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INSPECTION OF BRIDGE TIMBER PILING

OPERATIONS AND ANALYSIS MANUAL

Research, Development, and Technology
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16. Abstract

A non-destructive method for determining the in-place strength of bridge timber piling above and below water, developed under the Maryland Highway Planning and Research Program, is presented. It is an ultrasonic wave propagation method in which the in-place strength (load carrying capacity) of a timber pile is correlated to the pile's wave velocity normal to the grain, and to its in-place unit weight.

This manual covers the information an inspector needs for field testing, as well as the information needed by engineers in the office for analysis and data interpretation. The manual includes a description of the equipment and instructions for its use. The kinds of data to be collected as well as data collection procedures are covered. This is followed by instructions for data analysis, accompanied by all figures needed for data interpretation. To ensure quality of performance, the factors that contribute to the repeatability and consistency of the results are presented. Factors that might cause inaccuracies in the results are also highlighted. The conditions under which the method can be used, its limitations, as well as any potential problems involving its use are also presented.

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CONVERSION FACTORS TO SI METRIC UNITS

Multiply	by	to obtain
inches (in)	0.0254	meters (m)
inches (in)	2.54	centimeters (cm)
inches (in)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
yards (yd)	0.9144	meters (m)
miles (mi)	1.609	kilometers (km)
degrees (°)	0.01745	radians (rad)
acres (acre)	0.4047	hectares (ha)
acre-feet (acre-ft)	1233.	cubic meters (m^3)
gallons (gal)	3.785×10^{-3}	cubic meters (m^3)
gallons (gal)	3.785	liters (l)
pounds (lb)	0.4536	kilograms (kg)
tons (2000 lb)	907.2	kilograms (kg)
pounds force (lbf)	4.448	newtons (N)
pounds per sq in (psi)	6895.	newtons per sq m (N/m^2)
pounds per sq ft (psf)	47.88	newtons per sq m (N/m^2)
foot-pounds (ft-lb)	1.356	joules (J)
horsepowers (hp)	746.	watt (W)
British thermal units (Btu)	1055.	joules (J)

Some Definitions

newton - force that will accelerate a 1 kg mass at 1 m/s^2
joule - work done by a force of 1 N moving through a displacement of 1 m
1 newton per sq m (N/m^2) = 1 pascal (Pa)
1 kilogram force (kgf) = 9.807 N
1 gravity acceleration (g) = 9.807 m/s^2
1 hectare (ha) = 10,000 m^2
1 kip (k) = 1000 lb = 4448 N = 453.6 kgf = 0.5 ton

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CHAPTER 1

INTRODUCTION

Federal and state legislation require periodic inspection and evaluation of highway and railroad bridges and a rating as to their safe load carrying capacity. This periodic inspection is necessary to ensure the early detection of damage or deterioration and to prevent structural failure. Inspection is also essential for an economical decision with regard to bridge replacement or rehabilitation.

1.1 Causes and Effects of Timber Pile Damage and Deterioration

Because of the organic composition of wood and the harsh environment in which they are usually located, timber bridge piles deteriorate. The principal causes of deterioration of piles in service are: bacteria, fungi, insect attack, fire, mechanical wear, and marine borers.

Bacteria are microscopic organisms that live anaerobically on organic material. It has generally been believed that timber piles completely submerged in fresh water possess immunity to biological degradation. This was based on the assumption that a lack of oxygen is a deterrent to attack by most micro-organisms, 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 may, like fungi, inactivate or destroy preservatives such as creosotes.

Most wood decay is caused by fungi. Wood will only decay when placed in conditions that are conducive to the growth and development of fungi. Essential to the survival and growth of fungi are moisture, oxygen, and mild temperatures. Decay damage occurs above water between high and low tide and near the pile cap.

There are several kinds of wood boring insects that will attack wood for food and shelter, and seriously affect its integrity. These include termites, wharfborers, and carpenter ants.

Wood consists of organic compounds composed mainly of carbon and hydrogen. For this reason, they are 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. The intensity of attack is generally much more severe in tropical than in temperate climates, but it also depends on the species of the borer, the salinity of the water, and the type of wood from which the pile is made.

It is to be expected that 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 - generally 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
- loss of cross-sectional area.

The extent and effect of this decay or loss in area is very difficult to assess visually. This is because the timber pile may be completely decayed internally while its external appearance may be perfectly normal.

1.2 Method of Inspection

Since the causes of deterioration are many and varied and the protective measures used to guard against this deterioration are no guarantee that deterioration will not occur, it is necessary to periodically inspect timber piles. Inspection is necessary to determine whether or not damage has occurred and to what extent. 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 any unsafe piles. There are two basic types of tests: destructive and nondestructive.

Destructive methods are those, as the name implies, that to some degree affect or destroy the structural integrity of the material tested. 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. Destructive testing may impose undue strain on the pile. It also implies that the specimens tested represent the entire population of potential samples. In testing natural materials such as wood, this implication is considered a major disadvantage. 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. The following represents a list of existing nondestructive methods: radiography, resonance, nuclear, X-ray, visual, soundings, and sonics. Radiography, resonance, nuclear, and X-ray inspection methods have all proven to be of value 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. A discussion of these methods is not included here.

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 the possibility that inspectors will misinterpret what they see.

Sounding is also a very simple method of testing in-place timber piles above water. Its use is limited to providing an initial indication of deterioration, to be followed by destructive methods. In this method the pile is systematically tapped with a hammer and the sound emitted is interpreted by the inspector who rates the pile.

Ultrasonic testing is a well established means of inspection for many kinds of materials, such as metals and concrete, and can be readily used underwater. Various nondestructive pulse measuring instruments have been developed to evaluate the soundness of timber structures in service. This is the basis for the method further described in this manual.

CHAPTER 2

PRINCIPLE OF ULTRASONIC TESTING AND PARAMETERS MEASURED

2.1 Principle of the Ultrasonic Testing

Ultrasonic waves are stress waves at frequencies above 20 KHz. Ultrasonic waves are termed elastic waves since it is the elastic property of the medium that is responsible for the sustained vibrations required for ultrasonic wave propagation. Ultrasonic techniques have become accepted methods for inspecting many kinds of materials. They can be used to determine either the quality of the material tested or the existence of internal defects. Stress-waves in the range of 20 to 100 KHz are utilized in the nondestructive testing of timber structures. It has been shown that undamaged wood is an excellent transmitter of these waves, whereas damaged and decayed wood slows down transmission.

2.1.1 Wave Equation for Timber Piles

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. The strength and elastic properties differ in these three directions. The major differences in these properties are in the directions longitudinal and normal to the grain; differences between the tangential and normal directions are relatively small.

