Determining Lengths of Installed Timber Piles by Dispersive Wave Propagation

J. DARRIN HOLT, SHUNYI CHEN, AND ROBERT A. DOUGLAS

Timber piles are used as a primary means of support for many structures, such as bridges, throughout the continental United States and must periodically be inspected. Sometimes a pile's overall length is not known because pile records are incomplete or nonexistent; so, calculating the effects of scour on its embedment length can present a problem. A new nondestructive testing method is described that employs dispersive stress-wave propagation and special signal-processing techniques to find the lengths of installed timber piles. The method was studied and developed in the laboratory and then applied to installed piles in the field for which there were records. Some piles were pulled to verify the method directly. The computed pile lengths, compared with records or measurements after pulling, were within error bounds of approximately ±10 percent. The test method holds promise for calculating the depth and physical condition of deeply embedded piles as well as those embedded in shallow concrete footings, and it has been shown to be predictive for piles of varying physical conditions and ages.

Timber pilings are still used widely as a primary means of support for many structures. For example, of an estimated 13,900 state-maintained bridges in North Carolina, 6,500 or more are supported, at least in part, by timber piles. If this number were extrapolated to the continental United States using a more conservative estimate (5,000 bridges per state), as many as 240,000 bridges nationwide may be supported by timber. Further, if each bridge were supported by 4 to 6 piles, (the number of piles often exceeds 100 per bridge), then the total number of piles exceeds 1 million, and it may easily be twice that number. The estimates do not include the number of timber piles used in structures such as marine fender systems, pier structures, fishing piers, or mountain chalets and beach cottages.

With so many timber piles in use today across the country, it is important for any agency charged with inspecting them to be able to determine, in-place, whether a pile is still able to support a structure safely. The question is How can a pile's overall length and embedded length as well as physical condition be evaluated after years of service? Adequate testing and computational methods need to be available to inspectors and engineers so they can have the capabilities of nondestructively evaluating the current capacities of installed timber piles.

A research project was conducted to investigate a proposed testing procedure that employs dispersive stress-wave propagation to determine the lengths of installed timber piles (*1*). The test involves striking a pile on its side to create bending waves (transverse waves). The bending waves generated by the strike are dispersive; they are detected as they pass accelerometers (gages) mounted on the pile's side and are recorded on a digital oscilloscope. Once the wave speeds (phase velocities) of a selected group of frequencies and the times required for them to travel to the pile's buried toe (tip) and back are determined, the total distance traveled can be computed. With these measurements, a pile's overall and embedded length can be calculated from the locations of the gages and the pile's exposed length. The authors wanted to determine the feasibility of using such a method in the field. When piles of known lengths were tested in the field, the method was shown to be effective for predicting a wide range of physical conditions, installment ages, and pile treatments.

J. D. Holt, Civil Engineering Department, North Carolina State University, 839-A Barringer Drive, Raleigh, N.C. 27606. S. Chen, Civil Engineering Department, North Carolina State University, APT M-102 E. S. King Village, Raleigh, N.C. 27607. R. A. Douglas, Civil Engineering Department, North Carolina State University, Mann Hall, Room 208, Raleigh, N.C. 27695-7908.

MOTIVES FOR RESEARCH

To date there have been few investigations into nondestructively evaluating pile lengths (*2–4*). Years of scour have taken place since most of the timber piles still in use today were installed; although their overall length may be the same, their embedment (penetration) is not. If a pile's overall length and penetration are not known, it is difficult to determine how much embedment is left. A pile's bearing capacity actually may have diminished to the point that the structure it supports is unsafe to use.

The effects of scour on a pile's embedment can be measured directly, if a pile's overall length were recorded. However, timber piles in use today often were installed so long ago that there is no existing record of their installment. Even if records do exist, they may be incomplete or wrong. Finally, even accurate pile records won't indicate whether an internal deterioration or fracture has occurred that now prohibits adequate embedment.

