Spacing for Accuracy in Ultrasonic Testing of Bridge Timber Piles

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Abstract: Nondestructive ultrasonic testing is a more accurate alternative for assessing the strength of timber piles than the conventional practice of visual inspection. However, because the ultrasonic method is relatively new, there is a need to develop guidelines that can be used to define the spacing between test points required for a desired level of accuracy in testing. Analyses of data obtained from timber piles covering a range of compressive strengths were used to develop spacing guidelines. The data base consisted of nine treated southern yellow pine timber piles from four bridges in Maryland. Semivariogram modeling was used as the statistical procedure for characterizing the stochastic properties of the ultrasonic wave velocity measurements. Kriging is used to estimate the expected wave velocity for points between measured values. The results provide a relationship between the relative accuracy and the relative spacing of point measurements. Confidence intervals can be applied to assess the expected error variation between point measurements. The methodology presented in the paper can also be utilized in the nondestructive evaluation of other structural components.

Introduction

Federal and state legislation requires periodic inspection and evaluation of highway and railroad bridges, including rating them as to their safe load-carrying capacity. It has been pointed out that 35% of the nation's highway bridges were constructed before or during the 1930s (Galambos 1987) and that almost three out of every ten are defective. Therefore, it is vital that these bridges be effectively inspected in order to predict their remaining life and to verify their structural integrity. One aspect of the problem is the existence of a large number of timber-piling-supported structures that are old and deteriorating. Their periodic inspection is necessary to ensure the early detection of possible damage or deterioration and to prevent structural failure. Inspection and assessment of structural integrity are also essential for making economic assessments and decisions with regard to bridge replacement or rehabilitation.

Despite a 1975 underwater inspection of the piling, an unanticipated failure occurred to a timber pile supported bridge at Denton, Maryland, in early 1976. The underwater inspection, which followed standard visual inspection practices for that time period, had indicated reasonable soundness of the timber, but subsequent laboratory tests of pilings from this bridge indicated substantial reduction in material strength during the life of the piling. These deficiencies went undetected by the visual inspection techniques used at that time and were only determined after failure of the bridge. Since wood is a biological material, it is subject to decay fungi, abrasion, insect attack, and

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other factors that cause a reduction in strength with the length of time in service. Additionally, impact, fatigue, and overloading by traffic on bridges may cause additional damage to the piles. Thus, bridge timber-pile structural integrity and resistance to decay may decrease with time in service.

A research project supported by the Maryland State Highway Administration and the Federal Highway Administration (FHWA) was conducted by the University of Maryland. The main objective of the project was to develop a nondestructive test for determining the in-place strength of bridge timber piling above and below water. Piles such as those in the failed Denton Bridge and others that are immersed in fresh water for long periods of time can sustain damage to the wood microstructure, and a nondestructive test is the most practical tool for determining the in-place strength. This type of damage can reduce pile bearing capacity by actually changing material parameters, such as strength and density, without a loss of cross-sectional area. In addition to developing the nondestructive testing technique, there is a need to define the spacing requirements between test points along the pile based on a required level of accuracy. The main purpose of this paper is the development of a statistical procedure to enable the engineer to make a decision regarding the spacing requirements between test points in any nondestructive testing of any material or structural member, for a specific degree of accuracy. A systematic procedure that utilizes semivariogram modeling as the statistical procedure for characterizing the stochastic properties of the ultrasonic measurements is provided herein. The procedure is used to develop guidelines for defining spacing requirements for such measurements. These guidelines should be applicable to any program for nondestructive testing of other structural components.

Background

Recently the ultrasonic testing was used in characterizing the material properties of timber piles above and below water (Aggour 1986, 1987). The velocity measurements of the ultrasonic testing were correlated with the strength values from compression tests conducted on the same pile sections. Relationships were developed that can be used for establishing the in-place strength of bridge timber piling. The wave propagation in the radial direction of the timber piles was used, i.e., a direct transmission arrangement in which the transducers were facing each other across the section of the pile being tested, as shown in Fig. 1. Because the objective was to determine the strength of the pile in service and because the strength is not uniform across the cross section of the pile, measurements in the radial direction are more representative of the section tested. The direct arrangement also results in a maximum transfer of energy, as the transducers are highly directional and the propagated pulses 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 this reason, the direct transmission mode, with the transducers placed on opposite faces of the timber pile section, was the configuration selected for the research project.