The theory of elasticity assumes wood to be an orthotropic elastic material. It can be shown that the relationship between V_N, the velocity of wave propagation in the normal direction, and E_N, the elastic modulus in the normal direction, and ρ, the mass density of the material is

$$V_N = (E_N/\rho)^{1/2}$$

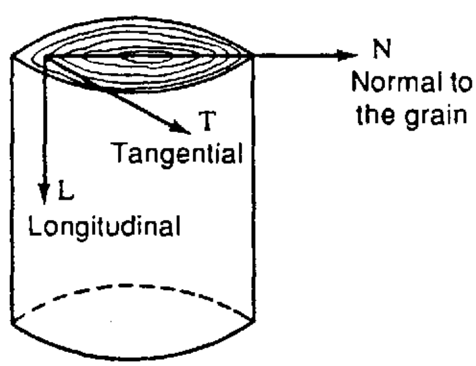

Figure 1. Timber Pile Axes of Symmetry

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It is therefore possible to calculate the elastic modulus of the material if the velocity of the stress wave and the mass density are known.

Ultrasonic testing therefore requires accurate measurements of the velocity of the propagation of the waves and the mass density of the material.

To assess the quality of wood from ultrasonic pulse velocity measurements, it is necessary for these measurements to be extremely accurate. This is accomplished by using equipment that generates pulses and accurately measures the time of the transmission through the specimen. The distance through which the pulse is propagated is also measured. The velocity can then be computed from these values.

2.1.2 Configuration of Transmission Arrangements

Three arrangements are possible when using ultrasonic equipment to measure the transit time of the wave, as shown in Figure 2. These are: a

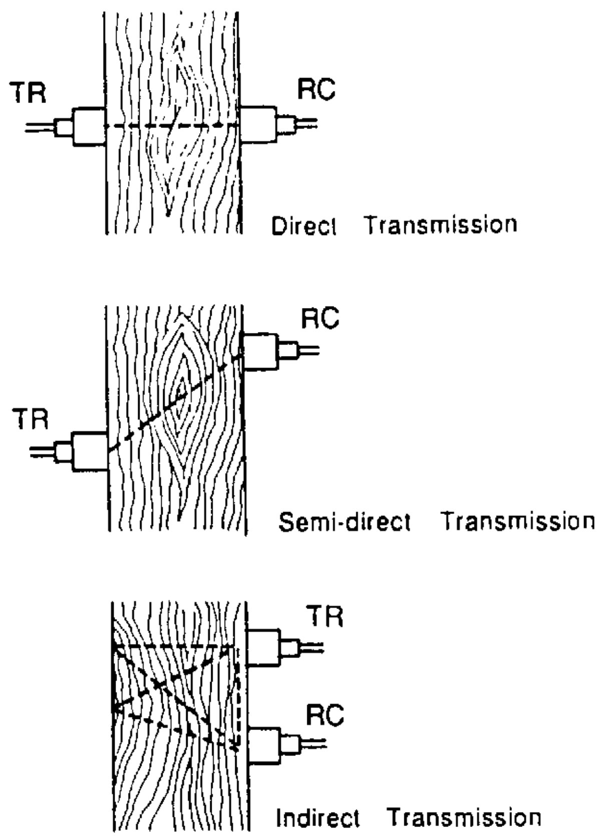

Figure 2. Possible Transmission Arrangements

direct transmission arrangement in which the transducers are facing each other across the section of the material tested; a semi-direct transmission where the two transducers are also across the section but at two 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 showed a higher velocity by 10% when compared to the tangential velocity. Wave velocity in the longitudinal direction was shown to be 2 to 3 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 2 to 3, but was a function of the unit weight of the wood. In fact, a decrease in the unit weight of the wood had a greater effect on the velocity normal to the grain than it did on the velocity longitudinal to the grain. This implies that the effect of decay is more pronounced in the wave velocity normal to the grain than in the direction longitudinal to the grain.

For this study, wave propagation in the normal direction was used. The reason for using the direct transmission is that it is more sensitive to detecting defects that are oriented perpendicularly to the pulse. As our objective was to determine the strength of the pile in service and since the strength is not uniform across the cross section of the pile, measurements in the normal direction are more representative of the section tested.

The direct arrangement also results in a maximum transfer of energy. The transducers are highly directional and the pulses propagated are mainly in the direction normal to the face of the transducers. The effective path length is well defined, being the distance between the faces of the transducers. For these reasons, the direct transmission mode was selected.

2.2 Parameters to be Measured

The wave velocity is needed to characterize the condition of the pile in-situ. The velocity is obtained by dividing the path length by the transit time. These parameters can be measured with sufficient accuracy, provided care is taken when conducting the tests.

2.2.1 Transit Time

The transit time T, is obtained by holding the transducers to the pile to be tested. The time is displayed and recorded at each section along the pile length.

2.2.2 Path Length

The distance between the two faces of the transducers D (path length), can be calculated by using the relationship, $D = \text{circumference}/\pi$ where the circumference is measured with a tape. D can be measured directly using the scissors or the framework (See Appendix B).

2.2.3 Velocity Calculation

The time and path length measurements are made at regular dept intervals along the timber pile during inspection. The velocity is given by

$$V_N = \frac{D}{T} \times \frac{1}{12} \text{ (ft/sec)}$$

where

V_N - wave propagation velocity (ft/sec)
D - path length (in.)
T - transit time (sec.) (usually in microseconds).

Example:

Time - 280 microseconds
Diameter - 12 in.

$$V_N = \frac{1}{12 \text{ in/ft}} \times \frac{12 \text{ in}}{280\text{x}10^{-6} \text{ sec}} = 3570 \text{ ft/sec}$$

CHAPTER 3

ULTRASONIC EQUIPMENT AND FACTORS AFFECTING ITS OPERATION

3.1 Ultrasonic Equipment

The equipment used is a commercial testing apparatus consisting of a portable ultrasonic digital read-out meter, and two lead zirconate titanate ceramic transducers each mounted in a stainless steel case and having a frequency of 54 KHz. The pulse repetition frequency is 10 pulse/sec; therefore interference from previous pulses is negligible. In addition, two coaxial cables, and a reference bar used to calibrate the instrument are included, as shown in Figure 3. The transducers connected by the cables to the read-out meter during the operation are devices that convert electrical energy to mechanical energy. The transmitting transducer capacitance is first charged to a high voltage and then discharged, which causes the transducer to vibrate at its own frequency of 54 KHz. The ultrasonic pulse generated is converted to an electrical signal in the receiving transducer. The transit time for the signal to pass from one transducer to the other is obtained from the read-out meter.

