Use of the Wave Equation by the North Carolina Department of Transportation

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Use of the wave equation analysis method offers the most complete and comprehensive control of pile driving of any method available today. It provides a means of increasing the engineer's confidence that not only is the required capacity being achieved but also that the pile is not being overstressed and that the pile-driving hammer is capable of driving the pile to the desired depth in the ground. An outline of the development of the wave equation analysis to control pile driving for the North Carolina Department of Transportation is presented. This process occurred over several years and culminated with the purchase of a pile driving analyzer in July of 1987. This paper contains three case histories demonstrating the use of this method.

The use of the wave equation to control pile driving is relatively new and is not widespread among state highway departments. The wave equation in conjunction with the pile driving analyzer (PDA) is gaining in popularity and will eventually displace other, less reliable means of determining pile capacity and driving stresses. This paper outlines the development of pile driving control through the use of the wave equation in the North Carolina Department of Transportation (NCDOT).

In 1977 the NCDOT sent two employees to Atlanta, Georgia, to attend a Federal Highway Administration Pile Wave Equation Seminar. The NCDOT then acquired the 1976 Wave Equation Analysis of Piles (WEAP) computer program and used it unofficially on pile projects to gain experience and develop confidence. Presently the NCDOT is using the 1986 WEAP computer program (*1*). With encouragement from the local FHWA bridge engineer, methods of correlating the wave equation computer output with pile load test results were practiced on at least four projects a year. The pile load test sites were chosen with regard to subsurface conditions and pile type. Around 1980 the NCDOT let to contract a large bridge project in the coastal plain using 54-in. prestressed concrete cylinder piles. The piles were 120 ft long with a 60-ft free length above finished grade. This was the first time NCDOT had used this type of pile; so, to ensure structural integrity during driving and to control the length and ensure capacity, the contract stated that the wave equation would be used instead of the *Engineering News* (EN) formula. The wave equation results were correlated with the pile load tests.

Since 1980, the NCDOT has used the wave equation to control pile driving on all the large coastal bridges and on other projects across the state that were judged to require pile-driving control. For about 90 percent of the bridges on which the wave equation is used, a load test or tests are conducted.

A considerable portion of North Carolina lies in the Blue Ridge Mountain and Piedmont Provinces, and many bridges are founded on spread footings or steel H-piling driven to rock. The EN formula is still generally being used for these structures, especially if the total linear feet of piling is less than about 4,000 ft. However, it is anticipated that North Carolina will use the wave equation exclusively for pile-driving control in the near future.

PILE DESIGN PROCEDURES

There are many different types of piles available and several types may be suitable for a given situation. The rationale behind pile selection, pile length, and allowable load is usually based on consideration of geotechnical data, bridge location, type of superstructure, and engineering judgment. Although the factors are interrelated, they can be accounted for in three pile design categories. A description of each follows.

Static Analysis

Once the structural load has been determined for proposed foundation alternates, the pile type, length, and size required to support that load are chosen from the results of bearing capacity and settlement analyses. Static analyses are made using methods after Vesic (*2*). Settlement analyses using laboratory consolidation test data are made, and the effects of drag-down on the pile or piles are computed. Generally, a bearing capacity safety factor of two is used and settlement is limited to 1 in. under dead plus live load.

Soil Driving Resistance

The soil resistance to be overcome in placing the pile to the required tip elevation is computed to determine drivability. This resistance is obtained after the design pile length is established by summing the side friction computed in the static analysis for all soil layers. The soil driving resistance in general will be greater than the soil support computed for a given pile length since compressible layers and soil above the scour line, which are ignored for support, will provide resistance to pile driving. A wave equation analysis is performed using damping parameters and a stress distribution corresponding to the static

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bearing capacity computation and assuming a commonly used hammer. The results of the analysis indicate the pile stresses to be expected as a result of driving and whether the pile can be driven to the full depth. Allowable driving stresses are taken from Vanikar (3).

Lateral Load

Based on the type of substructure selected, piles may be subject to substantial horizontal as well as vertical loads. For instance, piles that extend from the ground line to the superstructure must be designed for horizontal live loads. However, this type of bent is often the most economical. Horizontal load analysis is performed with the aid of the COM624 computer program (4). Allowable deflection is generally limited to 1 in. depending on the bridge with a safety factor of two against overturning. Also, piles in soft ground or piles with a free length are checked for buckling. Piles adjacent to embankments installed in soft ground are checked for the likelihood of being affected by lateral squeeze. Lateral squeeze is the horizontal pressure that may bend or push the piles outward. This thrust is as a result of the unbalanced fill load. The approach taken is after Cheney and Chassie (5).