In the research program, an instrument was used to generate ultrasonic pulses and to measure the corresponding time of travel of the propagated pulses. Transmission and reception of the pulses is via two 54-kHz transducers placed firmly against the pile. A device for holding the transducers

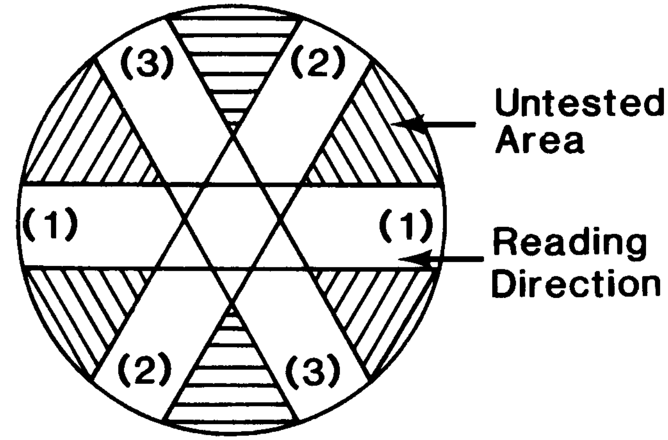

FIG. 1. Cross Section of Pile Showing Reading Directions

and measuring the pulse path length for above and below water measurements has been developed (Aggour et al. 1984). Various combinations of the following factors were considered in the research project: type of wood; type of treatment; direction of the grain; density of the wood; degree of decay; moisture content; and the effect of testing above and below the water line. The results of the tests performed on both new and old section of piles (piles in service) are presented in detail in (Aggour and Ragab 1982; Aggour et al. 1984). It was shown (Aggour 1987) that the compressive strength of a yellow pine timber pile can be predicted using a multivariable model that regresses the compressive strength on both the wave velocity normal to the grain of the pile and its unit weight. The empirical relationship that was developed based on the results of these tests for the treated old sections is:

$$\sigma_{cr} = 0.537\ V_N + 6.34\rho \qquad (1)$$

where σ_{cr} = the average compression strength in psi (1 psi = 6.89 kPa); V_N = wave velocity normal to the grain in ft/sec (1 ft/sec = 0.305 m/s); and ρ = in-place unit weight in pcf (1 pcf = 0.157 kN/m^3). Eq. 1 resulted in a correlation coefficient (R) of 0.983, which corresponds to a 97% explained variance. The first coefficient in this equation shows the sensitivity of the model to the 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. The sections of the piles tested were moist, with a moisture content close to the fiber saturation point (about 30 percent). For dry sections the following model can be used:

$$\sigma_{cr} = 0.292\ V_N + 46\rho \qquad (2)$$

Eq. 2 resulted in a correlation coefficient of 0.933, or 87% of the variation explained. The uses and limitations of these equations and others that are suitable for different conditions are discussed in more detail in Aggour et al. (1984, 1986).

Semivariogram Modeling and Kriging Estimation

In order to develop guidelines for the spacing requirements between test points in the nondestructive testing, assumptions about the properties of the structure must be made. For a structural member without decay we can assume that the member is homogeneous. However, recognizing that the properties of the member vary on the micro level, the properties must be viewed as random variables, with the value of a property assumed stationary over the structural member. For timber piles subjected to nondestructive testing, the cross-sectional dimensions will be small relative to the longitudinal dimension and the property being assessed by the nondestructive measuring device will be averaged at a cross section. Therefore, the random variable can be assumed to be one-dimensional, and the random variation along the length of the member will be the only stochastic characteristic of interest.

Semivariogram analysis provides the tools for describing the stochastic structure of a linearized random variable such as the properties of timber piles (McCuen and Snyder 1986). Kriging estimation, which uses the results of the semivariogram analysis as input, provides the means for making the best linear unbiased estimates (BLUE) of the property. The combination of semivariogram analysis and kriging estimation can then be used to describe the stochastic structure of timber-pile properties so that guidelines for nondestructive testing can be developed (McCuen and Snyder 1986).

