Nondestructive Testing of Timber Piles for Structures

M. SHERIF AGGOUR

Though an underwater inspection of the timber piles supporting a bridge at Denton, Maryland, indicated reasonable soundness of the timber, the bridge failed. Laboratory tests indicated a substantial reduction in material strength during the life of the piling. A nondestructive procedure for estimating the strength of in-service piles was therefore needed and was developed under the Maryland Highway Planning and Research program. The procedure is an ultrasonic wave propagation method in which the in-place strength of a timber pile is correlated with the wave velocity normal to the grain and the in-place unit weight of the pile. The relationship was developed and verified by testing yellow pine piles from 11 bridges in Maryland. The technique has been extended to the determination of the condition of piles supporting different types of structures. The nondestructive technique as developed for testing timber piles for bridges is presented. The type of data collected, information needed for data interpretation, equipment description, and factors that affect testing are included, as well as the conditions under which the method can be used and its limitations. The types of decay occurring in timber piles, determined by comparing the behavior of timer piles supporting bridges, asphalt tanks, and buildings, are discussed. It is concluded that the technique can be used in all three cases if the causes and types of deterioration and the limitations of the ultrasonic technique are understood.

Timber piles deteriorate because of the organic composition of wood. The principal causes of deterioration of piles in service are fungi, bacteria, insect attack, fire, mechanical wear, and marine borers. Most wood only decays when placed in conditions that are conducive to the growth and development of fungi. Moisture, oxygen, and mild temperatures are essential to the survival and growth of fungi. Decay occurs most often above the water between high and low tide and at the pile cap in timber piles for bridges.

Bacteria are microscopic organisms that live anaerobically on organic material. It was once believed that timber piles submerged in fresh water or buried underground possess immunity to biological degradation. The belief was based on the assumption that a lack of oxygen deters attack by most microorganisms and the knowledge that anaerobic bacteria, prevalent in such an environment, were generally incapable of causing significant damage to the pile material. However, it has become evident during the past two decades that bacteria play an important role in the degradation of wood. It has also been recognized that bacteria, like fungi, may inactivate or destroy preservatives such as creosotes.

Scheffer et al. (*1*) noted, from studying untreated southern pine piles removed from the Potomac River in Washington, D.C., that after 62 years of service the crushing strength of small specimens prepared from the pile above the mudline had been reduced by 60 percent, and that below the mudline had been reduced by 20 percent. Thus, a substantial reduction in crushing strength of the piles above the mudline and a moderate reduction in strength below the mudline occurred. In a similar study of bridge piles after 85 years in the Milwaukee River, Bendtsen (*2*) reported that the average modulus of rupture of red pine was 32 percent, the modulus of elasticity 27 percent, and the specific gravity 12 percent lower, respectively, than the published values in ASTM. Eslyn and Moore (*3*) showed that bacteria were present in all portions of all pile sections. Boutelje and Bravery (*4*) studied spruce and pine piles from the foundation of a 75-year-old building in Stockholm. The peripheral zone of the piles was soft to a depth of 1 to 2 in., resulting in a marked loss in the compressive strength, bending strength, and modulus of elasticity. Microscopic observations of the decayed material suggested that the degradation could be attributed to bacterial action. Singh and Butcher (*5*) reported on premature decay that was found in treated radiata pine posts in vineyards in the Poverty Bay region of New Zealand. Microscopic investigations indicated that bacteria were the first organisms to attack the post and that fungi infected them secondarily once the treatment had been rendered ineffective by the bacteria.

Despite an underwater inspection that had indicated that the piles were reasonably sound 1 year earlier, a bridge supported by timber piles failed at Denton, Maryland, in 1976. After the failure, laboratory tests on the red pine piles recovered by the state highway department indicated that, whereas there was no loss in cross-sectional area, the material strength of the pile had been significantly reduced.

In general, knowledge of the long-term effects of the environment on wood properties is limited. Bacterial deterioration proceeds slowly compared with fungal decay, and publications on bacterial attacks on wood are scarce.

Several kinds of wood-boring insects attack wood for food and shelter and seriously affect its integrity. The insects include termites, wharfborers, and carpenter ants. Wood consists of organic compounds composed mainly of carbon and hydrogen and thus is combustible. Therefore, fire is a hazard to timber structures in service. Mechanical wear of timber piles may involve abrasion from floating debris and impact by traffic. Several marine organisms, of which teredo and limnoria are the best known, are responsible for losses in cross-sectional area in timber piles in salt water, more so in tropical than in temperate climates. Besides climate, loss in cross-sectional area depends on the species of the borer, the salinity of the water, and the type of wood from which the pile is made.

Civil Engineering Department, University of Maryland, College Park, Md. 20742.

The structural integrity of timber piles and their resistance to bending and crushing may decrease with time in service. The effects of deterioration include loss of density (becomes extremely light in weight), increase in permeability (absorbs liquid and becomes waterlogged much more readily), loss in strength (caused by enzymatic degradation of the wood cellulose and lignin), and loss of cross-sectional area. The extent and effect of the decay or loss in area are difficult to assess visually because the timber pile may be completely decayed internally, whereas its external appearance may be normal.

METHODS OF INSPECTION OF BRIDGE PILES

Because the causes of deterioration are many and varied and the protective measures used to guard against it are no guarantee that deterioration will not occur, timber piles must be inspected periodically to determine whether and to what extent damage has occurred. This information can assist the engineer in determining the safe load-carrying capacity of the structure and in establishing a schedule for the replacement of unsafe piles. There are two basic types of tests: destructive and nondestructive.