CONTRACT SPECIFICATIONS

From the foregoing considerations, an economical pile is chosen with a foundation capacity and estimated length. These are shown in the general notes of the structure plans. The NCDOT Standard Specifications state that "the estimated length of piles shown on the plans and in the itemized proposal are for bid purposes only." Unless otherwise stated, the contractor is required to drive the piles to the design capacity and install them not less than 10 ft into natural ground.

Pile load test locations are shown in the plans with minimum tip elevations. The general notes also state that the wave equation will be used to determine bearing capacity in lieu of the EN formula, and that lengths for the piles to be installed will be determined by the engineer after the load tests are concluded. The pile load tests are shown in the bid items as per each. The average cost of a pile load test using the quick method in 20 ft of water is approximately $20,000 and half that for tests on land.

The contract special provisions state that the contractor shall submit for approval the specifications on the pile-driving hammer, cap block, and cushioning material that are proposed for driving the piles 2 weeks before work begins. The load test setup and equipment must also be submitted for review 2 weeks before load testing. The special provisions further state that the contractor shall use the same pile-driving hammer for production and test piles.

On long coastal bridges, test piles for length are used with pile load tests and listed by location in the special provisions. Test piles for length are used to verify that proposed production pile lengths will achieve capacity with a minimum of cutoff. Usually test piles for length are placed in bents on either side of a load test and are intended to provide information at the limits of a range of bents having similar subsurface conditions. The lengths of these piles are determined by the engineer after the pile load tests are satisfactorily completed and the test pile has been restruck. Based on the results of the load test and with confirmation from the test pile for length, the contractor is given production order lengths. Test piles for length are incorporated into the structure and paid for as production piles. Hammer blows are counted for the entire length and the pile may be restruck with a warm hammer, if necessary, to determine freeze.

PILE-DRIVING CONTROL WITH THE WAVE EQUATION

The NCDOT has found that the most reliable means for assuring pile capacity and predicting length of production piles is to load test a few piles and analyze them using the wave equation. The field control then consists of providing bearing graphs to the resident engineer and order lengths to the contractor. The NCDOT pays the contractor for the length installed in the ground to pile cut-off elevation. For any length that is cut off, the NCDOT Standard Specifications state,"When the engineer has determined the length of piles to be furnished and driven, the department will reimburse the contractor for pile cutoffs; however, the cutoffs will remain the property of the contractor."

The pile to be load tested is driven and driving data recorded as the number of blows per foot (BPF) for each foot of penetration. After a minimum period of 36 hr, the pile is tested vertically (in accordance with ASTM D1143-81—quick method). The pile is tested to two or three times the design load and every effort is made to determine the failure load. The failure load is determined by the use of Davisson's limit. Davisson's limit is defined as the load corresponding to the movement that exceeds the elastic compression of the pile by a value of 0.15 in., plus a factor equal to the diameter in inches of the pile divided by 120. After the ultimate load carrying capacity of the pile is determined and the pile is restruck with a warm hammer to determine the freeze, a wave equation analysis is performed. The soil damping parameters for the wave equation analysis are modified until the wave equation results in a value corresponding to the ultimate load as determined by the pile load test. The Smith damping values are adjusted while the soil quake of 0.1 remains unchanged. In general, if the side resistance is less than 30 percent of the total capacity as determined by the static analysis, only the tip damping is adjusted until the hammer BPF and ultimate capacity as given by WEAP agree with the pile load test failure load and final blow count. The stress distribution and the ratio of side resistance to total capacity for input in WEAP are taken from the static analysis. After this is achieved, a capacity table or bearing graph showing capacity versus BPF is constructed and used to determine the bearing capacity of production piles. Before the NCDOT determines the probable production order lengths, several test piles for length are driven to capacity according to the derived bearing graph. Any modifications to the length of production piles judged necessary are then made.