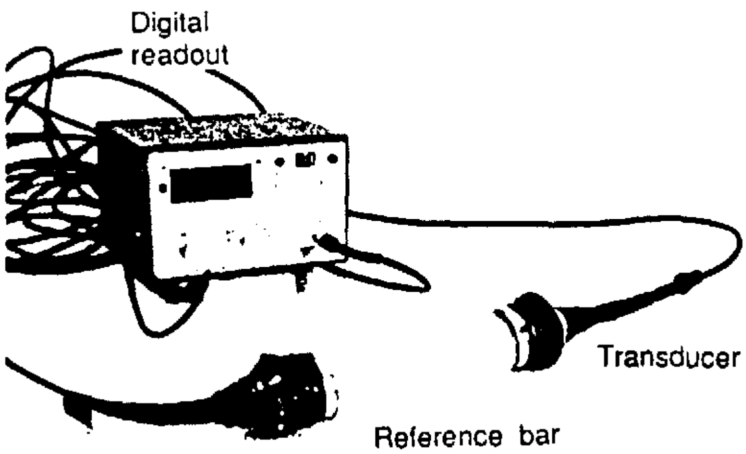

Figure 3. Ultrasonic Equipment and Reference Bar

In summary, pulses generated by one of the transducers are passed through the test specimen and picked up by the receiving transducer that transforms these mechanical pulses back into electrical pulses. The time measuring circuit then displays the transit time between the transducers.

3.2 Factors Affecting the Equipment

a. Surface preparation

The surface of the pile (above and below water) must be cleaned of foreign material to obtain a smooth surface at the location(s) where tests are to be conducted. A stiff wire brush is an ideal tool for this. When this does not work the pile surface should be scraped.

b. Calibration of equipment

The equipment is calibrated to set it to zero each time it is used. A reference bar is provided with the equipment to check the reference zero. A couplant such as a high vacuum grease is applied to the transducers before placing them on the opposite ends of the bar, the set reference control is adjusted until the reference bar transit time (engraved on the bar) is obtained on the read-out meter. An hourly check is recommended.

c. Application of couplant

Air free contact is necessary between the transducer and the surface of the pile in order to transmit the ultrasonic energy. Any air contact will attenuate the incident energy. A high vacuum grease (silicon based, available from chemical supply stores) should be used as a couplant. Couplants must be used in all testing above water. Since water is an excellent couplant there is no need for additional couplant when testing underwater.

d. Operator consistency

Consistent and reliable results are obtained when the transducers are held firmly to the test specimen. When light pressure is applied, great discrepancies occur. Therefore adequate care must be taken to ensure that the pressure applied through the transducers is constant and consistent when taking transit time measurements. When a reading becomes constant (the last digit will either remain the same or will oscillate between two adjacent values), a reliable result has been obtained.

e. Coaxial cables

The cables connecting the transducers have to be carefully separated when the instrument is in use. This is to prevent cross noise signals from the transmitting lead being picked up by the receiving lead, which results in inaccurate measurements.

f. Voltage supply

The power for the ultrasonic equipment may be supplied by its own battery or from a 115 volt power supply. The equipment works best when used from a power source of 115 volts. An onsite AC generator can supply this power. When operated from a battery care must be taken to ensure that the battery is properly charged (see manufacturer's specifications).

CHAPTER 4

FIELD CONSIDERATIONS AND INSPECTION PROCEDURES

The ultrasonic inspection procedure requires advanced planning to help minimize confusion and costly delay when used in the field. The following are practical preliminary considerations followed by a procedure to use for a successful field test.

4.1 Pre-Inspection Survey

The bridge to be inspected must be surveyed in advance to establish how deep the piles are submerged and to obtain a visual record of the condition of the piles and their surrounding environment. At this stage, the piles are identified and marked. The relative locations of piles to be tested are noted in a log in the order in which the tests are to be conducted.

The type of bracing between the piles, and the clearance between the water level and the top of the piles should be documented at this stage. This will enable the inspector to determine the best way to conduct the inspection: from the top of the bridge, from a boat, with or without a diver.

In the event that any foreign material is on the piles, it will be necessary to clean the piles at test locations before the inspection.

The pre-inspection survey should be performed by an inspector who is familiar with the ultrasonic inspection method.

4.2 Procedure for Ultrasonic Pile Test

Since tests will be conducted near water, local safety regulations may require additional personnel for safe operations.

4.2.1 Inspection Above Water

a. Personnel

A technician trained in using the ultrasonic method and equipment, and an assistant.

b. Equipment

1. An ultrasonic pulse generator, transducers, and electrical cables
2. Power source
3. Scissors and framework (see Appendix B)
4. Couplant
5. Wire brush, scraper, etc.
6. Ladder, boat, etc.
7. Pole climbing spurs and safety harnesses
8. Data recording forms.

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c. Testing procedure

1. Prepare surface: Pile surface is cleaned of foreign material (and if possible made smooth) at the location(s) along the pile length where tests are to be conducted. A stiff wire brush is an ideal tool for this.

2. Calibrate ultrasonic equipment: Check zero by placing a transducer at each end of the calibration bar using a grease couplant. The equipment is calibrated when it constantly reads the number engraved on the bar.

3. Apply couplant: Air free contact between the face of the transducers and the surfce of the pile is necessary. An air gap will attenuate the ultrasonic waves and produce distorted or incorrect readings. For tests above water a couplant is applied to the transducer surfaces to ensure solid contact between transducers and piles. It has been found that a silicon based, high vacuum grease is very satisfactory and easy to use.

4. Position transducers: The transducers are pressed firmly on to the surface of the pile. It is important to position the transducers directly opposite each other on the pile section before the reading is taken. Slightly reposition the transducers (up or down) to obtain the minimum time measurement. If the location is inconvenient, the scissors can be used to hold the transducers.

5. Measure path length: Measurements are taken and recorded. One can use either a tape to measure the circumference or make a direct reading with the equipment shown in Appendix B.

6. Reposition transducers: The transducer locations are rotated diametrically around the section as shown in Figure 4. For testing reliability two or three readings in different directions should be taken. The lowest transit time for that section or the average is used to compute the wave velocity (see Chapter 6).

7. Repeat tests: Steps (3) through (6) are repeated along the length of the pile at different levels, as shown in Figure 5.

8. Evaluate measurements: Time measurements from steps (4) through (7) are evaluated to see if they make sense. If necessary, steps (6) and (7) are repeated until consistent results are obtained. Figure 6 shows an example of a blank data form, and Figure 7 an example of a completed form.

9. Calculate: Calculate the crushing strength of the pile at each section tested using the equation presented in Chapter 5.