Destructive methods, as the name implies, are those that to some degree affect or destroy the structural integrity of the material tested by imposing undue strain on the pile. The effect may be slight, as in probing with an ice pick or knife; moderate, as in taking a small core sample; or totally destructive, as in cutting a pile section and crushing it. The specimens tested represent the entire population of potential samples, a major disadvantage in testing natural materials such as wood. In addition, destructive methods may not give a true representation of the load-carrying capacity of the pile.

Nondestructive testing methods permit inspection of the material without impairing its usefulness. Radiography, resonance, nuclear, and X-ray inspection methods have all proven to be valuable in determining wood properties and the extent of wood deterioration in the laboratory. The equipment required for each of these methods does not as yet lend itself to field testing of piles above and below water. Visual inspection is the most widely used of all nondestructive testing procedures; it is simple, easy to perform, and usually low in cost. The basic disadvantages of this method are that inspection is limited to the surface of the pile and that inspectors may misinterpret what they see. Sounding is also a simple method of testing in-place timber piles above water. The pile is systematically tapped with a hammer, and the sound emitted is interpreted by the inspector who rates the pile. The method is limited to providing an initial indication of deterioration to be followed by destructive methods. Ultrasonic testing is a well-established means of inspection for many kinds of materials, such as metals and concrete, and can be readily used under water. Various nondestructive pulse-measuring instruments have been developed to evaluate the soundness of timber structures in service.

SONIC AND ULTRASONIC TESTING IN WOOD

In the last 30 years several studies have been conducted on the evaluation of the mechanical properties of wood and the detection, by ultrasonic testing, of internal defects in it. Lee (*6*) used the ultrasonic technique to test the structural safety of the damaged roof of an 18th-century mansion. Jensen (*7*) used the sonic test technique for the detection of internal decay in wood poles. He found that the frequencies associated with sound poles were higher than those associated with internally decayed poles. The ultrasonic test technique was used by Muenow (*8*) to inspect 11 sections of wood utility poles from the Commonwealth Edison Company, primarily to determine variations of properties from one pole to another. McDonald et al. (*9*) used ultrasonics in determining the quality of lumber in an attempt to grade it more efficiently during cutting. Pellerin (*10*) measured the transmission time of a stress wave through a piece of wood and showed that stress wave analysis could give a good indication of the quality of the interior of the piling, because the progress of a wave is slowed by increasing numbers and sizes of defects. Agi (*11*) found that the velocity and strength of sound waves passing through wood varied inversely with voids in the wood caused by marine borers, a principle that is used to detect the loss in cross-sectional area of piles due to marine borers. Vanderbilt et al. (*12*) used the sonic test technique for evaluating the strength and stiffness of large timber poles through their service life, and Goodman et al. (*13*) used probability methods in their design. For wood frame structures Lanius et al. (*14*) used a stress-wave propagation technique to examine the strength of joists in a structure. Pellerin et al. (*15*) used stress-wave measurements in estimating the ultimate compressive stress of decayed and termite-attacked wood specimens, as did Hoyle and Rutherford (*16*) in the inspection of timber bridges and decks.

A research project supported by the Maryland State Highway Administration and FHWA was conducted at the University of Maryland. A large number of new piles and piles from 11 bridges in Maryland were tested to develop a reliable nondestructive method to determine the strength of timber piles above and below water using ultrasonic wave propagation. In ultrasonic tests, pile sections are subjected to rapidly alternating stress waves at low amplitudes. Undamaged wood is an excellent transmitter of these waves; damaged and decayed wood delays transmission. This provided an opportunity to compare nondestructive testing results from field measurements in piles before they were removed from service with laboratory nondestructive tests on the same piles. The data were correlated with strength determination values from compression tests. In addition, small specimens were cut from the piles and the mechanical properties determined for such variables as unit weight, moisture content, effect of treatment, and direction of grain. Statistical relationships between the wave velocity, compressive strength of the piles, and unit weight were developed that enable an engineer to determine the strength of a pile in place. Full details of the research project are given elsewhere (*17–20*).

PRINCIPLE OF ULTRASONIC TESTING AND EQUIPMENT

Principle of Ultrasonic Testing

Ultrasonic waves are stress waves at frequencies above 20 kHz and are termed elastic waves because it is the elastic property of the medium that is responsible for the sustained vibrations required for ultrasonic wave propagation. Wood is characterized by three mutually perpendicular axes of symmetry: longitudinal (L), normal (N), and tangential (T) to the wood grain, as shown in Figure 1. There are major differences in the strength and elastic properties in the directions longitudinal and normal to the grain, whereas the differences between the tangential and normal directions are relatively small. The quality of wood can be determined from ultrasonic pulse velocity measurements using equipment that generates pulses and accurately measures the time of the transmission through the specimen. By measuring the distance through which the pulse is propagated, the velocity can be computed.

Three arrangements are possible when using ultrasonic equipment to measure the transit time of the wave: a direct transmission arrangement in which the transducers are facing each other across the section of the material tested, a semidirect transmission in which the two transducers are also across the section but at different levels, and an indirect transmission with both transducers on the same surface. Tests conducted in the direction normal to the grain on species of new pine piles indicated a 10 percent higher velocity compared with the tangential velocity. Wave velocity in the longitudinal direction was shown to be two to three times that of the velocity normal to the grain. In testing old piles (yellow pine), it was found that the relationship between the velocity in the directions normal and longitudinal to the grain was no longer two to three, but a function of the unit weight of the wood.