The wave equation is also used to limit damage to the pile during driving by analysis and approval of the cap block, cushion, and pile-driving hammer. The contractor is required to submit this information through the resident engineer, and on approval, the resident engineer and contractor receive instructions on inspection of the cushion material and at what decreased thickness the cushion is required to be changed. The maximum and minimum BPF to ensure that the pile is not overstressed in either compression or tension are included. If the hammer has different stroke settings, the blow count before a change is determined. Tentative approval for the pile-driving equipment is given before the load test, but final approval must wait until the wave equation has been correlated with the load test results. The test pile must be installed using methods the contractor proposes to use on the production piles.

CASE HISTORIES

US-17 over the Intercoastal Waterway

The first bridge project on which the wave equation was used to control pile driving was the dual bridges on US-17 over Lake Drummond Canal in Camden County, North Carolina. This site is located in the Coastal Plain Province. Lake Drummond is an alternate route of the Intercoastal Waterway and required 65 ft of vertical clearance. The contract was let in 1980 for $8,156,777 and contained 20,000 linear ft of 54-in. prestressed concrete cylinder piles at a unit bid of $100/ft. The unit bid price for a pile load test was $75,000. The load tests were carried to 849 tons or three times the design load.

Two pile load tests were conducted. Results of the load tests indicated that 60 ft of penetration would provide adequate bearing capacity in fine to coarse sand with a standard penetration test (SPT) of 20+ BPF. The bearing graph is shown in Figure 1.

The contractor received approval to use a Conmaco 300 single-acting steam hammer and one 5½-in. plywood cushion. The cap block was Dura-Cush. Graphs were provided that showed the tensile stresses versus blow count for both the short and long hammer strokes. (Figures 2 and 3, respectively). The contractor requested and received approval to prejet approximately one-half the pile penetration to shorten the installation time. The approval was based on the contractor's use of the short hammer stroke.

After installation was begun, tensile cracking of the piles was detected in the upper 50 ft of the 120-ft pile. The contract provided for inspection inside the piles. An investigation of the pile-driving operation revealed that the cracking was occurring under soft driving either under the short hammer stroke or when the long stroke was first initiated. The hammer approval specified that the short stroke was to be used until a blow count of 52 per ft was reached. It was not ascertained that this was the case. Further investigation revealed that the cushion was not being changed or inspected often enough to prevent its complete deterioration.

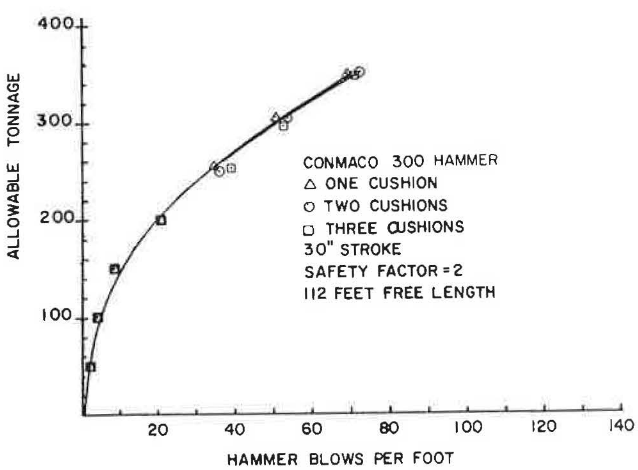

FIGURE 1 Bearing graph for 54-in. cylinder pile: Allowable tonnage versus hammer blows.

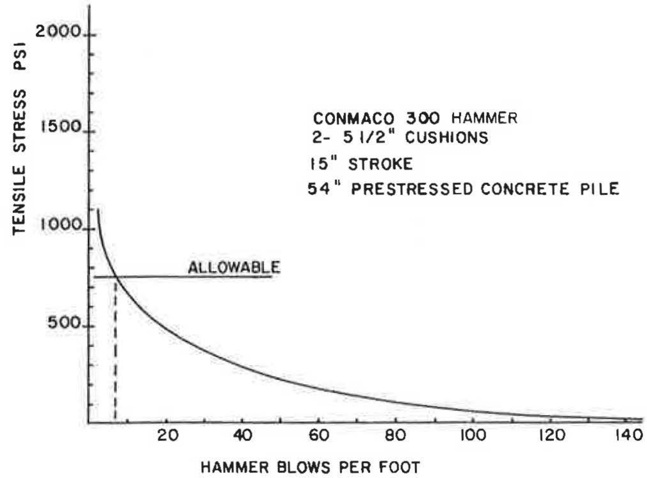

FIGURE 2 Tensile stress under short hammer stroke.