Semivariogram Analysis

The property of a timber pile at any location x along the length of the pile will be denoted as $z(x)$. The same property has a value of $z(x + h)$ at a distance h from the initial point measured at x. For relatively small separation distances, the values $z(x)$ and $z(x + h)$ will probably be autocorrelated; for large separation distances, the autocorrelation will be zero, i.e., the values $z(x)$ and $z(x + h)$ will be independent. For very small h, the autocorrelation should be large, and it should decrease to zero as h increases. At some point, the value $z(x)$ will be independent of $z(x + h)$; this point is called the range of influence and is denoted as r.

Of interest in assessing the stochastic structure of a property is the variability between the two values separated by distance h. The variogram, which is denoted as $2\gamma(h)$, characterizes the variability of the property z between the two points:

$$2\gamma(h) = \frac{1}{n}\sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2 \qquad (3)$$

in which n = the number of measurements made at separation distance h; and x_i = the location of a point with respect to some reference point. Eq. 3 has the form of the expected value and is actually the expected value of the random variable $[z(x) - z(x + h)]^2$:

$$2\gamma(h) = E([z(x) - z(z + h)]^2) \qquad (4)$$

In order to quantify the variogram, realizations of the property must be available. A sample estimate of $2\gamma(h)$ is denoted as $2\hat{\gamma}(h)$. In application of Eqs. 3 and 4, we assume that the intrinsic hypothesis is valid; this hypothesis states that the value of the variogram depends only on the separation distance

h and not the location x of the sample points (Journal and Huijbregts 1978). In other words, Eqs. 3 and 4 assume that the difference $z(x) - z(x + h)$ is a random variable with second-order stationarity.

Eqs. 3 and 4 define the variogram. Dividing these values by 2 yields the semivariogram $\gamma(h)$. The semivariogram is used in the second phase of the problem, i.e., the estimation problem with kriging. Just as probability functions are fit using sample data that may be presented as a histogram, a sample semivariogram computed with Eq. 3 can be used to fit a semivariogram function or model. The most frequently used semivariogram model is called a spherical model and has the form:

$$\gamma(h) = \gamma_r \qquad \text{when } h > r \qquad (5a)$$

$$\gamma(h) = \frac{\gamma_r}{2}\left[\frac{3h}{r} - \left(\frac{h^3}{r^3}\right)\right] \qquad \text{when } h \le r \qquad (5b)$$

in which r = the range of influence; and γ_r = a semivariogram model parameter called the sill. γ_r is often quantified using the variance of the sample measurements $z(x)$. The spherical model is just one of many models used to represent a semivariogram; it is widely used because its properties are easily computed and it has the shape and scale properties that characterize many data measurements.

Error Variance

The ultimate objective of the analysis problem is to provide a means of estimating the property of the timber pile at any point x along its length. In addition to the best estimate of the property, we must also be interested in the accuracy of the estimate. If we have a value of the property $z(x)$ measured at a single point x along the length of the pile, then assuming other information is not available, our best estimate of the property at a point $x + h$ is $z(x)$. The variogram defines the accuracy of the estimate. That is, if we have a single point estimate of the property $z(x)$ at a point, then our best estimate of the property at any other point $x + h$ is $z(x)$ and the accuracy of $z(x + h)$ is the error variance $2\gamma(h)$. The standard error of estimate S_e would be the square root of the error variance.

If instead of a single point sample, we collect a sample of n measurements along the length of the timber pile, then our best estimate of the property would be a weighted mean value of the individual points:

$$\hat{z} = \frac{1}{n}\sum_{i=1}^{n} w_i z(x_i) \qquad (6)$$

in which w_i = a weight for $z(x_i)$ that reflects the importance of measurement $z(x_i)$. The error variance of z is no longer $2\gamma(h)$ because the larger sample size, i.e., n rather than 1, should be expected to reduce the error variance. The reduction in the error variance depends on the number of points in the sample and the relative independence of the sample points.