For this study, wave propagation in the normal direction was used because it is more sensitive to detecting defects that are perpendicular to the pulse. Because the objective was to determine the in-service strength of a pile and because the strength is not uniform across the cross section of a pile, measurements in the normal direction are more representative of the section tested. In addition, the transducers are highly directional, and the pulses propagated are mainly in the direction normal to the face of the transducers so that the direct arrangement results in a maximum transfer of energy. The effective path length, being the distance between the faces of the transducers, is well defined. For these reasons, the direct transmission mode was selected.

Ultrasonic Equipment

The equipment is a commercial testing apparatus consisting of a portable ultrasonic digital readout meter and two ceramic transducers, each mounted in a stainless steel case and having a frequency of 54 kHz. Electrical pulses generated by one of the transducers are passed through the test specimen and picked up by the receiving transducer, which transforms these mechanical pulses back into electrical pulses. The time-measuring circuit in the readout meter then displays the transit time between the transducers.

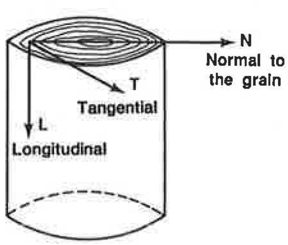

FIGURE 1 Timber pile axes of symmetry.

Factors Affecting the Testing

The surface of the pile (above and below water) must be cleaned of foreign material to obtain a smooth surface where tests are to be conducted. The equipment must be calibrated each time it is used. Air-free contact is necessary between the transducer and the surface of the pile to transmit the ultrasonic energy, because any air contact will attenuate the incident energy. A high-vacuum, silicon-based grease can be used as a couplant for testing above water. Because water is an excellent couplant, there is no need for additional couplant when testing under water.

INTERPRETATION OF DATA TO DETERMINE PILE CONDITION

Data obtained from the ultrasonic tests are used to characterize the in-service condition of the timber piles. The equations were obtained by correlating (*a*) the velocity of the ultrasonic wave in the pile sections, (*b*) strength values from compression tests conducted on the same sections, and (*c*) unit weight. Relationships were developed that can be used to establish the in-place strength of bridge timber piling if both the wave velocity and unit weight are known.

To determine the reduction in strength of the piles tested while in service, it was necessary to compare their existing properties with those of new piles. Therefore, tests were conducted on full-size sections from both new piles and old piles removed from service. The new piles were both treated and untreated southern yellow pine. Sections were cut from in-service treated yellow pine piles from 11 bridges that had either been replaced or were being repaired. Several of the piles were tested ultrasonically in place, removed, sectioned, and tested in compression after their unit weights were calculated.

Pile Condition Rating

Properties of New Piles

New full-size piles of yellow pine, both untreated and creosote treated, were tested in the laboratory to determine their properties. The average compressive strength parallel to the grain and wave velocity normal to the grain of these new piles are presented in Table 1. These data can be used as a basis on which to determine the in-service condition of piles.

Properties of In-Service Piles

The compressive strength of the pile is a function of both the wave velocity and its in-place unit weight. Because it is dif-

TABLE 1 AVERAGE VALUES OF COMPRESSIVE STRENGTH, WAVE VELOCITY, AND UNIT WEIGHT FOR SECTIONS CUT FROM NEW PILES

	Compressive Strength σ_{cr} (psi)	Wave Velocity V_N (ft/sec)	Unit Weight γ pcf
Untreated Yellow Pine (N=20)	6227	6340	34.9
Treated Yellow Pine (N=34)	5005	6010	43.2

N = number of sections

ficult to determine the unit weight by nondestructive means, it is more convenient to determine the condition of the pile on the basis of the wave velocity only, which can be obtained easily. The criteria in Table 2 are estimates that were developed to classify the condition of dry treated yellow southern pine piles on the basis of wave velocity. For example, a velocity of less than 3,000 ft/sec indicates that the pile is in poor condition, generally indicating that the center of the pile is rotten. When no reading is obtained, the pile probably has a large internal decayed area. Caution should be exercised in using this information alone, without consideration of the unit weight.

Strength Determination for Testing Above Water

Dry, New Treated Sections

For new treated sections of yellow pine (and a velocity of approximately 4,500 ft/sec or higher), the compressive strength of a timber pile can be predicted by using a multivariable model that regresses the compressive strength on the wave velocity normal to the grain of the pile and its unit weight. The empirical relationship developed on the basis of the results of the experimental tests is

$$\sigma_{cr} = 0.535V_N + 41.35\gamma \qquad (1)$$

TABLE 2 APPROXIMATE CRITERIA FOR PILE CONDITION (DRY)

Wave Velocity, V_N ft/sec	Pile Condition
5500 and higher	excellent (new)
4500 - 5500	very good (new)
4000 - 4500	good
3500 - 4000	average
3000 - 3500	questionable
less than 3000	poor

where

σ_{cr} = average compressive strength (psi),
V_N = wave velocity normal to the grain (ft/sec), and
γ = in-place unit weight (pcf).

The first coefficient in this equation indicates the sensitivity of the model to wave velocity across the section of the pile, and the second coefficient indicates the sensitivity of the model to the unit weight of the material.

