foundation, with the impacts being supplied by a 1.4 kg (3 lb) instrumented hammer hitting the side of the bridge column above grade. The signals were received by a small diameter hydrophone suspended in the water-filled PVC casing. A typical PS test result from this testing is presented in Fig. 2 for a test done with the hydrophone moved at 1 foot intervals for the entire length of the casing. As seen, the arrival time versus depth plot starts with a velocity versus depth slope of about 3,658 m/s (12,000 ft/s). This is typical of the compression wave velocity of concrete. At a depth of about 29 m (94.9 ft) below grade, the slope of the arrival time plot changes abruptly to about 2011 m/s (6,600 ft/s). This is the typical compression wave velocity of the saturated sands expected to be at and below the tip of the foundation. The foundation bottom depth is at the intersection point of the two lines (at the inflection depth).

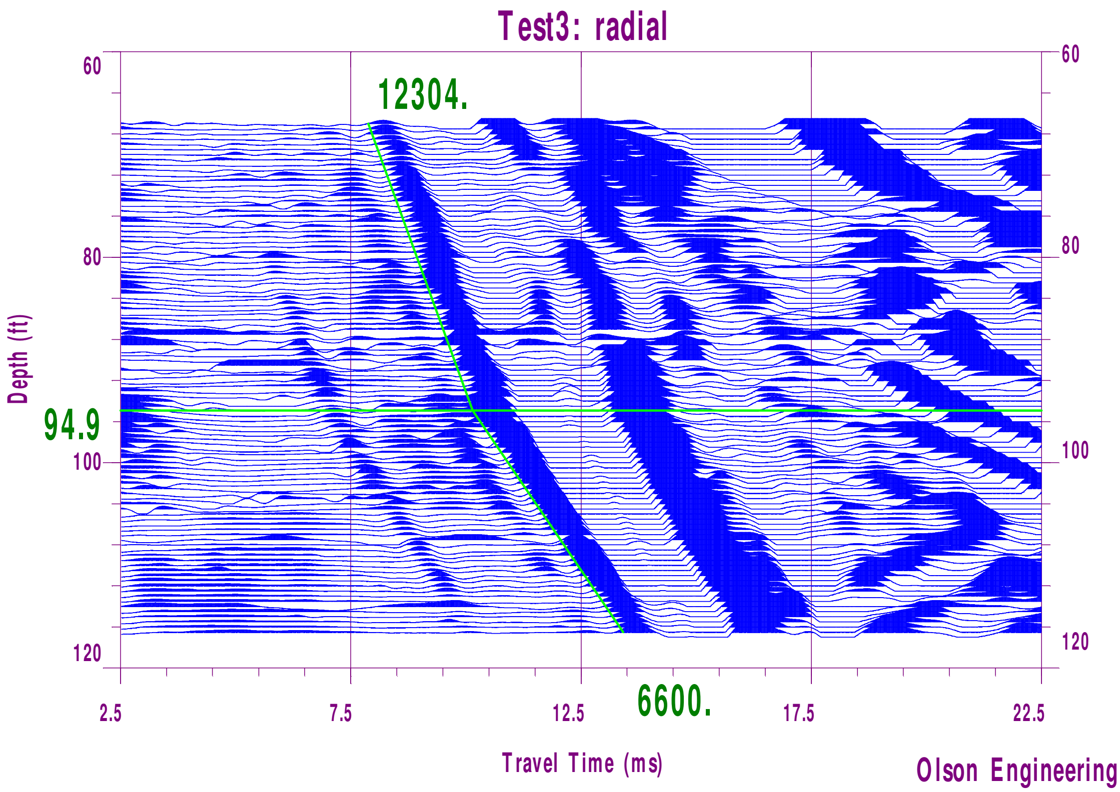

Figure 2: Sample PS Test Result for Concrete Bridge Pile – Tip at 29 m (94.9 ft)

Example PS Test Data – Steel Sheet Piles in New Orleans Levees

A series of tests were performed using the PS test method on sheet piles along the tops of levees in New Orleans, Louisiana in 2005 and 2006. The levee walls in the area of the testing consisted of steel sheet piles driven into the levee soil, topped by a concrete wall which extended several feet into the soil of the levee with the tops of the steel sheet piles embedded into it. The PS data sets were collected using both the PS/CPT and conventional PS testing using boreholes and by a Geoprobe CPT rig (see Figure 3) at selected locations near the levee walls.

The conventional PS data was collected for receiver depths from about 10 feet below the sheet pile tips up to just below grade. The impacts to the wall were done by impacting the concrete wall in both vertical and horizontal directions, as well as on the steel sheet pile itself at one location where a small excavation had been made to expose the top of the steel below the concrete.