To develop an expression for the error variance when the sample consists of n measurements, with each sample point having a weight w_i, both the error variance associated with each sample point and the point to be estimated and the error variance among the sample points must be assessed. The first source of the error variance would be the weighted average variogram value between sample point i and the point to be estimated, $2\Sigma w_i\gamma(h_i)$, where h_i is the separation distance between sample point i and the point to be estimated. As the sample size increases, the first part of the error variance will decrease because of the greater level of confidence associated with larger samples. Therefore, the within sample variation must be subtracted from the point sample variation because it reflects variation that is not part of the total error variation. The within sample variation is the weighted average semivariogram value between each point in the sample. Therefore, the error variance, S_e^2, is given by:

$$S_e^2 = 2\sum_{i=1}^{n} w_i\gamma(h_i) - \sum_{i=1}^{n}\sum_{j=1}^{n} w_i w_j \gamma(h_{ij}) \quad (7)$$

in which h_{ij} = the separation distance between sample points i and j. The second term on the right-hand side of Eq. 7 is the variance that is internal to the sample points.

Estimation by Kriging

Semivariogram analysis is not an end in itself; it is intended to be used as part of the estimation process. However, estimation requires us to decide which of the sample points to use for estimation and what weight should be given to each sample point. Given that the data analysis yields values for the range of influence and sill for Eq. 5, it seems reasonable that only sample points located within the range of influence of the unknown point should be used to make estimates with Eq. 6, and the weight given to each sample point should be inversely proportional to the ordinate of the semivariogram corresponding to the distance separating the sample point and the unknown point.

To formulate a solution, we need to satisfy the four requirements for statistical modeling: (1) An estimation model, which is given by Eq. 6; (2) an objective function that defines "best" fit; (3) constraints, when necessary, that place limitations on the solution; and (4) a data base. The data base consists of the sample points $z(x_i)$, which are used with the linear estimation model of Eq. 6. In statistical modeling, "best" is often taken to imply that the error, or estimation, variance is a minimum. Thus, we have as the objective to minimize the error variance. But for the kriging solution, if we want an unbiased model, we must impose the constraint that the sum of the weights, w_i, equals 1:

$$\sum_{i=1}^{n} w_i = 1 \quad (8)$$

The resulting values of w_i will thus be classed as "best linear unbiased estimators," or BLUE.

It can be shown (McCuen and Snyder 1986) that the estimation variance, which will be denoted as σ_e^2 and S_e^2 for the population and sample, respectively, depends on the values of the unknown weights, the structure and magnitude of the semivariogram, the location and magnitude of the sample points, and the type of estimation to be made (i.e., point, core length, field, or volumetric). We can minimize the error variance by taking derivatives of the objective function with respect to each unknown and setting the derivatives equal to zero; this provides a set of n equations with n unknowns.

While the solution of these n "normal" equations would produce a minimum error variance, the resulting model would not be unbiased. For this, the constraint of Eq. 8 must be included in the system of normal equations. Thus the objective function is to minimize:

$$S_e^2 - \lambda\left[\left(\sum_{i=1}^{n} w_i\right) - 1\right] \quad (9)$$

in which λ = an unknown. It should be apparent that the solution procedure for kriging is an example of Lagrangian optimization, with λ being the Lagrangian multiplier. There are $n + 1$ unknowns (i.e., the n values of w_i and λ), and there are $n + 1$ equations (i.e., Eq. 8 and the n derivatives of Eq. 9 with respect to each w_i). Thus, we only need an expression for estimating σ_e^2 to find the solution.

To obtain a solution to the estimation of the value at a point, whether the sample points are distributed linearly in either space or time, an estimate of the error variance can be made by:

$$S_e^2 = 2\sum_{i=1}^{m} w_i\bar{\gamma}(S_i, Y) - \sum_{i=1}^{m}\sum_{j=1}^{m} w_i w_j \bar{\gamma}(S_i, S_j) - \bar{\gamma}(Y, Y) \quad (10)$$