Moist, Old Treated Sections

For a moisture content close to the fiber saturation point and old treated sections having a wave velocity between 3,000 and 4,500 ft/sec, the following model can be used, where γ is the moist unit weight:

$$\sigma_{cr} = 0.537V_N + 6.34\gamma \qquad (2)$$

Dry, Old Treated Sections

For dry and old treated sections having a wave velocity between 3,000 and 4,500 ft/sec, the following model can be used, where γ is the dry unit weight:

$$\sigma_{cr} = 0.292V_N + 46\gamma \qquad (3)$$

Dry, Very Decayed Treated Sections

For dry and very decayed sections have a wave velocity less than 3,000 ft/sec, the following model can be used:

$$\sigma_{cr} = 0.127V_N + 40\gamma \qquad (4)$$

Strength Determination for Testing Below Water

It is known that as the moisture content increases, the velocity decreases and the total unit weight increases. The wave velocity for several sections from different piles having different degrees of decay was determined when the sections were dry. The sections were then allowed to absorb water by storing them in a tank full of water. The absorbed water caused swelling and resulted in weakening of the fibers. The wave velocity was then determined under water over a period of several months until the time reading became constant. These wave velocities are shown in Figure 2, which can be used to determine the velocity through the wood in air-dry condition if the velocity under water is known, or vice versa.

The data points on the figure are concentrated in two regions. In one, the underwater velocity is more than 4,000 ft/sec and the corresponding velocity in air-dry condition is about 10 to 20 percent more than the underwater velocity. This range represents piles in good condition, and the difference in velocity is due to the moisture content. In the other region, the velocity under water is less than 2,000 ft/sec, and the corresponding velocity in air-dry condition is almost twice the

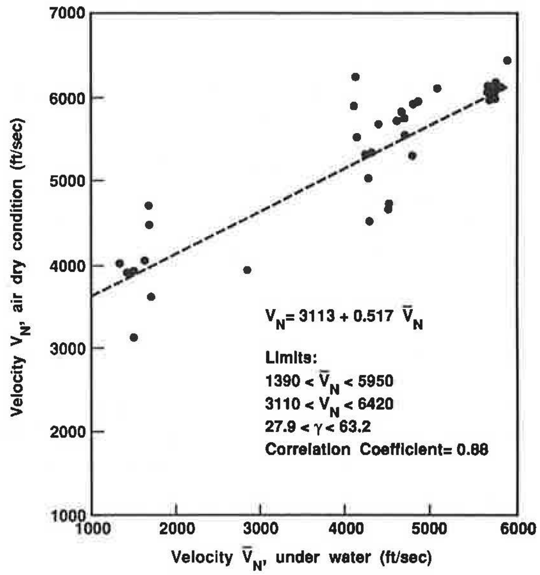

FIGURE 2 Relationship between wave velocity in air-dry condition to wave velocity under water.

underwater velocity. This range represents piles in poor condition.

In field applications the velocity under water is determined, and the velocity in air-dry condition can then be estimated using Figure 2. The velocity in air-dry condition being known, Equations 1, 3, and 4 can then be used.

Two sets of sections were prepared using the same treated piles from different bridges for the purpose of performing compression tests parallel to grain; one set at air-dry condition and the other at wet condition. It was found that the crushing strength of the sections at air-dry condition was about 1.48 times that of the few sections tested at wet condition.

Determination of In-Place Unit Weight

To predict the compressive strength of a pile section using the equations developed, it is necessary to measure the velocity across the section in the direction normal to the grain and the average unit weight of the section in place. The velocity can be easily determined; however, the unit weight is more difficult to determine. The engineer has several options. At present, the most accurate way to determine the unit weight of a full cross-sectional slice of a pile is by weighing the section, measuring its volume, and calculating its unit weight at the specified moisture content. For in-service piles a convenient method is to use small cores bored from the pile. It is also possible to compare the pulse velocity from a suspected area of deterioration with that from an area known to be sound, thereby eliminating the need to determine the unit weight of the timber. When it is not possible to determine the average unit weight of a pile, an approximate value for the unit weight can be estimated from knowledge of the wave velocity. Naturally, the use of such approximate relationships reduces the accuracy of the strength computed. The following are approximate unit weight equations using the ultrasonic method.

Moist Treated Piles

An approximate linear relationship between the wave velocity and the unit weight for moist wood is

$$V_N = 7{,}845 - 67\gamma \quad (5)$$

where V_N is the wave velocity normal to the grain (ft/sec) and γ is the in-place unit weight of the material (pcf). The equation can be used to predict an approximate unit weight of a moist pile from the wave velocity. However, this equation is limited to velocities ranging between approximately 3,500 and 5,500 ft/sec, as shown in Figure 3. For velocities below 3,500 ft/sec or above 5,500 ft/sec, it is recommended that a constant value of unit weight equal to 65 pcf and 35 pcf, respectively, be used.

Dry Treated Piles

The unit weight of dry sections versus the wave velocity normal to the grain was plotted as shown in Figure 4. To predict an approximate value of the unit weight of a dry treated pile, for a wave velocity of 4,000 ft/sec and higher, use the approximate linear relationship

$$V_N = 250\gamma - 4{,}750 \quad (6)$$

For a velocity less than 4,000 ft/sec, use the approximate relationship

$$V_N = 156\gamma - 1{,}460 \quad (7)$$

Stiffness Determination

To evaluate the load-carrying capacity of a pile, the prediction of the in-place strength is most important. Stiffness is also important because the deformation and vibrational characteristics of the pile, and hence the structure, are a function of the modulus of the pile. Both the modulus and the dete-