USING DISPERSIVE WAVES TO FIND IN-PLACE PILE LENGTHS

Dispersion occurs when individual frequencies in a signal travel at their own velocity. Conventional signal-analysis techniques for dispersive behavior are based upon the Fourier transform. Such methods find relative phase angles for individual frequencies between two gage locations. The relative phase is used to determine the time required for the frequencies to travel a known distance, thus allowing phase velocity to be computed. However, it is not possible to tell whether the computed phase is the actual value or whether the actual value is the computed value plus some integer multiple of the frequency's period. For this reason, Fourier transform methods are inherently difficult to use when calculating the wave speeds and travel times of frequency components in a dispersive signal.

In recent years, researchers at North Carolina State University (NCSU) have been able to perform dispersive-wave computations successfully using a mathematical technique known as the Short Kernel Method (SKM). The SKM technique made it possible to design the testing procedure the authors describe. The wave speeds and travel times of the harmonic components of dispersive, bending waves can be monitored and used to calculate a pile's overall length using the SKM method.

Use of Bending Waves

Several types of stress waves are generated whenever a solid with a bounded geometry is struck. The waves include longitudinal, shear, surface, and bending waves. Within a bounded geometry, all these waves, including the longitudinal wave, will be dispersive in nature. Bending waves are the easiest to create in the context of an installed piling, however, and they contain a high percentage of the total energy of wave motion. Therefore, they were chosen as the agent for determining in-place pile lengths.

Striking a pile transversely to its longitudinal axis creates two separate sets of bending waves. One set travels upward toward the pile's head (butt or top) where it is reflected and sent downward along the pile. The second wave set travels toward the pile's buried toe where it is reflected and sent back upward. These two wave sets traverse the length of a pile, one behind the other, reflection after reflection, until they eventually die out. During their travels, dispersion causes the waves' forms to change continuously, and tracking the waves individually becomes increasingly difficult. If bending waves were not dispersive, it would be possible to simply measure the distance between two characteristic features of a wave directly with an accelerometer. As a wave passed the gage's locations, wave speeds and travel times would be recorded, and from these records the wave's travel distance could be calculated. In contrast, to find wave speeds and travel times for a dispersive wave, one must first find these quantities for a chosen range of the wave's harmonic components.

Separating a dispersive wave into its harmonic components to determine the phase velocities of its individual frequencies, and the time they take to travel a pile's length, can be accomplished by either of two signal-processing techniques: the Fourier phase method or SKM. Both of these methods have been used in dispersive signal analysis, although the Fourier phase method has been predominant. The SKM is a dispersive signal-analysis procedure that was developed by R. A. Douglas for finding the wave speeds of dispersive signals recorded from inversely layered media (*5–7*).

Mathematical Basis for Determining Pile Length

SKM is a frequency-dependent scanning operation based on the cross-correlation procedure described by Bendat and Piersol (*8*). Mathematically, a single value of the SKM at some particular frequency can be stated as follows:

$$\text{SKM}(j, k) = \sum_{i=1}^{N_2-N_1} f(\tau_i) \cdot g[(\tau_i + j \cdot \Delta t), k] \cdot \Delta t \qquad (1)$$

where

SKM (j, k) = j^{th} term of the cross-correlation currently being performed at the k^{th} frequency,
f = the time record from one accelerometer,
g = the fragment of kernel used to perform the cross-correlation,
$N2$ = the number of data points in f, and
$N1$ = the number of data points in g.

SKM uses a user-determined frequency, the kernel seed, and aligns it with the signal so that the first points are adjacent. The cross products are then formed and summed, keeping all algebraic signs. This summation represents the first point on an SKM plot of the signal. Next, the kernal is shifted by a preselected number of data points and the cross products formed again to obtain another point on the SKM graph. The process is repeated either to $N2$ points or to some lesser limit. After a time record is scanned, the resulting SKM plot will have positive and negative peaks. The amplitudes of these represent the degree of correlation between the kernel and its frequency counterpart in the original time record.