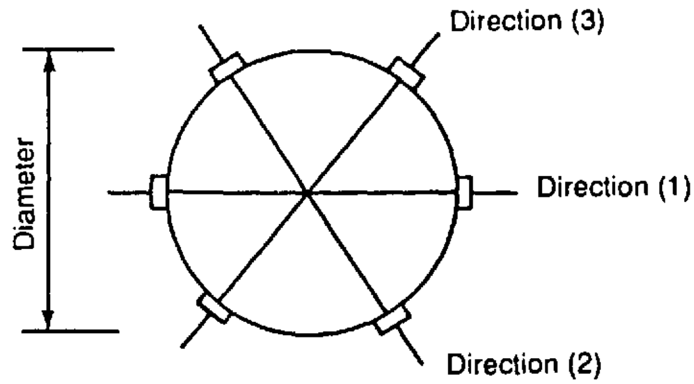

Figure 4. Cross Section of the Pile Showing Different Directions of Readings

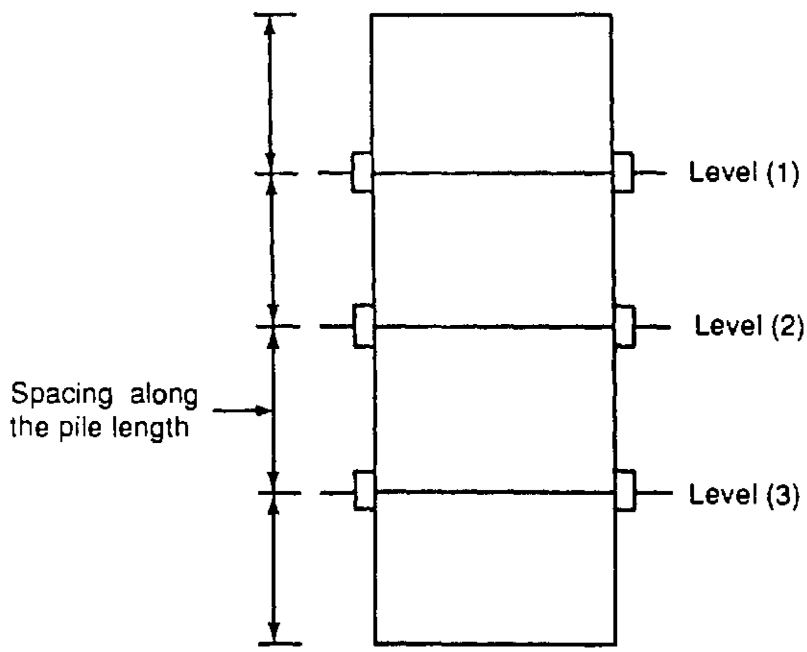

Figure 5. Locations of the Transducers Along the Pile Length

ULTRASONIC TESTING DATA FORM

Bridge Name and Number : ______________________

Date : ______________ Tested by : ______________

Bent No : ______________ Length of Pile above mudline : ______________

Pile No : ______________ Length of Pile above water : ______________

Notes : ______________________

____

Test No.	Depth from Top	Average Diameter	Travel Time Normal to Grain (μ sec)		Velocity
			Direction (1)	Direction (2)	

Figure 6. Example of Data Form

ULTRASONIC TESTING DATA FORM

Bridge Name and Number : ______________________

Date : ____________ Tested by : ____________

Bent No : ____________ Length of Pile above mudline : ____________

Pile No : ____________ Length of Pile above water : ____________

Notes : ______________________

____

Test No.	Depth from Top	Average Diameter	Travel Time Normal to Grain (μ sec)		Velocity ft / sec
			Direction (1)	Direction (2)	
1	1'	10"	146	155	5540
2	2'	10"	151	148	5570
3	3'	9.5"	146	145	5440
—	3.5' —	Water	Level —	—	—
4	4'	9.5"	165	160	4870
5	5'	9.0"	162	170	4520
6	6'	9.0"	178	172	4280

Figure 7. Example of Completed Data Form

4.2.2 Inspection Below Water

The procedure is similar to that above water, with the exceptions discussed below.

a. Personnel

A technician trained in using the ultrasonic method and equipment, and an assistant (capable of diving if measurements more than three feet below water are taken).

b. Additional equipment

1. Use either special underwater transducers or wrap transducers used above water in a water-tight sealant to guard against damage due to moisture. Experience has shown that RTV silicone rubber is a good sealant.

2. Diving equipment (if depth is over three feet).

c. Testing procedure

1. Prepare surface: Pile surface should be cleaned as it was for tests above water. Foreign material must be removed from the piling at test locations before performing the inspection. Underwater growth can be removed with hand tools such as a chipping hammer or with scrapers.

2. Calibrate ultrasonic equipment: Same as for above water.

3. Apply couplant: There is no need to use a couplant underwater since water is an excellent couplant.

4. Position transducers: For underwater testing, it is most efficient to use a diver with a portable air supply. The diver holds the transducers, moves along the pile, and at each level presses the transducers to the pile. Should direct communication between the diver and inspector not be available a rope attached to the diver's wrist is pulled to indicate that a reading has been taken. The diver then proceeds to the next level and so on. At the bottom of the pile the diver rotates the location of the transducer 90° and comes up the pile, again in steps, taking a reading at each step.

5. Measure path length: Measurements using the framework are then made by the diver and relayed to the inspector.

6. Repeat tests: If necessary, repeat the steps until consistent results are obtained.

7. Calculate: Calculate the crushing strength of the pile at each level tested using the equation presented in Chapter 5.

CHAPTER 5

INTERPRETATION OF DATA TO DETERMINE PILE CONDITION

Data obtained from the tests are used to characterize the condition of the timber piles in service. The equations used in this chapter were obtained by correlating (1) the velocity of the ultrasonic wave in the pile sections; (2) strength values from compression tests conducted on the same sections; and (3) unit weight. Relationships were developed that can be used to establish the strength of bridge timber piling in place if both the wave velocity and unit weight (described later) 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. For this reason 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 eleven 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. The unit weights were calculated prior to the compression tests.

5.1 Pile Condition Rating

a. 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. This data can be used to determine the condition of piles in service.

b. 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. Since it is difficult to determine the unit weight by nondestructive means, the condition of the pile can be based only on the wave velocity, which can be easily obtained. The criteria in Table 2 were developed to classify the condition of the piles based only on wave velocity for dry treated yellow southern pine.

Using the criteria, a velocity of less than 3000 ft/sec indicates that the pile is in poor condition. This generally indicates that the center of the pile is rotten. When no reading is obtained the pile probably has a large internal decayed area.

The criteria presented in Table 2 are only an estimate. Caution should be excersised in using this information alone, without consideration of the unit weight (as discussed in Chapter 7).