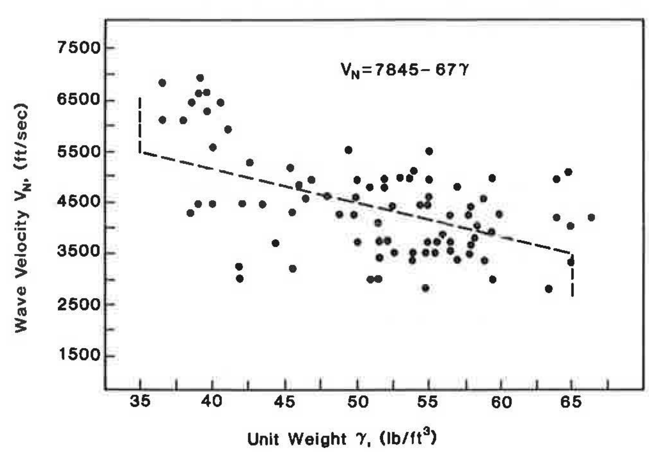

FIGURE 3 Average relationship between wave velocity and unit weight of moist treated pile sections.

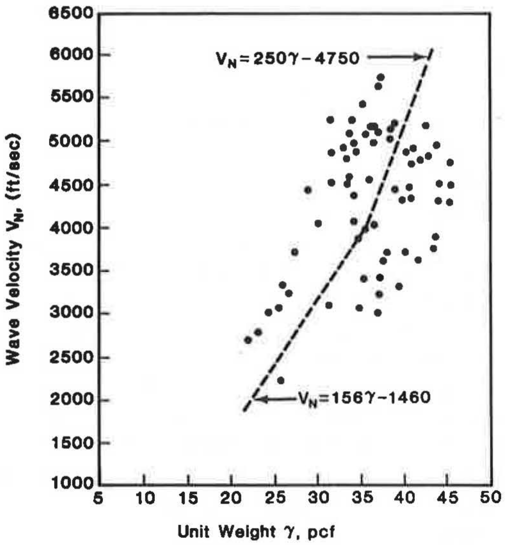

FIGURE 4 Average relationship between wave velocity and unit weight of dry treated file sections.

riorated length of the pile, relative to its total length, were shown to have a significant effect on the behavior of the pile. To determine its modulus the following relationship was developed from experimental data for dry in-service treated piles:

$$E_L = 0.465 V_N^{1.232} \quad (8)$$

where E_L is the dynamic modulus parallel to the grain in ksi and V_N is the wave velocity normal to the grain in ft/sec.

CONSIDERATIONS IN ASSESSING PILE CONDITION

Several factors affect an accurate assessment of timber piling using the ultrasonic method presented, including the number of tests needed at an elevation, the effect of a crack on transit time measurements, and the spacing requirements versus desired accuracy.

Number of Tests Needed at an Elevation

Because the pulses propagated from the transducers are mainly in the direction normal to the face of the transducers, depending on the number of measurements at each section, some blind areas (i.e., areas that are not tested for possible decay) will be encountered. Figure 5 shows the relationship between the untested area of a pile section and the number of measurements made for piles with diameters of 10 and 12 in. and transducers having a diameter of 2 in. After two measurements in two perpendicular directions, four wedges, each 14 percent of the total pile area, remain untested. After three measurements in different directions, six untested wedges, each approximately equal to 6.5 percent of the total area, remain. Therefore, at least two readings taken normal to each

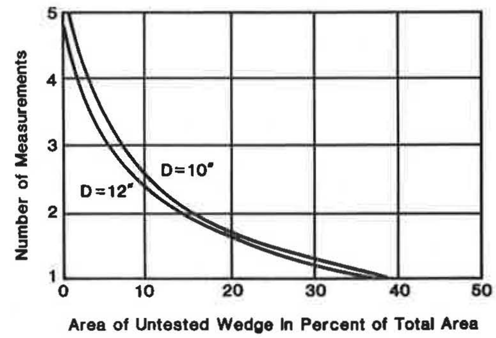

FIGURE 5 Effect of number of measurements on area of untested wedge.

other at the same elevation should be made if reliable data are to be collected.

Effect of a Crack on Transit Time Readings

Repeatability of transit time readings taken at a specific location and in the same direction through a pile has been demonstrated. A variance of less than 4 percent was shown in 50 tests. Variances up to ±45 percent were experienced for some transit time readings taken at the same elevation of a pile for readings normal to each other. The considerable difference between the two readings can be explained as follows: the longer of the two readings passed through a "pocket" of decay not encountered by the other reading; the longer of the two readings traveled around the periphery of a natural flaw, such as a crack filled with air (as when shakes are present); or a combination of these causes.

Inspection of decayed piles shows that decay almost always starts at the center of a pile and radiates outward as it advances. The decay can almost always be detected because all transmitted waves travel through the center of the pile. In some piles, however, the decay was not located in the center; such decay will probably be detected through the use of multiple readings.

To study the effect of naturally occurring cracks in wood on the wave velocity, transit time readings were taken across two smooth wood sections separated by predetermined distances that simulated cracks of various widths. The transit time increased as the width of the gap increased. A gap of 0.1 in. reduced the velocity by an average of 28 percent. Therefore, a narrow crack can affect the velocity considerably.

From tests performed on dry timber piles with and without decay, it was found that wood without decay has a unit weight greater than about 35 pcf, whereas wood with decay has a unit weight less than 35 pcf. Thus, in pile sections free of knots (because knots change the homogeneity of a section), different time readings taken at the same elevation in different directions in a pile indicating variances in transit times are suspect.