Figures 1 and 2 offer a descriptive explanation. Figure 1 represents a typical test setup, and Figure 2 presents accelerometer records stored from a test using such a setup. In Figure 2, with abscissa labeled as time and ordinate as amplitude, the top trace is the time record stored from the accelerometer closest to the

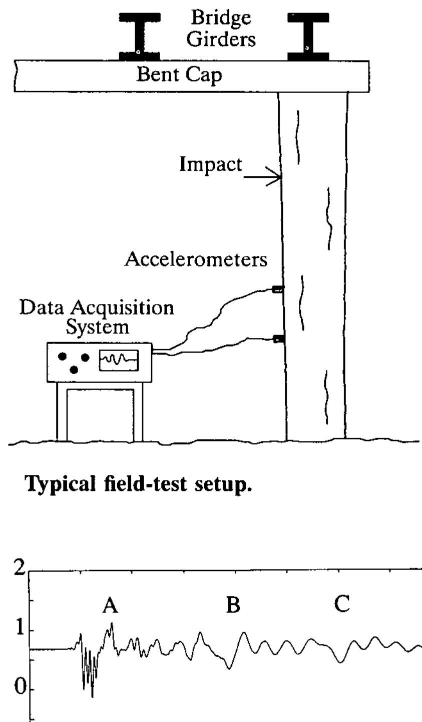

FIGURE 1 Typical field-test setup.

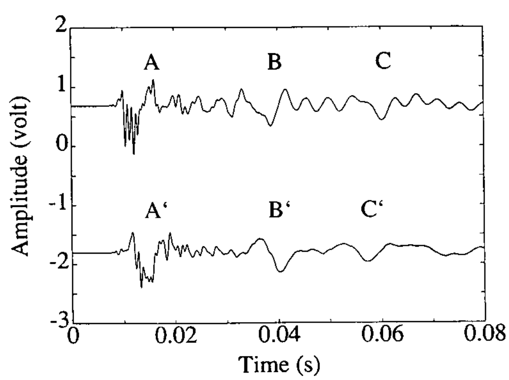

FIGURE 2 Time records from two accelerometers.

pile's head in Figure 1, and the bottom trace is recorded from the gage nearest the ground. The two regions in Figure 2 labeled A and A′ are the first wave recorded as it passed the gage's locations traveling downward from the impact; regions B and B′ are the second wave that first traveled from the impact toward the pile head, reflected, and then passed through the gages on its way down; and regions C and C′ are the wave, first appearing in regions A and A′, after reflecting from the pile's buried toe, and having traveled back under the accelerometers.

Figure 3 shows the superimposed SKM plots of the two time records in Figure 2, assuming a 1-cycle 500-Hertz (Hz) kernel. The solid line is the SKM of the uppermost time record in Figure 2, whereas the dotted line is the SKM plot of the bottom record. Again, the abscissa is labeled as time and the ordinate as amplitude. As seen in Figure 3, the SKM has acted as a "sieve," in that it extracted the 500-Hz component from the signals and displayed its approximate location inside both time records. One can use the first significant positive peaks in the SKM plots, labeled as D and E, to compute a phase velocity. To do this, simply find the number of data points between these two peaks and use Equation 2.

$$C_p = \frac{G_L}{Npts \cdot \Delta t} \tag{2}$$

where

C_p = the phase velocity,
G_L = the gage length (distance) separating the accelerometers,
$Npts$ = the number of data points between peaks D and E, and
Δt = the time step at which the time records were stored originally.

The peaks labeled F and G in Figure 3 can be identified as the return of the 500-Hz frequency from the pile toe. This return signal can be identified easily because the SKM trace from the second gage, the dotted line, appears to lead the one from the first gage, the solid line, as it should. By finding the difference in time between peaks D and G, or E and F, along with the phase velocity from Equation 2, a length can be calculated. The computed length actually will be twice the distance from either accelerometer used for the computation to the pile's toe. The pile's overall length can be determined by adding to this computed value the distance from

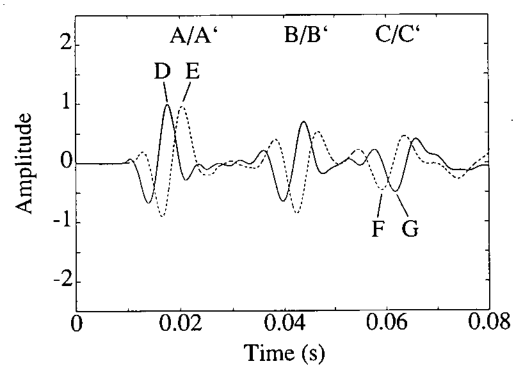

FIGURE 3 SKM Plot using a 1-cycle 500-Hz kernel.

the pile's head to the accelerometer, Equation 3.

$$OL = T_b + \frac{C_p \cdot Npts \cdot \Delta t}{2} \tag{3}$$

where

OL = the pile's overall length,
T_b = the distance from the head to the particular gage being used for the computation,
C_p = the phase velocity from Equation 2,
$Npts$ = the number of data points between peaks D and G or E and F, and
Δt = the time step at which the accelerometer records were stored.