in which S_i = the ith sample element; Y indicates the value of the criterion variable, e.g., the wave velocity where the estimate is needed, and $\bar{\gamma}(C_i, C_j)$ = the average semivariogram value between all combinations of C_i and C_j, where C_i and C_j are dummy variables and may be either S_i or Y. In Eq. 10, S_i and Y would represent the ith ultrasonic wave velocity measurement for the sample and the unknown value of the wave velocity at any point along the length of the timber pile. The summations of Eq. 10 include only the m sample points within the range of influence since points beyond the range of influence have $w_i = 0$. Eq. 10 indicates that the error variance consists of three parts. The first term represents the variation associated with differences between the sample point measurement S_i and the criterion Y for which a value is needed. The second term reflects the variation within the sample; that is, the average semivariogram value for all elements of the sample. The third term, i.e., $\bar{\gamma}(Y, Y)$, reflects variation that is not error variation, so it must be subtracted from the total expected variation between the sample and the unknown value of the criterion. The third term is similar to the second term in that it represents variation that is not error variation, yet it contributes to the total variation between the sample elements and the unknown value of the criterion. For a system in which there is a single point of interest, the average semivariogram value for a separation distance of zero must also be zero. The subtraction of the two terms indicates that we must reduce the error variation because we are interested in a mean value (i.e., the mean of all future estimates).

Having formulated the objective function (Eq. 10) the optimal values of the w_i and λ can be obtained by Lagrangian optimization. The "normal" equations are obtained by algebraic manipulation:

$$\lambda + \sum_{j=1}^{n} w_j\bar{\gamma}(S_1, S_j) = \bar{\gamma}(S_1, Y) \quad (11a)$$

$$\lambda + \sum_{j=1}^{n} w_j\bar{\gamma}(S_2,S_j) = \bar{\gamma}(S_2,Y) \quad (11b)$$

$$\vdots$$

$$\lambda + \sum_{j=1}^{n} w_j\bar{\gamma}(S_n,S_j) = \bar{\gamma}(S_n,Y) \quad (11c)$$

$$\sum_{j=1}^{n} w_j = 1 \quad (11d)$$

As an example, if the sample consists of three points, Eqs. 11a–d reduce to:

$$\lambda + w_1\bar{\gamma}(S_1,S_1) + w_2\bar{\gamma}(S_1,S_2) + w_3\bar{\gamma}(S_1,S_3) = \bar{\gamma}(S_1,Y) \quad (12a)$$

$$\lambda + w_1\bar{\gamma}(S_2,S_1) + w_2\bar{\gamma}(S_2,S_2) + w_3\bar{\gamma}(S_2,S_3) = \bar{\gamma}(S_2,Y) \quad (12b)$$

$$\lambda + w_1\bar{\gamma}(S_3,S_1) + w_2\bar{\gamma}(S_3,S_2) + w_3\bar{\gamma}(S_3,S_3) = \bar{\gamma}(S_3,Y) \quad (12c)$$

$$w_1 + w_2 + w_3 = 1 \quad (12d)$$

Eqs. 11a–d represent a set of $n + 1$ simultaneous equations with $n + 1$ unknowns, which can be solved either analytically or numerically. The solution provides the weights that yield the minimum error variance as defined by Eq. 10.

Data Base Used in This Study

For this paper, data were obtained from Aggour (1987) and Aggour and Ragab (1982) where tests were conducted on yellow-pine sections from both new piles (purchased brand new for the experiments) and old piles (piles in service). The velocity measurements were taken along the length of the pile. At each cross section measured, two or three readings in different directions (as shown in Fig. 1) were taken to enhance the reliability of the data.

Piles from four different bridges only were utilized in this paper. Some of the piles were in good condition, while some piles were in a decayed condition. The nine piles used in the analysis were: two piles from the Denton bridge at Denton, Maryland, in Caroline County; three piles from bridge No. 9015 on Maryland Route 392 over Marshyhope Creek, Dorchester County; one pile from bridge No. 0404 on Sandyfield Road, crossing Nine Pin Branch, Worcester County; and finally three piles from the bridge on Smithville Road in Dorchester County, Maryland. Measurements of wave velocity along the length of the piles were made in either one, two, or three directions, with a total of 19 pile/direction combinations, as shown in Table 1.