Consider a pile section of yellow pine 10 in. in diameter that was tested ultrasonically. The first reading was 180 μsec, giving a V_N of 4,630 ft/sec. From Equation 6, $\gamma = 38$ pcf, and from Equation 1, $\sigma_{cr} = 4{,}048$ psi. The data indicate that decay is not present in this pile. If a second reading is 270 μsec, 50 percent higher than the first reading, then V_N = 3,086 ft/sec. From Equation 7, γ = 29 pcf, and from Equation 3, σ_{cr} = 2,235 psi. The second reading indicates that decay is present, but it conflicts with the first reading. The second reading was probably affected by a crack in the pile. A third reading should be taken and the larger reading discarded. The rejection of a measured value is acceptable because small cracks inside the pile affect the velocity of the wave but not the strength of the pile. However, if two readings of 300 and 400 μsec are obtained, the density is now estimated at 27.2 and 22.7 pcf, respectively. Because each of these numbers is low, decay should be expected. The second reading may indicate either crack in addition to decay or an extra pocket of decay. The computed crushing strength of the pile is 1,440 and 1,173 psi, respectively. Both values indicate a marked reduction in strength over the in-service life of the pile. The difference in the transit time reading in this case is purely academic. When testing below water, the effect of such cracks is negligible, because waves are transmitted across cracks filled with water.

Spacing Requirements for Desired Accuracy

Transit time readings should be taken at regular depth intervals. A 1-ft interval along the pile, up to 4 ft above and below the waterline, and a 3-ft interval elsewhere were found to be adequate. Extra readings should be taken at intermediate points when needed to identify the physical extent of the decay. If the top of the pile is not covered, readings should also be taken there. Methods to define the spacing between test points required for a desired level of accuracy are available elsewhere (*21*).

LIMITATIONS

A detailed description of ultrasonic testing and interpretation is presented in a manual developed for FHWA (*22*). In addition, a videotape demonstrating the use of the ultrasonic method and equipment under various conditions has been prepared and is available from FHWA. The following are the main limitations of the method affecting its use.

- The method is valid in fresh water and in marine environments in the absence of marine borers. If the user knows that there are marine borers or is not sure, caution must be used in interpreting the readings. Small holes caused by marine borers could cause misinterpretation of the data. A large hole is most likely to be missed when measured by direct transmission under water.
- Most of the tests conducted to establish a data bank for new and in-service piles were on southern yellow pine, the main type of timber pile found in Maryland. It is important to know what species of timber is being tested. In many cases the species is not known, and in such a case it is recommended that a section in good condition with no decay be located (borings, sounding, could be used). The wave velocity at any location can then be compared with the readings of the good section and the relative condition of the pile determined. In some cases, the in-place strength of the timber piles is not needed but the relative condition of the piles is. In such cases, changes in the wave velocity may be compared to identify any change in the properties of the wood. There is no need to determine the species of the pile in such a case.
- In the method presented, both the wave velocity and the unit weight of the wood are needed to determine the in-place strength of the timber pile. The velocity at which sound waves travel through the timber pile in a specific direction can be easily determined. The unit weight is difficult to assess because it can only be determined accurately by destructive means. When the unit weight is not determined independently it can be inferred, though not particularly accurately, from the wave velocity. The strength of the pile is then computed on the basis of this information. The wave velocity is the only parameter actually measured to predict the strength. Though acceptable, such a situation reduced accuracy. More accurate results will be obtained when both the wave velocity and the unit weight are determined separately. There is, of course, a trade-off between accuracy and the ease with which the data are collected.
- To determine the loss of strength in a pile, both the original and the in-place strength should be known. However, the original properties of the pile material are usually not known. Average values published by ASTM, for example, can provide a reasonably good basis for comparison. In addition, engineers should keep in mind that each wood species used as piling material has local-property variation within the length of the pile.
- To date a degree of accuracy of ±20 percent in determining the strength of timber piles has been obtained. This degree of accuracy may be sufficient for timber piles, but such criteria may not be sufficient for other wood structures.

CONDITION OF TIMBER PILES IN PLACE

For a successful application of the method in the evaluation of timber piles, an understanding of the causes and types of deterioration of timber piles is essential. Further research into the cause of deterioration is needed, especially in the area of bacterial attack and the environmental conditions conducive to its growth. Figure 6 shows three different types of deterioration that timber piles experience. In the first type the piles are supporting a bridge, in the second a tank, and in the third a building.

Piles Supporting Bridges

From the experimental program, the crushing strength along the length of the piles was determined. The data from the piles tested indicated that along the pile length a reduction in strength between 10 and 40 percent had occurred; however, at the waterline (between high and low tide) a larger reduction took place in two of the bridges (up to 80 percent in one of the piles tested). This means that there existed a severely decayed part at the waterline in some piles, and the degree of decay decreased going either up or down along the pile.

In some cases piling whose external appearance suggested no damage and appeared to be in satisfactory condition indicated no wave transmitted. When these piles were removed it was found that a large decay pocket was present at the