An example of a PS test performed on a levee wall location is presented in Figure 4. This test was conducted using vertical impacts to the top of the concrete wall with a 1.4 kg (3 lb) instrumented impulse hammer, as shown in Figure 5. This location had a cased borehole installed using a CPT rig to install a small diameter PVC casing without a drill rig, as described in the previous section. Data was collected for receiver depths from 0.6 m (2 ft) to 9.1 m (30 ft) below grade using an Olson Instruments Freedom Data PC for both signal conditioning and digitization/storage as shown in Figure 6. It should be noted that the borehole was located only about 0.76 m (2.5 ft) from the levee wall at this location, which provides for the best possible data. The data set showed clean data with a clear sheet pile tip depth. As seen in the figure, the steel sheet pile tip is apparent at a depth of 6.6 m (21.5 ft) below grade. The tip of the sheet pile acted as a point diffraction source, with much of the energy traveling in the pile coupling to the firmer sandy soil located only at or near the tip. Above the tip, the slope of the plot is negative, indicating that most of the energy picked up by the receivers at shallower depths was coming also from the pile tip and not from the sides of the pile. This unusual result is not uncommon with steel sheet piles, and still results in an easy to see pile tip depth indication.

Figure 3: Geoprobe CPT rig at Levee Concrete Wall on Sheet Pile

A seismic cone penetrometer probe for PS and seismic testing with three triaxial geophones and a hydrophone is shown in the photograph presented in Figure 7. The photo in Figure 8 presents both a small diameter hydrophone for 25.4 mm (1 inch) ID PVC casings installed with the Geoprobe rig and a larger hydrophone for 38 mm (1.5 inch) ID PVC and larger casings installed with a conventional borehole drilling rig which were used in the PS tests.

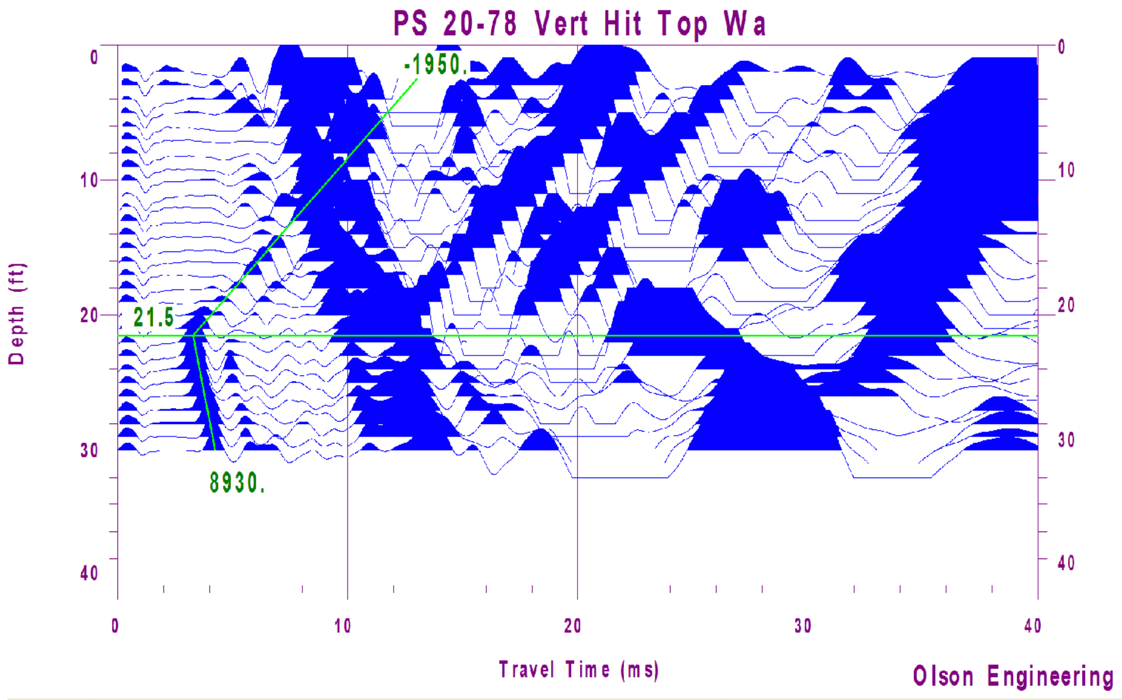

Figure 4: Sample PS Data on Levee Concrete Wall/Steel Sheet Pile – Note Sheet Pile Tip Depth is indicated by Diffraction Event at 6.6 m (21.5 ft)

Figure 5: Impacting the Top of the Levee Wall

Figure 6: Freedom Data PC for PS Borehole Test

Figure 7: Seismic Cone Probe with 3 Triaxial Geophones and 1 Hydrophone

Figure 8: Small and Large Hydrophones for PS Testing in Water-Filled PVC Casings

Parallel Seismic Test Recommendations

For successful use of the PS method, regardless of whether data is collected with a PS/CPT system or a standard PS test setup, there are several considerations which must be taken into account at each proposed testing site.