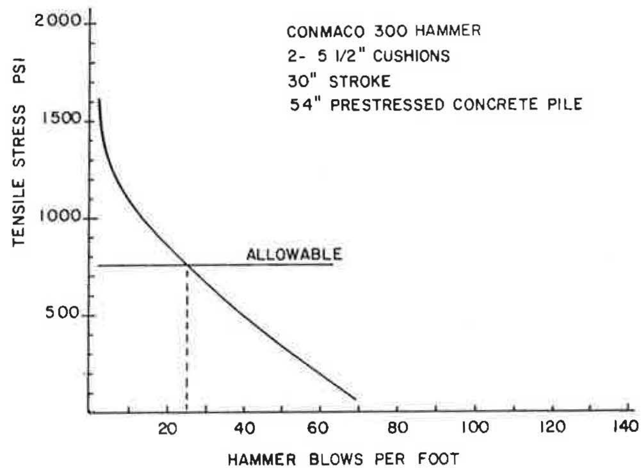

FIGURE 3 Tensile stress under long hammer stroke.

Additional wave equation analysis resulted in calling for the use of two 5½-in. plywood cushions, with the provision that, provided the top cushion is compressed to a thickness no less than 4¾ in., the cushion may be reused as the bottom cushion on the next pile to be driven. The remaining piles were driven without incident and the cracked piles were repaired and left in place. Presently, when approval is given for the cushion, a thickness is specified at which the cushion must be replaced.

NC-32 over Albemarle Sound

A recent project on which the wave equation is being used to control pile driving is the bridge over Albemarle Sound on NC-32 in Washington and Chowan Counties. This project was let to contract in 1985 and is an 18,465-ft bridge providing 65 ft of vertical clearance. The contract is for $22,389,850 and contains 156,840 ft of 20- and 24-in. prestressed concrete piles at unit bid prices of $35 and $38/ft, respectively. The unit bid price for a pile load test is $25,000. The load tests were carried to two times the design load of either 100 or 135 tons depending on the bent location. This bridge site is located in the Coastal Plain Province of North Carolina. Five pile load tests have been conducted. Results of the load tests indicate that 70 to 80 ft of penetration will provide adequate bearing capacity in silty fine sand and clayey silt with an SPT of 10 to 25 BPF. The contractor received approval to use a Delmag-D 62-22 diesel hammer, one 10-in. plywood cushion, and 3.5 in. of Micarta cap block.

Three of the five load tests exhibited freeze effects. Preliminary wave equation analyses for hammer approval indicated that 15 BPF with the pile hammer were required; however, the final blows per foot on the test piles ranged from 7 to 13. After 36 hr, the piles sustained 200 to 315 tons ultimate load. This range was sufficient for a safety factor of two. The restrike blow count ranged from 19 to 39.

An example of correlating the WEAP program with a pile load test and using the results to control pile driving and to determine pile order lengths is as follows.

The static capacity computations for a 24-in. prestressed concrete pile installed to elevation −82 in materials similar to those shown in Figure 4 indicated an ultimate capacity of 186 tons. The capacity at the pile tip was 132 tons, whereas the side resistance was 54 tons, or 29 percent of the total. The side resistance was assumed to be distributed in a rectangular shape along the pile.

The test pile driving record is also shown in Figure 4. The blow count at the end of driving was 13 (BPF) and after 4 days the restrike blow count was 19 (BPF).