Semivariogram Analysis of Bridge Piles

The velocity measurements for the nine timber piles were subjected to semivariogram analyses. The analyses were conducted independently for measurements in different directions through the piles; this yielded 19 separate estimates (pile/direction combinations) of the semivariogram parameters. Three of the nine piles were shown by compression strength tests to

TABLE 1. Computed Semivariogram Parameters

Bridge (1)	Pile/direction (2)	Estimate of: Sill (ft/sec)^2 (3)	Estimate of: Range of influence (ft) (4)
Denton	DB/1	51,000	1.5
	DB/2	91,000	1.5
Denton	DD/1	56,000	1.0
	DD/2	83,000	1.0
	DD/3	122,000	1.0
Sandyfield	SB/1	380,000	1.5
	SB/2	160,000	1.5
	SB/3	249,000	1.5
Marshyhope	MG/1	650,000	4.5
	MG/2	700,000	4.5
Marshyhope	M2/1	500,000	9.0
	M2/2	970,000	7.5
Marshyhope	M3/1	1,100,000	7.5
	M3/2	970,000	7.0
Smithville	UA/1	860,000	3.0
	UA/2	720,000	2.0
Smithville	UB/1	180,000	2.0
	UB/2	780,000	3.0
Smithville	UC/2	460,000	3.5

Note: 1 ft = 30.5 cm.

be in good condition in comparison to new piles, with the remaining six piles shown to be in poor condition. The piles from Denton and Sandyfield bridges were found to be in good condition, while the piles from Marshyhope and Smithville bridges were in poor condition. The resulting semivariogram parameters are given in Table 1. The fitted semivariograms for four of the 19 pile/direction combinations are shown in Fig. 2. The sample points show a rising limb to a point approximately equal to the variance of the points and then sample points that scatter about the sill. The approximations are especially good considering the small number of points available for estimating the semivariogram. The poorer fit shown in Figs. 2(a) and 2(b) results from the smaller sample sizes and the presence of decay. For the eleven pile/direction combinations for the piles with decayed wood fiber, the mean sill and mean range of influence are 717,000 and 4.9 ft (1.49 m), respectively; the corresponding values for the pile/direction combinations for piles in good condition are 149,000 and 1.3 ft (0.4 m), respectively. The larger sill for the defective piles results from the nonhomogeneity of the compressive strength along the pile due to decay. This nonhomogeneity results in greater variation in the velocity measurements, with lower velocities through the defective portions of the piles. The nonhomogeneity in strength and, therefore, velocity is also responsible for the larger range of influence for the defective piles. For the defective piles tested, the range of influence was approximately twice the length of the region characterized by low velocity measurements. The computed value of the sill increased as the difference between the velocities for the defective and good portions of the pile increased.

Statistical Criteria for Establishing Spacing Guidelines

The data from the semivariogram analyses provides the basis for establishing spacing guidelines for nondestructive testing. To determine the critical mean value of the sill that distinguishes between good and defective piles, a hypothesis test on the mean can be used. At this point, we are interested in the mean value of the sill because it is this value that indicates the separation between acceptable quality and decayed wood. In performing such a test, there are two types of statistical errors that can occur. The type I error is the case of rejecting the null hypothesis when, in fact, the null hypothesis is true. The type II error is the case of accepting the null hypothesis when, in fact, the null hypothesis is false. For our case, the null hypothesis (H_0) is that the mean sill equals some value μ_0. The alternative hypothesis is that the mean μ is statistically greater than μ_0. The implication of the type I error would be that the samples obtained during testing would indicate that the null hypothesis of an acceptable mean should be rejected when, in fact, the timber pile is not defective; this would lead to an economic loss associated with replacing or restoration of the timber pile when it was not actually necessary. The implication of the type II error is that the null hypothesis of a safe structure would be accepted when, in fact, the pile is probably defective; this would lead to the decision not to replace or restore