In choosing the negative peaks F and G in Figure 3, the assumption was made that the 500-Hz component reverses its algebraic sign once it is reflected from the pile toe. This may not always be the case; sign reversal is possibly dependent upon the degree of confinement of the embedded portion of the pile. Both assumptions were made during the analysis and a range of lengths were reported. Note that no knowledge of soil conditions surrounding a pile was available when performing the computations.

RESEARCH METHODOLOGY

This research involved the analysis of data gathered from both the laboratory and field. The initial phase involved writing software for the data analysis and developing a hands-on approach and laboratory models that included a 9-m timber pile. Following the laboratory work, test piles were made available by the North Carolina Department of Transportation (NCDOT), including four freestanding, installed timber piles that ranged in length from 7 m to 12 m. The four piles were driven to selected depths of embedment at the NCDOT Bridge Maintenance Yard in Raleigh, North Carolina, and were an invaluable means of testing concepts developed in the laboratory.

The field work focused on piles chosen from a list of bridges supplied by the NCDOT for which there were existing records. Bridge piles were selected so as to obtain a mix of both interior-bent and end-bent piles, ranging from new to badly deteriorated. Their in-place ages ranged from 1 to 42 years. Two of the piles tested were part of a marine fender line at the North Carolina State Ports Authority in Wilmington, North Carolina. As was agreed, NCDOT did not make any records from the bridges available to the research team until after testing and computations were completed.

TEST EQUIPMENT

Equipment used for data generation and acquisition was easily transported to the field each time and quickly set up. Equipment included a digital oscilloscope, accelerometers (waterproof and non-waterproof), signal conditioners, power supplies, tools for creating the signals, and a laptop computer for storing data. Accelerometers were mounted with their axes oriented transversely to the pile's longitudinal axis, as shown in Figure 1. Wood mallets and metal hammers of various sizes were used to create analyzable signals; no standardized device was needed because the signals did not need to be identical. All data recorded were stored on the laptop for later analysis on a laboratory PC.

TEST RESULTS

A total of 40 piles were tested, including the 4 test piles installed at the NCDOT Bridge Maintenance Yard. Of the 40 piles, 26 permitted comparison between the calculated values and overall length values, either from pile records or from measurements taken after pulling. Sixteen of the 26 piles were friction piles (supported by shear forces), and the other 10 were supported by concrete footings. The remaining 14 could not be analyzed either because of bad signals, because no return wave was found in their time records, or the pile's records were not clear enough for identification.

Figure 4 is a graph displaying results for the 26 valid piles, and Figure 5 is an enlarged view of the lower portion of Figure 4. Diagonal lines extending from the origin in both of these figures are the lines of zero difference between computed and recorded or measured values. The lines to either side of the zero-difference line represent a ± 10 percent difference. The term "percent difference" is used here rather than "percent error" because the "actual" lengths were taken from pile records. Such records are subject to error because they may not account for partial or complete fracture(s), brooming of the pile toe, or wearing away of the toe that could have occurred during driving. When such events occur, they effectively decrease a pile's overall length, although the pile's overall length before driving may be all that is recorded.

The 16 piles supported by shear forces (skin friction) were the ones of principal interest in this research. The 16 piles are represented in the figures by horizontal bars whose lengths are a measure of the range of lengths computed for a particular piling, with vertical terminator bars at each end. The range of values for any one pile reflects the dispersion phenomenon, in that different frequencies were found to have different wave speeds and return times by the SKM computations. The computed results showed correlation with the pile records to the extent that percent differences ranged from -11.8 percent to $+8.5$ percent. The negative percentage implies the computed lengths were too short and the positive value indicates that computed lengths were too long.