TABLE 1 - Average Values Of the Compressive Strength, Wave Velocity, and Unit Weight for Section 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

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	very good
3500 - 4000	average
3000 - 3500	questionable
less than 3000	poor

5.2 Strength Determination for Testing Above Water

a. Dry, new treated sections

For new treated sections of yellow pine (and for a velocity of approximately 4500 ft/sec and higher) the compressive strength of a timber pile can be predicted by using a multi-variable 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 based on the results of the experimental tests is:

$$\sigma_{cr} = 0.535\ V_N + 41.35\ \gamma \qquad (5.1)$$

where

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

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

b. Moist, old treated sections (for sections of piles under water)

For moist (moisture content close to the fiber saturation point, about 30%) and old treated sections, (wave velocity from 3000 ft/sec up to 4500 ft/sec) the following model can be used:

$$\sigma_{cr} = 0.537\ V_N + 6.34\ \gamma \qquad (5.2)$$

c. Dry, old treated sections

For dry and old treated sections, (wave velocity from 3000 ft/sec up to 4500 ft/sec) the following model can be used:

$$\sigma_{cr} = 0.292\ V_N + 46\ \gamma \qquad (5.3)$$

d. Dry, very decayed treated sections

For dry and very decayed sections, (wave velocity less than 3000 ft/sec) the following model can be used:

$$\sigma_{cr} = 0.127\ V_N + 40\ \gamma \qquad (5.4)$$

5.3 Strength Determination for Testing Below Water

It is known that as the moisture content increases, the velocity decreases and the unit weight increases. Several sections from different piles were tested dry 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. These sections were tested under water over a period of several months at which time the velocity reading became constant. From these measurements a correction factor (CF) was developed. The correction factor from Figure 8 can be used to determine the velocity through the wood in air dry condition if the velocity under water is known, or vice versa. As can be

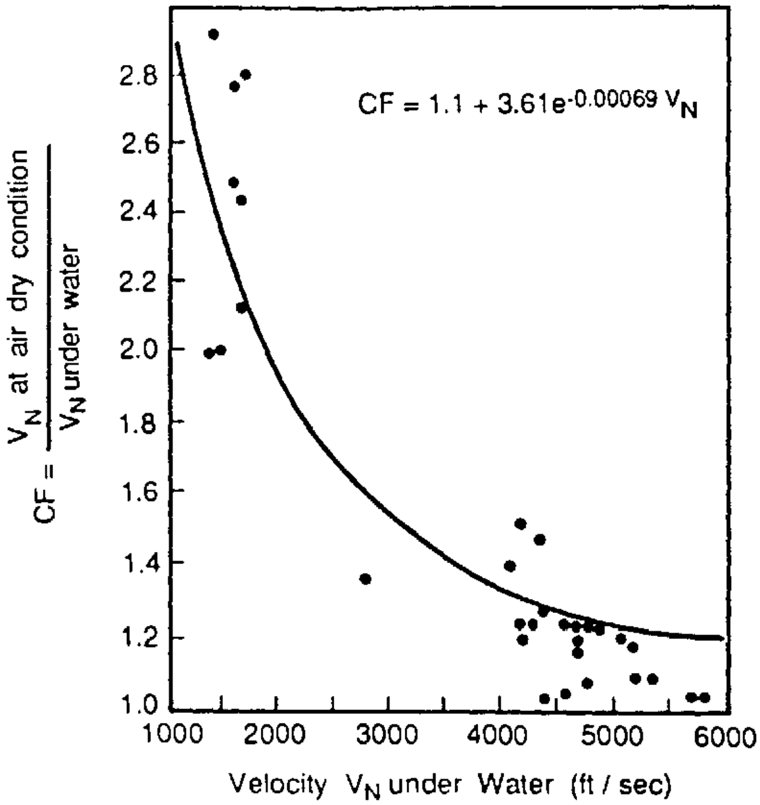

Figure 8. Correction Factor as a Function of V_N Under Water

seen for piles in good condition (new) the factor varies from approximately 1.1 to 1.2. The factor increases with the reduction in the wave velocity. For underwater tests, the measured velocity should be multiplied by the factor (CF) to obtain the velocity at air dry condition. Knowing the velocity at air dry condition, equations 5.1, 5.3, and 5.4 can then be used.

Two sets of sections were prepared from 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 set at wet condition. It was found that the crushing strength of the sections at air dry condition is 1.48 times that of the sections at wet condition, i.e., a pile under water loses about 32 percent of its strength.

5.4 Determination of the In-place Unit Weight

In order 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.

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 piles in service, a convenient method is to use small cores that are 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, it is possible to determine an approximate value for the unit weight from knowledge of the wave velocity. Naturally, the use of such approximate relationships will reduce the accuracy of the strength computed. The following are approximate unit weight equations using the ultrasonic method.

a. Moist treated piles

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

$$V_N = 7845 - 67\gamma \qquad (5.5)$$

where

V_N = wave velocity normal to the grain (ft/sec)
γ = 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 3500 ft/sec to 5500 ft/sec, as shown in Figure 9. For velocities below 3500 ft/sec and above 5500 ft/sec it is recommended that a constant value of unit weight equal to 65 pcf and 35 pcf respectively be used.

b. Dry treated piles

The unit weight of dry sections were plotted versus the wave velocity normal to the grain as shown in Figure 10.

In order to predict an approximate value of the unit weight of a dry treated pile, for a wave velocity of V_N of 4000 and higher, use the approximate linear relationship