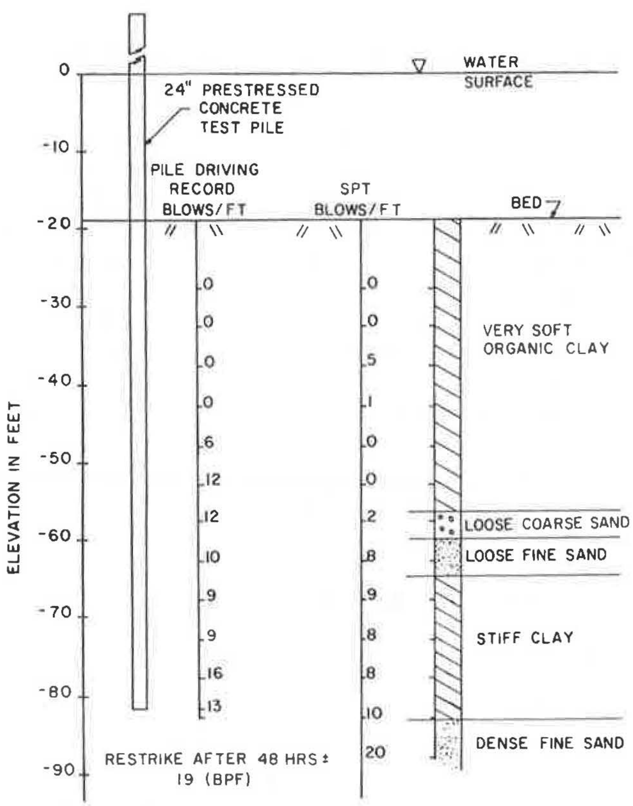

FIGURE 4 Boring log-pile load test site.

The pile load test graph is shown in Figure 5 and indicates an ultimate load of 197 tons. The correlation of WEAP with the ultimate test load is shown by the bearing graphs in Figure 6. Two curves are shown, one labeled "Prior to Load Test" and one labeled "Adjusted for Load Test." The damping and quake values assumed are shown in Table 1. The adjusted curve was used to control pile driving for 86 pile trestle bents, including 3 test piles for length. The average tip elevation of the test piles for length was −88. The subsequent production pile order lengths were based on this tip elevation, with an extra 4 ft added to the length.

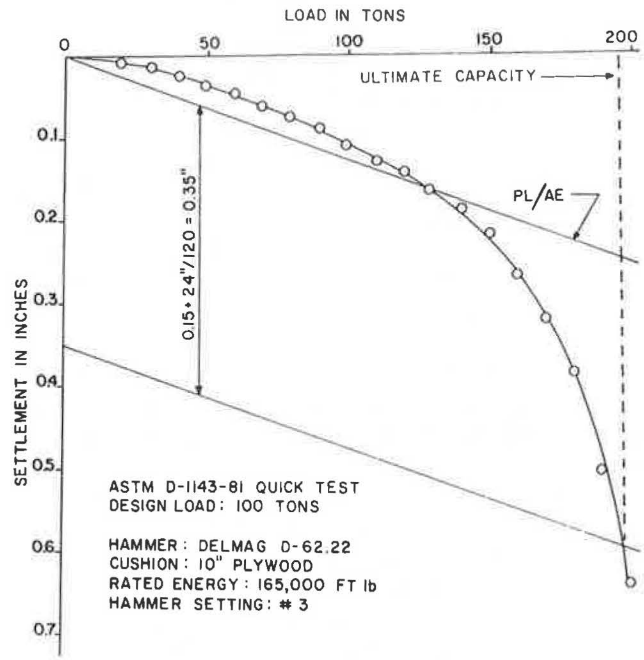

FIGURE 5 24-in. prestressed concrete pile load test.

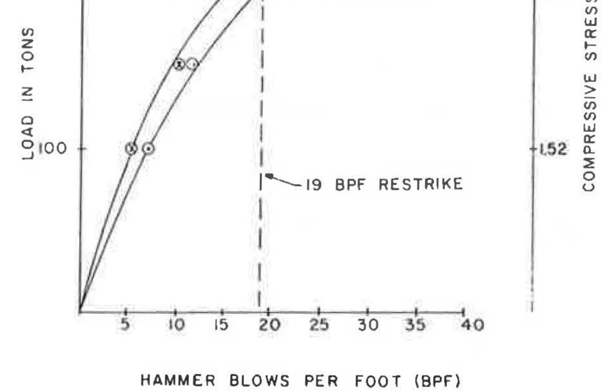

FIGURE 6 Bearing graph for 24-in. prestressed concrete pile.

TABLE 1 ASSUMED DAMPING AND QUAKE VALUES FOR PILE LOAD TEST

Soil Parameters	Before Load Test	After Load Test
Smith side damping	0.20	0.20
Smith toe damping	0.10	0.24
Side quake	0.10	0.10
Toe quake	0.10	0.10

NOTE: Percent side resistance from static analysis = 29 percent.

To verify the capacity of production piles, a schedule of restriking the test piles for length between 1 and 24 hr was devised. The desired result was to determine how quickly a pile would gain capacity. The test pile was left 4 ft high and driven 6 in. after 1, 3, 7, and 24 hr. From this data a chart of strength gain versus time was developed (Figure 7).