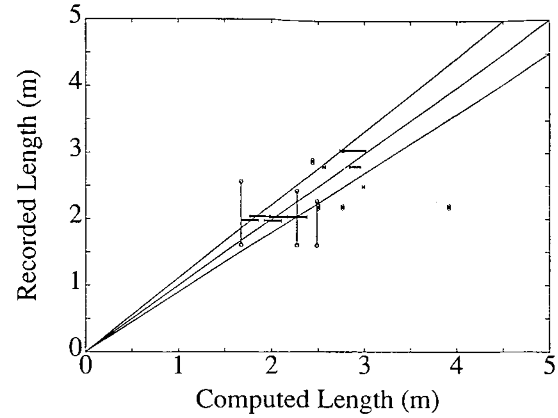

FIGURE 5 Computed overall-length values compared with pile records or measurements after pulling (lower portion).

In Figure 5, the symbols representing piles resting on rock and set in concrete are indicated by vertical lines. The single computed value shown for any vertical line is the average of all the length calculations for that pile. It is compared with the distance from the pile head to the top of the concrete, the lower value on a vertical line, and the distance from the head to rock, the upper value on the line. The only exception to this notation is that of the three piles represented by horizontal bars located between the computed values of 2.56 m and 2.98 m and the recorded values of 2.50 m to 2.80 m. These three piles were also found to be embedded in concrete, but no distance from the pile head to the top of the rock was available. Therefore, a range of computed answers is given for them, which is compared only with the head-to-concrete distance.

Of the 26 piles shown in Figures 4 and 5, 7 were pulled up by NCDOT; they are displayed independently in Figure 6. These are the only piles that permitted direct comparison of the test method results against true measured lengths. The results showed correlation with the measured values to the extent that percentage errors ranged from -10.8 percent to $+6.7$ percent.

One pile was pulled that did not permit an overall-length computation because no return signal was found during the test. The

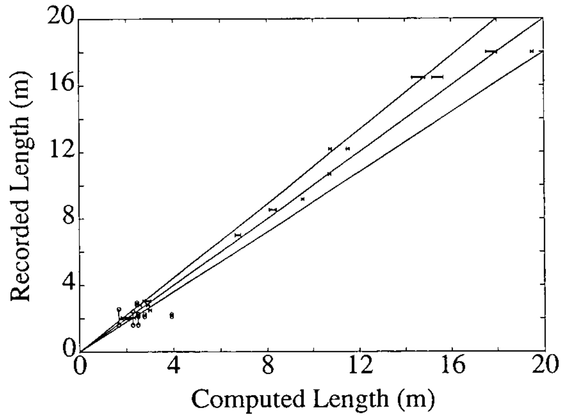

FIGURE 4 Computed overall-length values compared with pile records or measurements after pulling (all piles).

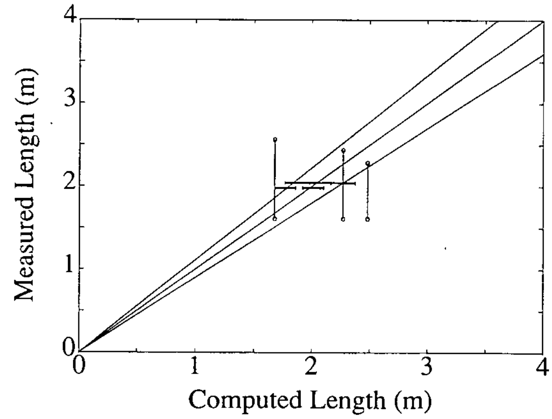

FIGURE 6 Computed overall-length values compared with measurements of piles pulled after testing.

pile was found to have been broken sometime during its service life and disfigured to the point that it was no longer straight. Analysis of this pile may indicate that if a pile's time records are unusually "noisy" or cannot be deciphered, there may be grounds to question a pile's condition. At this stage in the development of the method, however, more evidence is needed.

Piles with Shallow Embedments in Concrete Footings

The 10 piles resting on rock and embedded in concrete were shorter and had more shallow embedments as compared with the other piles. Whether the testing method can determine the actual length of a pile in a concrete footing has not been proven. In all cases, computations gave varying answers that were either (a) too short and above the footing, or (b) a value within the footing, or (c) sometimes below and past the footing.