$$V_N = 250\gamma - 4750 \qquad (5.6)$$

For a velocity less than 4000 ft/sec, use the approximate relationship

$$V_N = 156\gamma - 1460 \qquad (5.7)$$

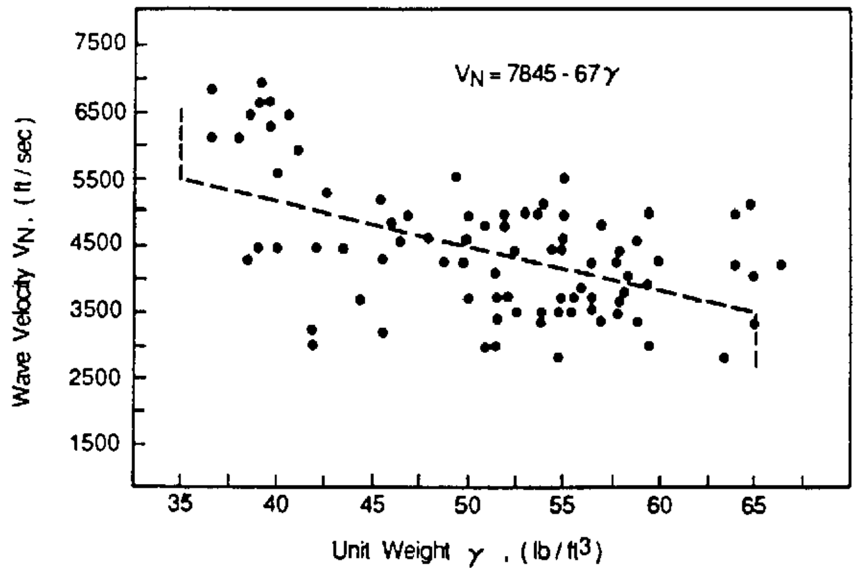

Figure 9. Average Relationship Between Wave Velocity and Moist Unit Weight

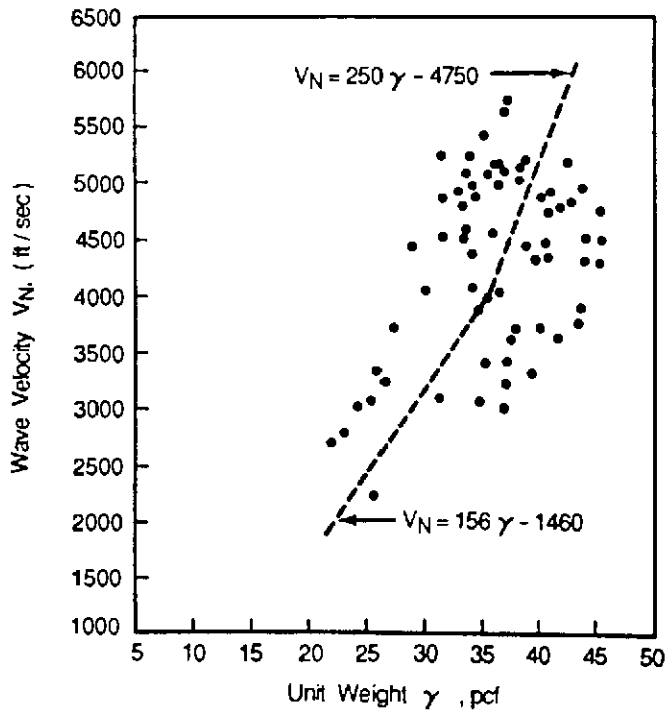

Figure 10. Average Relationship Between Wave Velocity and Dry Unit Weight

5.5 Stiffness Determination

To evaluate the load carrying capacity of a pile, the greatest need is for procedures to predict its in-place existing strength. Stiffness is also important because the deformation and vibrational characteristics of the pile, and hence the bridge, are a function of the modulus of the pile. Both the modulus and the deteriorated length of the pile (relative to its total length) were shown to have a significant effect on the pile's behavior. To determine its modulus use the following relationship developed from experimental data for dry in-service treated piles:

$$E_L = 0.0465\ V_N^{1.232} \tag{5.8}$$

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.

5.6 Examples

In this section, numerical examples are presented to show how to use the equations to determine the remaining compressive strength of an in-service pile.

Example 1. New section

A pile section has a diameter D of 12.0 in, the average time reading T using the V-meter is 166 microseconds, and the material unit weight = 40 pcf, what is the compressive strength of this pile section?

Solution:

Step 1: Determine the wave velocity.

$$V_N = \frac{D}{T} = \frac{12/12}{166\times10^{-6}} = 6024 \text{ ft/sec}$$

Step 2: Determine the compressive strength from equation 5.1.

$$\sigma_{cr} = 0.535\ V_N + 41.35\ \gamma$$

$$= 0.535 \times 6024 + 41.35 \times 40$$

$$= 4877 \text{ psi}$$

Example 2. Section of treated pile tested above the water line

If the velocity measured normal to the grain $V_N = 4000$ ft/sec, find the compressive strength.

Solution:

Step 1: Determine the approximate unit weight of the section tested. Use equation 5.6 (dry).

$$\gamma = \frac{1}{250}(V_N + 4750) = \frac{1}{250}(4000 + 4750) = 35 \text{ pcf}$$

Step 2: Determine the compressive strength from equation 5.3.

$$\sigma_{cr} = 0.292\ V_N + 46\ \gamma$$

$$= 0.292 \times 4000 + 46 \times 35$$

$$= 2778 \text{ psi}$$

If the section was assumed to be moist, use equation 5.5.

$$\gamma = \frac{1}{67}(7845 - V_N) = \frac{1}{67}(7845 - 4000) = 57.4 \quad \text{pcf}$$

then the compressive strength will be: (equation 5.2)

$$\sigma_{cr} = 0.537\ V_N + 6.34\ \gamma$$

$$= 0.537 \times 4000 + 6.34 \times 57.4$$

$$= 2512 \text{ psi}$$

The values are close for assuming either dry or moist conditions. Thus for sections above water where it is not known if the section is moist or dry either assumption will be acceptable.

Example 3. Section of treated pile tested below water

If the velocity measured in water V_N = 1500 ft/sec, find the compressive strength.

Solution:

Step 1: Determine the equivalent velocity measured in air.

$$V_N(\text{in air}) = CF \times V_N(\text{in water})$$

where CF is the correction factor.

For V_N(in water) = 1500 ft/sec, the correction factor

CF = 2.38 from Figure 8. Thus,

$$V_N(\text{in air}) = 2.38 \times 1500 = 3570 \text{ ft/sec}$$

Step 2: Determine the dry unit weight from equation 5.7.

$$\gamma = \frac{1}{156}(V_N + 1460) = \frac{1}{156}(3570 + 1460) = 32.2 \text{ pcf}$$

Step 3: Determine the compressive strength using equation 5.3.

$$\sigma_{cr} = 0.292\ V_N + 46\ \gamma$$

$$= 0.292 \times 3570 + 46 \times 32.2$$

= 2524 psi

Example 4. Section of dry and decayed pile

If the velocity measured V_N = 2500 ft/sec, find the compressive strength.

Solution:

Step 1: Determine the unit weight of the section tested.

Since the section is dry use equation 5.7

$$\gamma = \frac{1}{156}(V_N + 1460) = \frac{1}{156}(2500 + 1460) = 25.4 \text{ pcf}$$

Step 2: Determine the compressive strength using equation 5.4

$$\sigma_{cr} = 0.127\ V_N + 40\ \gamma$$

$$= 0.127 \times 2500 + 40 \times 25.4$$

$$= 1334 \text{ psi}$$

CHAPTER 6

CONSIDERATIONS IN ASSESSING PILE CONDITION

Several factors affect an accurate assessment of bridge piling using the ultrasonic method that should be considered in planning the tests and gathering the data. These include the number of tests needed at an elevation, the effect of a crack on transit time measurements, spacing requirements versus desired accuracy and the number of piles to be tested.

6.1 Number of Tests Needed at an Elevation

The area tested using this method is a function of the diameter of the pile and the diameter of the transducer. The transducers used in this work have a diameter of 2 inches. The area not tested consists of several wedges, as shown in Figures 11 and 12. The area of one of these wedges represents an area of possible undetected decay. Figure 13 shows the relationship between the untested area of a pile section as a function of the number of measurements made for piles with diameters of 10 and 12 in. After two measurements, four wedges each 14 percent of the total pile area remain untested; and after three measurements, six untested wedges, each approximately equal to 6.5 percent of the total area remain.