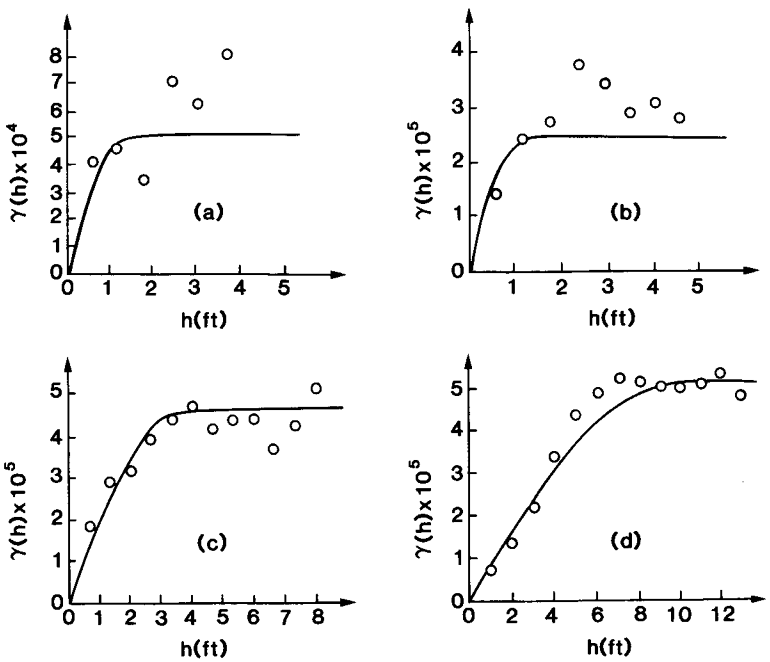

FIG. 2. Fitted Semivariograms for Good and Defective Timber Piles: (*a*) Denton Bridge, Pile DB, Direction 1; (*b*) Sandyfield Bridge, Pile SB, Direction 3; (*c*) Smithville Bridge, Pile UC, Direction 2; and (*d*) Marshyhope Bridge, Pile M2, Direction 1 (Note: 1 ft = 30.5 cm)

the pile when it should have been, which could result in failure. Clearly, the type II error is more important than the type I error, and we would want the probability of making a type II error to be smaller than the probability of making a type I error.

There are four variables in the decision to select the critical value of the criterion. The sample size and the critical value are the two that are used in the decision making. The probabilities of the type I and type II errors, which are denoted as α and β, are the two statistical variables involved in the decision. Thus, by setting α and β, the value of the criterion C_γ can be determined. Assuming a normal distribution approximation to the mean value of the sill, the values of α and β are given by:

$$\alpha = P(\bar{\gamma}_r > C_\gamma | \mu = 717{,}000) = P\left(z > \frac{C_\gamma - 717{,}000}{\frac{113{,}500}{\sqrt{n}}}\right) \qquad (13)$$

and

$$\beta = P(\bar{\gamma}_r < C_\gamma | \mu = 717{,}000) = P\left(z < \frac{C_\gamma - 717{,}000}{\frac{113{,}500}{\sqrt{n}}}\right) \qquad (14)$$

If, for example, we assume values for α and β of 1% and 0.5%, respectively, which are commonly used in statistical analysis, then solving Eqs. 13 and 14 yields $C_\gamma = 402{,}000$.

Following the same procedure as before for the mean value of the range of influence, a critical value C_r can be determined. Using the mean values of the range of influence for the good and defective piles of 1.31 ft (0.4 m) and 4.86 ft (1.48 m) (see Table 1), with a standard deviation of 0.2588 ft (0.079 m) from the data on good piles, we can relate the statistical parameters α and β to the physical parameters as follows:

$$\alpha = P(\bar{\gamma} > C_r | \mu = 1.31) = P\left(z > \frac{C_r - 1.31}{\frac{0.2588}{\sqrt{n}}}\right) \qquad (15)$$

and

$$\beta = P(\bar{\gamma} < C_r | \mu = 4.86) = P\left(\frac{C_r - 4.86}{\frac{0.2588}{\sqrt{n}}}\right) \qquad (16)$$

Assuming values of 1% and 0.5% for α and β, respectively, Eqs. 15 and 16 yields $C_r = 1.9$ ft (0.58 m).

The statistical analysis has suggested that the criteria to be used to distinguish between semivariogram parameters of normal or structurally sound and decayed piles are 400,000 and 1.9 ft (0.58 m) for the sill and range of influence, respectively. In comparing these critical values with the sample values (Table 1) obtained from the 19 pile/direction combinations, only one of the 19 failed to meet these criteria. The velocities measured in direction 1 for pile UB (i.e., pile UB/1 in Table 1) from the Smithville bridge has a sill value (180,000), which was lower than the C_γ; however the limit on the range of influence was exceeded, which indicates a decayed pile. From reviewing the velocity measurements for pile UB/1, it was evident to the writers that the low sill occurred because the decayed part was at the cap of the pile rather than at the water line, which is where the decay was located on the other decayed piles. The low velocity readings for the other decayed piles were nearer the center of the pile, which is responsible for the larger values of the sill.