Factors Affecting Overall-Length Calculations

At the outset of the research, it was recognized that several factors could affect the calculations of overall length, including structural constraints, soil confinement, pile condition, and the effects of a pile's taper on wave speeds. For example, preliminary test results indicate that bending-wave speeds diminish as a wave moves to lesser diameters, as they would in a tapered pile, and speed up again after they reflect off the pile toe. No further information or mathematical correction for the taper effect were available at the time the data were analyzed; however, a more comprehensive investigation was being conducted by Douglas and Holt (*1*).

As regards the effects of structural constraints, such as cross-bracing, no formal, experimental investigation was conducted. An attempt was made to minimize such effects, however, by creating signals whose lateral oscillation was perpendicular to the plane of the bracing. The effects of pile confinement by the surrounding soil was not addressed due to time constraints. The effect of pile condition was being investigated at the time of the research, but results were not available. No corrections were made to the overall-length calculations previously presented for any of these possible effects. One or more of these factors may have been at play for piles that did not yield computational results when tested.

OTHER TESTS

A number of other tests were performed on each pile during the field work. It was realized early in the research program that it would be potentially valuable to start creating a data base to relate measurable parameters to a pile's mechanical and observable condition. Wave propagation tests for condition and wave speeds were conducted, sounding tests were performed, and visual inspections and descriptions were recorded in detail. One of the wave-propagation tests involved using a pitch-catch-type velocity meter to measure the time for a mechanical pulse to travel a known distance. Such time measurements were made routinely along a pile's diameter (radially) and in the direction of its longitudinal axis. These measurements then were used to compute both longitudinal and radial wave speeds for comparison with the wave speeds found from the SKM computations.

Figure 7 shows a graph of SKM wave speed versus radial wave speed. A relationship of this type may prove useful for evaluating piles with such a short, exposed length that it would be difficult to mount two accelerometers. In such cases, if one gage can be mounted and a return signal identified, then radial-velocity measurements may provide an indication as to an approximate SKM wave speed to use in making the length calculations. The degree of error that will be present in such wave-speed approximations has not yet been determined.

Another wave-propagation test was conducted each time to indicate a pile's physical condition. This test involved wave-speed determinations and frequency-amplitude loses between two accelerometers moved along a pile's exposed length. Time records were processed according to the Fourier transform in order to examine frequency and magnitude data. SKM wave speed calculations also were done for frequencies higher than those used in the length computations. Results from these tests were preliminary at the time of this paper.

CONCLUSIONS

For timber piles that depend on embedment and shear forces to carry load, the proposed wave-propagation method for determining overall lengths, using bending waves and digital signal-processing of dispersive signals by SKM, has been demonstrated to hold promise. The percent difference between computed lengths and pile records varied from −11.8 percent to +8.5 percent. The percent error between computed lengths for piles measured after being pulled varied from −10.8 percent to 6.7 percent. The method also holds promise for identifying piles with short embedment. The objectives of our research were met: The dispersive-wave method was shown to be feasible for determining in-place pile lengths, and a field-testing method was developed.

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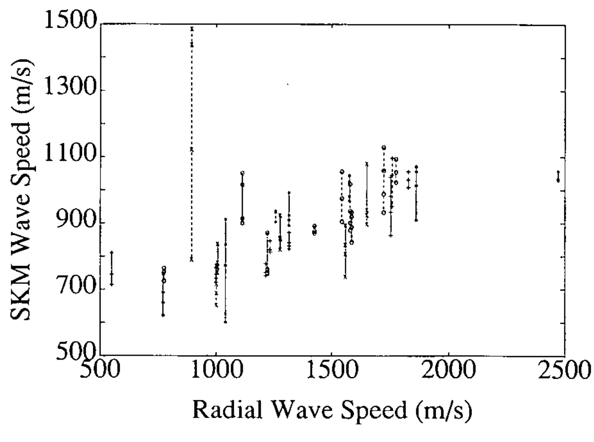

FIGURE 7 SKM wave speed versus radial wave speed.

studies, were made possible by a grant from the Sea Grant program of the National Oceanic and Atmospheric Administration.

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