Therefore, two readings taken normal to each other at the same elevation, are the minimum number of measurements that should be made if reliable data is to be collected.

6.2 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 fifty tests. Variances up to plus or minus 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:

1. the longer of the two readings passed through a "pocket" of decay not encountered by the other reading;

2. the longer of the two readings travelled around the periphery of a natural flaw, such as a crack filled with air (such as when shakes are present);

3. a combination of the above.

Inspection of decayed piles shows that decay almost always starts at the center of a pile and then radiates outward as it advances. The decay, therefore, can almost always be detected since all transmitted waves travel through the center of the pile. In some piles, however, it was observed that the decay was not located in the center. Based on the information presented in Section 6.1 this decay will probably be detected.

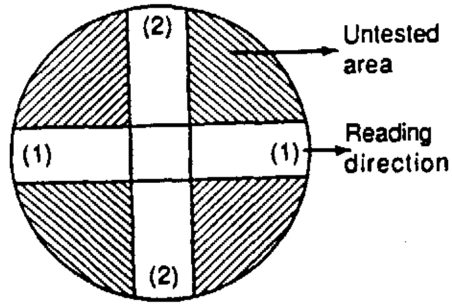

Figure 11. Cross Section Tested Two Times, Shaded Areas Represent Untested Wedges

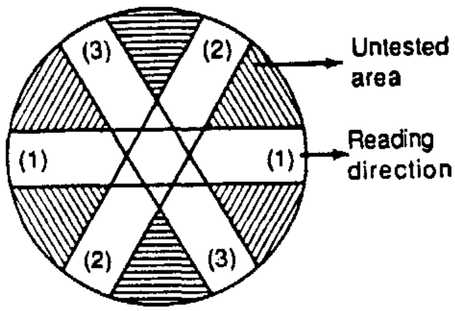

Figure 12. Cross Section Tested Three Times, Shaded Areas Represent Untested Wedges

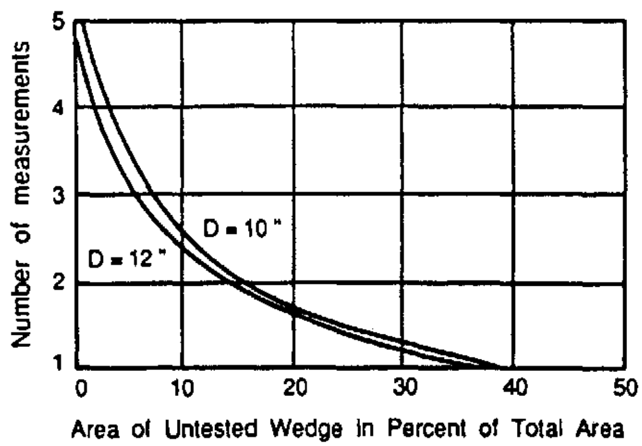

Figure 13. Effect of the Number of Measurements on the Area of the Untested Wedge

To study the effect of naturally occurring cracks in wood, transit time readings were taken along the length of two smooth wood sections separated only by spacers. It was found that the transit time increased as the width of the gap increased. A gap of 0.1 in. reduced the velocity an average of 28%. Therefore, a narrow crack can considerably affect the velocity.

From tests performed on dry timber piles with and without decay it was found that wood with decay exhibits a wave velocity V_N less than 3500 ft/sec, and wood without decay a velocity greater than 4500 ft/sec. Also, wood without decay has a unit weight greater than 30 pcf, whereas wood with decay has a unit weight less than 30 pcf. Thus, in pile sections free of knots (since knots change the homogenity of a section), readings taken at the same section in a pile indicating an increase in transit time are suspect.

Using this information the validity of the transit time readings may be evaluated.

Consider a pile section of yellow pine 10 in. in diameter that was tested ultrasonically. The first reading was 180 microseconds, this gives: V_N = 4630 ft/sec. From equation 5.6, γ = 38 pcf and from equation 5.1, σ_{cr} = 4048 psi. This data indicates decay is not present in this pile.

Say a second reading is 270 microseconds, 50 percent higher than the first reading, this leads to: V_N = 3086 ft/sec. From equation 5.7, γ = 29 pcf and from equation 5.3, σ_{cr} = 2235 psi. This data, by itself, would indicate decay is present, but from the first reading, this is not possible. The second reading was most likely affected by a crack in the pile. A third reading should be taken and the 270 microseconds reading discarded. (Small cracks inside the pile will affect the velocity of the wave but will not affect the strength of the pile.)

However, if two readings of 300 and 400 microseconds are obtained, the density is now estimated at 27.2 and 22.7 pcf respectively. Because each of these numbers is low, decay can be expected. The second reading may indicate a crack in addition to decay or an extra pocket of decay. The crushing strength of the pile is 1440 psi using T = 300 microseconds, and 1173 psi using T = 400 microseconds.

Either result indicates a marked reduction in the strength of the pile. The accuracy of the transit time reading <u>in this case</u> is purely academic.

When testing below water, the effect of such cracks will be negligible since waves are transmitted across cracks filled with water.

6.3 Spacing Requirements for Desired Accuracy

Transit time readings should be taken at regular depth intervals. A one foot interval along the pile, up to four feet above and below the waterline, and a three foot interval elsewhere, were found to be adequate. Extra readings should be taken at intermediate points when needed, to locate where the decay ends. 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 in References 5 and 6.

6.4 Number of Piles To Be Tested

Whenever possible all piles under a bridge should be tested. Experience to date has not indicated a pattern of decay among the piles on any one bridge.

CHAPTER 7

CONSIDERATIONS IN USING THE ULTRASONIC METHOD

In ultrasonic testing, several considerations should be clear to both the engineer and the inspector to obtain reliable and repeatable results.

7.1 Conditions Under Which The Method Can Be Used

7.1.1 Marine Environments

The procedure described is used to assess the strength of bridge timber piling, in place, above and below water. It is suitable for piles that are immersed in water for long periods of time and sustain damage to the wood microstructure, such as the Denton Bridge that collapsed in Maryland in 1976. This type of damage can reduce pile load carrying capacity by changing material parameters such as strength and density.

At a certain temperature and degree of salinity a variety of marine borers invade timber piles and cause a loss in wood surface area, or erode away the interior of the pile. The two main types of marine borers are Limnoria and Teredo. Limnoria can attack treated piles and cause damage to the surface of the pile. Visual inspection is sufficient to determine the extent of the damage. Teredo borers can attack untreated piles and damage the interior of the pile. This type of damage is difficult to determine visually.

The method is valid in fresh water and in marine environments in the absence of marine borers. If the user knows there are marine borers, or is not sure, caution must be taken in interpreting the readings. Small holes caused by marine borers can cause confusion in interpreting the data.