The most effective PS testing is done when the transducer is located as close as possible to the foundation under test. Typically, the borehole to foundation distance should be 3 m (10 feet) or less for the highest quality and greatest foundation tip depth accuracy. This requirement is to reduce the effects of the velocity and attenuation of the surrounding soil, particularly at sites with unsaturated soil conditions. Where saturated soil conditions exist, PS tests have been successfully performed with larger horizontal offsets from foundation edges. The CPT rig used for the new PS/CPT tests allows the probe to be pushed into the soil at locations as close as 1.5 to 2.1 m (5-7 feet) from the foundation edge, depending on access conditions

Ideally, the borehole (for traditional PS tests) or probe penetration depth (for PS/CPT tests) should extend at least 4.5 m (15 ft) below the minimum required foundation depth (from a capacity/scour perspective considering the subsurface geology) or suspected foundation depth, whichever is greater. This requirement is to ensure that data is collected to the depth of interest. If the borehole or probe is not at least somewhat deeper than the foundation bottom, one may only be able to determine that the foundation is at least as deep as the borehole or probe at the maximum depth (unless a foundation bottom diffraction event is recorded). We have seen a number of cases where the tip depth can be seen in the PS data at transducer depths above the tip depth based on diffractions from the pile tip. However, this type of analysis is not considered to be as reliable as collecting data to depths below the foundation tip and should only be used in cases where the borehole or probe is not or cannot be advanced to the required depth. It should be noted that when collecting data with a PS/CPT setup, it is possible to monitor the data from the PS tests as well as soil conditions from CPT data as the probe is gradually inserted deeper into the soil. Thus, the bottom depth of the foundation can be determined during the course of the testing along with the soil properties. This allows the early termination of testing if the foundation is found to be shallower than expected, or, conversely, allows the operator to continue testing until the bottom depth is seen if the foundation is deeper than expected.

For use of the PS/CPT system, site soil conditions must be suitable for testing with a CPT system. Thus, sites with shallow rock or boulders are not generally suited to this type of testing with a CPT rig. In addition, the testing cannot be extended into the bedrock for sites with shallow bedrock or sites where the piles bear into bedrock. Thus, this system is most suited for testing driven piles or other foundations placed into relatively soft to medium stiff clays or loose to medium dense sands and silts. Tests of sheet piles in a levee system are an ideal application for the PS/CPT system, since it can be driven along the levee top, and the soil conditions are ideal for pushing an instrumented cone probe to the depths required.

Based on experiences with PS testing of hundreds of unknown foundations as well as research tests conducted on known foundations, typical PS accuracies of 5% for bottom depth prediction are expected. If the data quality is poor, or the boreholes are located farther than 1.5 -2.1 m (5-7 ft) from the shaft being tested, accuracies of 10% may result. The accuracy of the method is greatest for sites with homogenous soil profiles, especially in the area around the foundation tip depth. Finally, the clearest and most reliable results are produced by using a relatively high frequency source such as a steel sledge or instrumented hammer with a hard tip to impact the foundation top or column/pile cap.

Conclusions

The PS test method has been found in previous research to be the most accurate and versatile method for unknown foundation length determination. One major drawback to this method has been the requirement for drilling a cased borehole at each test location. The combined PS/CPT system allows the collection of both soil data and PS foundation length data with the ease of a simple CPT test in locations where the soil profile allows direct pushing of the cone probe to depths below the pile tip depth. For sites with stiffer soils, the same cone probe rig can be used to install a cased borehole using hollow steel casing and a vibratory hammer. This casing can then be used to quickly perform a PS test using "conventional" methods, but still without requiring the use of a large truck-mounted drill rig. The flexibility and mobility of the new system should allow for easier and more cost effective collection of PS data on a wider variety of sites than was previously possible. In addition, the ability to determine soil conditions in parallel with PS data collection results in a more "complete package" of information for engineers who ultimately need both sets of data to estimate the actual capacity of the foundation element being tested.

References

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