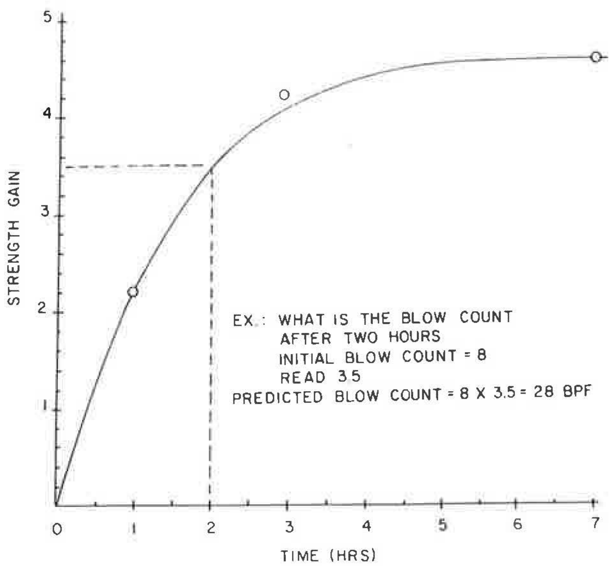

FIGURE 7 Strength gain versus time.

Following the time-dependent tests, the resident engineer was given the following information to schedule redriving of selected piles to verify the capacity of any pile or group of piles. Generally, in a group only one pile was redriven that did not exhibit the required capacity at the end of initial driving.

- If the blow count for the final count is greater than 12 BPF but less than required blow count, redrive the pile 6 in. after a 1-hr period.
- If the blow count for the final count is less than 12 BPF but greater than 8 BPF, redrive the pile 6 in. after a 2-hr. period.
- If the final blow count is less than 8 BPF, redrive the pile 6 in. after a 3-hr period.
- If the required capacity is not obtained after the initial waiting period, use the redrive blow count to choose the next appropriate waiting period, or redrive after 24 hr.

At the time of this writing, all piles in place have achieved the required capacity. In the event the required capacity was not achieved, the addition of piles or pile splicing would have been considered.

It is felt that the pile-driving control based on a wave equation analysis instead of the current NCDOT Standard Specifications and EN formula provided a more logical, and justifiable, engineering method to accept pile lengths that did not show immediate bearing capacity and thereby saved considerable time and money. The NCDOT Standard Specifications would have required that the pile be driven until capacity was achieved according to the EN formula with no time allowed for freeze.

A pile-driving analyzer was purchased in July 1987 and will be used on this project to further verify strength gain.

US-64 and US-264 over Roanoke Sound

A project was let in the fall of 1987 for a bridge on US-64 and US-264 over Roanoke Sound between Manteo and Nags Head in Dare County. The bridge will be 5,544 ft long and provide 65 ft of vertical clearance. The contract contains 50,560 linear ft of 22-in. prestressed concrete piles, with four pile load tests to be carried to 300 percent of the required bearing of 100 tons.

In addition to pile-driving control with the wave equation, the contract special provisions state that the pile-driving analyzer will be used on this project, and that the engineer will require approximately 1 hr/pile to install the measuring equipment. It further states that it is anticipated that 50 piles will be dynamically tested.

The contractor is instructed to notify the engineer at least 5 working days before driving piles at any location where a dynamic test is anticipated. The contractor is also to supply a source of electrical power and an air compressor. For those piles on which redriving is required, a freeze period of 24 hr minimum is specified.

This is the first contract that contains special provisions regarding the pile-driving analyzer, and future contracts will doubtless be modified to reflect the experiences on this bridge.

CONCLUSION

The wave equation analysis method provides a useful means to control pile-driving, especially when all concerned in a state agency are informed and are acquainted with the information that is required from the contractor. The wave equation analysis is a substantial improvement over dynamic formula, but there are still unknowns regarding hammer performance and soil parameters. It is hoped that the pile-driving analyzer, in conjunction with available pile analysis programs, will provide information on the hammer energy transferred to the pile and the soil constants required in the wave equation analysis.

It is anticipated that the acquisition of the pile-driving analyzer by the NCDOT will further refine construction control and reduce the number of pile load tests required, as well as permit the contractor to substitute different hammers for the one used in driving load test piles without conducting an additional pile load test.

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