7.1.2 Material Other Than Southern Pine

Most of the tests conducted to establish a data bank for new and in-service piles were on southern yellow pine. This is the main type of timber pile found in Maryland. Readings were taken at cross sections free of visible knots.

It is important to know what species of timber is being inspected. 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 in such a case, to determine the species of the pile.

7.2 Limitations

- 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 from the wave velocity. The strength of the pile is then computed based on this information. The wave velocity is the only parameter actually measured to predict the strength. While acceptable, such a situation reduces 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 ease with which the data is collected.

- To determine the loss of strength in a pile, both the original strength and the strength in-place 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 a local property variation within the length of the pile.

- Criteria for rehabilitation of timber bridge piles is quite different than for other wood structures. The method of repair is determined by the degree to which the pile is damaged. Strength is usually restored to timber piles when a pile has lost 20% to 50% of its cross-sectional area. This is accomplished by using such methods as concrete jackets and PVC wraps. When 50% or more of the cross-sectional area has been damaged, replace the pile. A degree of accuracy of ± 20% should be sufficient in determining strength. This low degree of accuracy may be sufficient for inspecting timber piles but such criteria may not be sufficient for other wood structures.

Prior to replacing the piles, it is recommended that cores be taken to identify the species and check for defects and deterioration.

- Because it is difficult to determine moisture conditions in the field, and since wave velocity is a function of moisture content, wave velocities will be more accurate when they are obtained in the dry condition (for testing above water).

7.3 Potential Problems

- When testing dry sections, voids or cracks are easily identified by a sharp decrease in velocity. The pulse that arrives at the receiving transducers will have diffracted around the periphery of the defect increasing the transit time. If the defect is large enough the sound energy will be so severely attenuated from reflection, refraction, diffraction, and scattering that it will not be detected by the receiving transducers. For this case no readings are obtained. When timber is moist, the situation can become worse, since moisture will also attenuate the signal. In some cases amplifiers were used to help ensure that the sound energy could be detected by the receiving transducers.

- Sometimes during a test, large variations in transist time readings occur. The inspector, in such cases, should continue to hold the transducers in place until a constant, stable reading appears.

- It is essential that the transducers make good contact with the surface of the pile, are aligned horizontally, and remain steady while a reading is taken. To depart from these conditions will affect the velocity that is computed and subsequently the accuracy of the results.

7.4 General Considerations

- Ultrasonic and compressive tests on sections cut from piles from different bridges were obtained along the length of the piles. The results indicated the existence of two types of decay: uniform decay along the length of the pile (with a reduction in strength between 10 to 40%); and decay at the water line or in the splash zone. The length of the decay in the splash zone was found to be about 4 ft to 6 ft with a larger reduction in strength (up to 80% in one of the piles tested).

- It has been demonstrated that different personnel with adequate knowledge of the equipment and the technique can produce practically the same results. It is advantageous for the inspector to understand the conditions under which decay exists and how to recognize it visually. The inspector should also understand the ultrasonic method to be able to recognize when the readings obtained make sense. In general, it is necessary to repeat readings to obtain consistent results.

- Underwater inspection should be scheduled during that period of the year when conditions are most favorable, such as periods of low tide or optimum under water visibility.

- To estimate the severity of the deterioration of a pile, a visual inspection supplemented by a depth of penetration device may be sufficient. If the load carrying capacity of a pile in-place is required, use the ultrasonic method.

- An inspection procedure used to determine if damage is occurring or has occurred in timber bridge piles has been presented. The information is used to predict the load carrying capacity of the pile. It can also provide information on which to base a maintenance plan to meet the current or anticipated need for rehabilitation or replacement of the piles, and aid in estimating the remaining service life of the bridge.

- A video tape demonstrating the use of the ultrasonic method and equipment under various conditions has been prepared and is available from the Federal Highway Administration.

GLOSSARY

Anaerobic - Able to live and grow without air or free oxygen.
Cellulose - Chief substance composing the cell walls or woody part of plants.
Enzymatic Degradation - Degradation caused by organic substances produced in plants that cause changes by catalytic action.
Lignin - An organic substance closely allied to cellulose.
Mass Density - Mass per unit volume.
Microsecond - 10^{-6} seconds.
Shake - A situation where the wood fibers separate in a radial mode.
Splash Zone - Zone between the low and high water marks.
Unit Weight - Weight per unit volume.

APPENDIX A

DEVELOPMENT OF THE INSPECTION PROCEDURE

Despite an underwater inspection of the piling one year earlier, a bridge supported by timber piles failed at Denton, Maryland, in 1976. The underwater inspection had indicated that the piles were reasonably sound. After the failure, laboratory tests on piles recovered by the State Highway Department indicated that while there was no loss in cross-sectional area, the material strength of the pile had been significantly reduced. These deficiencies went undetected by the inspection techniques used at the time.

A research project supported by the Maryland State Highway Administration and Federal Highway Administration was conducted at the University of Maryland 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.

A large number of new piles and piles from eleven different bridges in Maryland were obtained. This provided an opportunity to compare the nondestructive testing results from field measurements in piles before they were removed from service with laboratory nondestructive tests on the same piles. This data was correlated to 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.

For full details of the research project see References 1 and 3.

APPENDIX B

EQUIPMENT

Scissors

When testing above water a special piece of equipment, shown in Figure 14, can be used to hold the transducers directly opposite each other. It is a scissors type device, made of plastic that is used to hold the transducers in-place and measure the distance between them. The transducers are held at one end and there are handles at the other end. An engraved scale is provided close to the hinge that allows for direct measurement.

Framework

The framework shown in Figure 15 can be used to hold the transducers directly opposite each other both above and below water. The framework has one arm that is fixed and another that slides on a scale for direct measurement of the diameter of the pile.

Ultrasonic Equipment

The equipment used is a commercial testing apparatus, known as a "V" meter manufactured by James Electronics Inc., Chicago, IL. Similar equipment that can generate pulses and measure the time between the transmitting and receiving transducers is available.

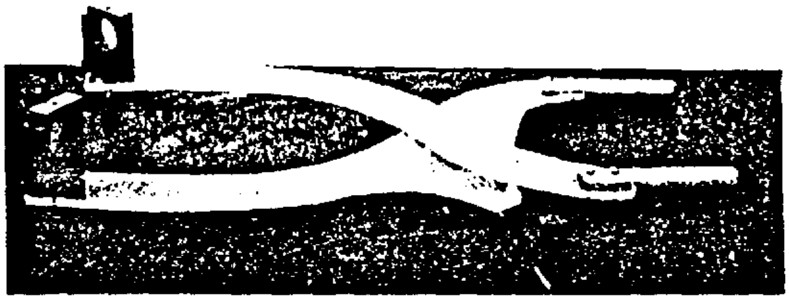

Figure 14. Above Water Scissors

Figure 15. Framework for Measuring the Diameter of the Pile

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