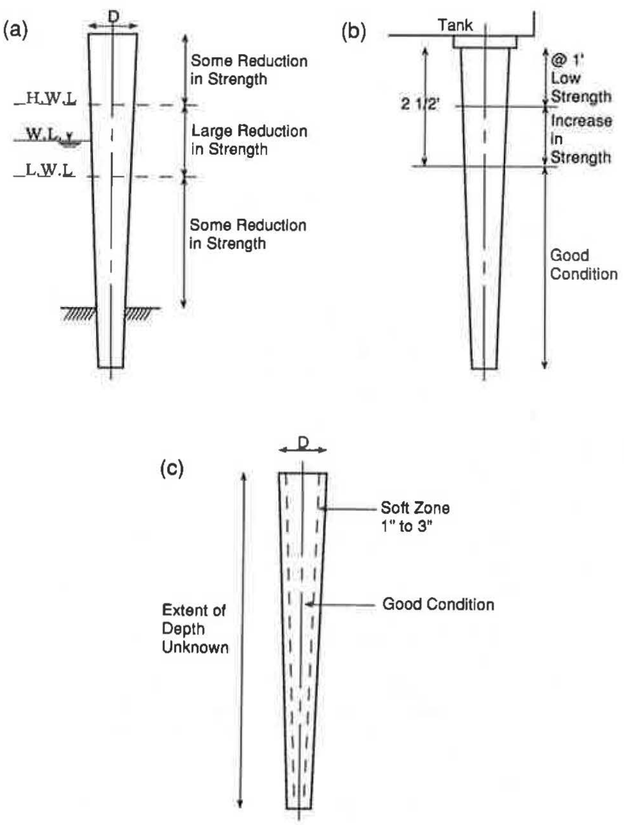

FIGURE 6 Types of deterioration of timber piles: (a) piles supporting bridges, (b) piles supporting tanks, and (c) piles supporting buildings.

center, surrounded by extensive internal decay with a shell of sound wood 2 to 3 in. thick remaining in the pile. In general, it was found that decay had occurred at the pitch of the section, whereas the treated outer ring was in better condition.

The recent failure of a bridge over the Pocomoke River in Maryland in 1988 illustrates the need for further research on the causes of deterioration of timber piles. The highway accident report from the National Transportation Safety Board (*23*) indicated that one of the causes of the failure was the continued effects of fungi, bacteria, aquatic insect larvae infestation (caddisflies), and tidal currents. These worked together to reduce the diameter of the submerged untreated timber piles by more than 2 in. in some of the piles.

Piles Supporting Tanks

Tanks that are used for storing hot asphalt are, in many instances, supported on timber piles. A study of five tanks indicated the following trend: for the top 1 ft, the pile had less than one-fourth the expected strength. For the next 1 to 1.5 ft, the strength improved markedly. Below a depth of 2.5 ft, the ultrasonic testing indicated that the pile was in good condition. Destructive testing was undertaken to verify the ultrasonic testing, and good correlations were obtained between the destructive and nondestructive measurements. The moisture content at the top section of the pile varied from 110 to 200 percent, and in some cases the dry unit weight was as low as 20 pcf. Most of the piles tested were treated Sitka spruce, except for one tank supported by yellow pine piles.

To perform the test, an excavation was undertaken to expose the piles. To minimize the amount of excavation, piles on the outside perimeter and occasionally piles in the second or third row were tested. The high temperature of the hot asphalt in the tank had caused damage to the tops of the piles (*24,25*). The length having a reduced strength, however, will depend on the temperature of the asphalt and the surrounding environmental conditions.

Piles Supporting Buildings

In this area again, limited data are available. From the data presented by Boutelje and Bravery (*4*) on the Stockholm building and from a similar situation in Boston (*26*), it can be stated that the peripheral zone of the piles becomes soft to a depth of 1 to 3 in. The soft zone had a very high moisture content and caused a marked loss in the strength of the pile.

A similar situation was encountered for piles supporting a building. In preparation for tests, excavation exposed the pile tops from 3 to about 10 ft below the cap bottom. Again, a soft zone that could be pealed was encountered under which was a much stronger material where ultrasonic readings were obtained. In the foregoing three cases, bacteria were the suspected cause of the deterioration.

SUMMARY AND CONCLUSIONS

Natural materials such as wood have inherent variances, and when the material is in service it is subjected to different elements that cause deterioration and, therefore, a change in strength. For this reason the prediction of their properties is much more difficult than for man-made materials. The paper discussed the testing method and data interpretation as well as factors that affect the testing, the conditions under which the method can be used, and its limitations.

The use of the technique for the evaluation of timber piles other than for bridges indicated the importance of understanding the conditions that lead to wood deterioration. The results of the field investigation and laboratory testing of bridge timber piles indicated the existence of two types of decay: uniform decay along the length of the piles (with a reduction in strength between 10 and 40 percent) and decay at the waterline or in the splash zone. The length of the decay in the splash zone was about 4 to 6 ft with a larger reduction in strength (up to 80 percent in one of the piles tested). In most cases a decayed or soft area was noted in the center, and the peripheral zone was in good condition. For the piles on the hot asphalt tanks the tops of the piles were soft, and for the buildings the peripheral zone was soft and the inside was in better condition.

An understanding of the causes of decay, the behavior of the ultrasonic technique, and its limitations is important for the successful inspection and evaluation of timber piles. Further research and data are needed to determine the condition of timber piles that have been in service for a long time. This is important for maintenance and replacement to meet current or anticipated loading demands and to aid in estimating the remaining service life of the structure.

ACKNOWLEDGMENTS

The research reported herein was sponsored by the Maryland State Highway Administration in cooperation with FHWA. The author is grateful to Earle S. Freedman, A. Scott Parrish, Jr., and E. J. White, Jr., of the Maryland Department of Transportation for their support and contributions. The manual and videotape were supported by FHWA. Appreciation goes to Thomas Krylowski for his comments and review.

REFERENCES

1. T. C. Scheffer, C. G. Duncan, and T. Wilkinson. Condition of Pine Piling Submerged 62 Years in River Water. *Wood Preserving*, Vol. 47, No. 1, 1969, pp. 22–24.
2. B. A. Bendtsen. Bending Strength and Stiffness of Bridge Piles After 85 Years in the Milwaukee River. Research Note FPL-0229. Forest Service, U.S. Department of Agriculture, Madison, Wis., 1974.
3. W. E. Eslyn and W. G. Moore. Bacteria and Accompanying Deterioration in River Pilings. *Material and Organismen*, Vol. 19, 1984, pp. 263–282.
4. J. B. Boutelje and A. F. Bravery. Observations on the Bacterial Attack of Piles Supporting a Stockholm Building. *J. Inst. Wood. Sci.*, Vol. 4, 1968, pp. 47–57.
5. A. P. Singh and J. A. Butcher. Wood Degrading Bacteria in Posts. *What's New in Forest Research*, No. 174, 1989.
6. I. D. G. Lee. Ultrasonic Pulse Velocity Testing Considered as a Safety Measure for Timber Structures. *Proc., 2nd Symposium of Nondestructive Testing of Wood*, Spokane, Wash., 1965, pp. 185–203.
7. L. C. Jensen. Sonic Detection of Internal Decay in Wood Poles. *Proc., 2nd Symposium on Nondestructive Testing of Wood*, Spokane, Wash., 1965 pp. 207–221.
8. R. A. Muenow. The Ultrasonic Nondestructive Evaluation of Wood Utility Poles, Wood and Concrete Railway Ties and Trestles, and Other Similar Structures. Technical Paper V-117. James Electronics, Inc., Chicago, Ill., 1966, pp 1–6.
9. K. A. McDonald, R. G. Cox, and E. H. Bulqrin. Locating Lumber Defects by Ultrasonics. Research Paper FPL 120. Forest Service, U.S. Department of Agriculture, Madison, Wis., 1969.
10. R. F. Pellerin. Nondestructive Testing of Wood—A Possible Method for Timber Piling. *Proc., 4th Nondestructive Testing of Wood Symposium*, Vancouver, Wash., 1978, pp 169–174.
11. J. J. Agi. Nondestructive Testing of Marine Piling. *Proc., 4th Nondestructive Testing of Wood Symposium*, Vancouver, Wash., 1978, p. 187.
12. M. D. Vanderbilt, J. R. Goodman, and J. A. Puckett. Testing of Large Timber Poles. Paper A-43. Present at Society for Experimental Stress Analysis Spring Meeting, San Francisco, Calif., 1979.
13. J . R. Goodman, M. D. Vanderbilt, M. E. Criswell, and J. Bodig. *Probability-Based Design of Transmission Line Structures: Vol. 1—Strength and Stiffness of Wood Utility Poles*. Report 2040. Electric Power Research Institute, 1981, 453 pp.
14. R. M. Lanius, Jr., R. Tichy, and W. M. Bulleit. Strength of Old Wood Joists. *Journal of the Structural Division*, ASCE, Vol. 107, No. ST12, 1981, pp. 2349–2363.
15. R. F. Pellerin, R. C. DeGroot, and G. R. Esenther. Nondestructive Stress Wave Measurement of Decay and Termite Attack in Experimental Units. *Proc., 5th Nondestructive Testing of Wood Symposium*, Pullman, Wash., 1985, pp. 319–352.
16. R. J. Hoyle, Jr., and P. S. Rutherford. *Stress Wave Inspection of Bridge Timbers and Decking*. Final report. Washington State Transportation Center, July 1987, 156 pp.
17. M. S. Aggour and A. Ragab. *Safety and Soundness of Submerged Timber Bridges Piling*. Interim Report FHWA/MD-82. Maryland Department of Transportation, June 1982, 421 pp.
18. M. S. Aggour, A. M. Ragab, and E. J. White, Jr. Determination of In-Place Timber Piling Strength. In *Transportation Research Record 962*, TRB, National Research Council, Washington, D.C., 1984, pp. 69–77.
19. M. S. Aggour, A. Hachichi, and M. A. Mayer. Nondestructive Evaluation of Timber Bridge Piles. *ASCE Special Publication on Evaluation and Upgrading of Wood Structures*. Structures Congress 86, New Orleans, La., Sept. 1986, pp. 82–95.
20. M. S. Aggour. *Safety and Soundness of Submerged Timber Bridge Piling*. Report FHWA/MD-87-08. Maryland Department of Transportation, Jan. 1987.
21. R. H. McCuen, M. S. Aggour, and B. M. Ayyub. Spacing for Accuracy in Ultrasonic Testing of Bridge Timber Piles. *Journal of Structural Engineering*, ASCE, Vol. 114, No. 12, Dec. 1988, pp. 2652–2668.
22. M. S. Aggour. *Inspection of Bridge Timber Piling, Operations and Analysis Manual*. Report FHWA-IP-89-017. FHWA, U.S. Department of Transportation, 1989.
23. *Highway Accident Report—Collapse of the S.R. 675 Bridge Spans over the Pocomoke River near Pocomoke City, Maryland, August 17, 1988*. PB89-916205, NTSB/HAR-89/04. National Transportation Safety Board, 1989.
24. The Forest Products Laboratory. *Wood Handbook*. USDA Agriculture Handbook 72, U.S. Government Printing Office, 1955.
25. W. L. James. Effects of Temperature and Moisture Content on Internal Friction and Speed of Sound in Douglas Fir. *Forest Products Journal*, Vol. 11, No. 9, 1961, pp. 383–390.
26. G. Kyanka. The Evaluation and Predicted Service of 19th Century Untreated Pilings in an Urban Environment. International Conference on Wood Poles and Piles, Fort Collins, Colo., 1989.