Estimation and Accuracy

The estimated value of the wave velocity at any point along the pile other than at the location of the sample points can be obtained from Eq. 6. Eq. 10 is used to estimate the accuracy of the estimated value. The estimated value is a function of the sample values within the range of influence and the weights, which are a function of the semivariogram model and its parameters. The standard error is a function of the sample size and the model parameters, γ_r and r. Where the sample measurements are made with a constant separation distance, Δh, two dimensionless parameters can be formed, S_e/γ_r and $\Delta h/r$. The first dimensionless parameter is the ratio of two measures of variance, with S_e representing the error variance and γ_r representing the total variation of the variable. The second dimensionless ratio is the ratio of two distances, with Δh representing the variation between the location of the sample points and r the variation within which points influence the estimated value. Fig. 3 shows the value of the maximum value of S_e/γ_r as a function of $\Delta h/r$ for a spherical semivariogram model; this figure was derived by varying the two dimensionless parameters over a range of values and computing the error at a point half way between the two sample points. The error relative to the maximum is shown in Fig. 4, which shows the standard error as a function of the location between two sample points separated by a distance Δh. The maximum error occurs at a point half way between the two sample points, with the error decreasing from the maximum

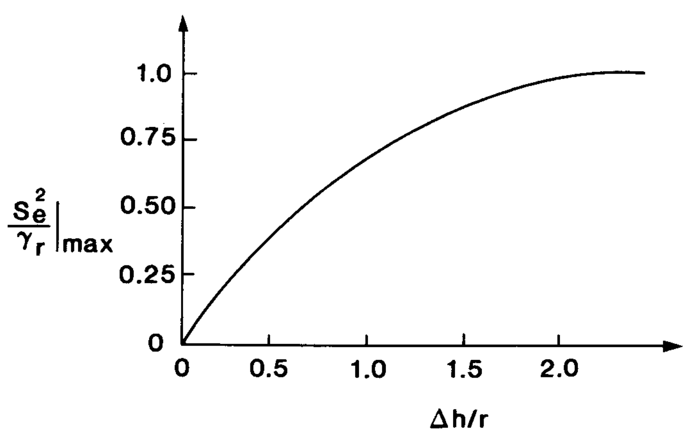

FIG. 3. Maximum Relative Error of Estimation $(Se^2/\gamma_r)_{max}$ **for Spherical Semivariogram as Function of Relative Spacing of Measurements,** $\Delta h/r$

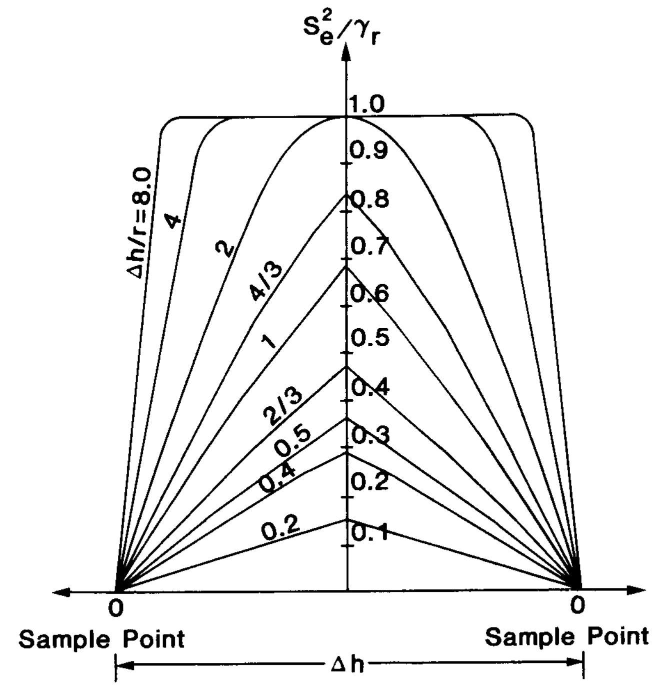

FIG. 4. Relative Error of Estimation Se^2/γ_r **between Sampling Points Separated by Distance** Δh **as Function of Spacing Relative to Semivariogram Parameters**

when a sample point is approached. When the ratio $\Delta h/r$ equals 2.0, then the point that is midway between the two sample points is located a distance equal to the range of influence and thus the sample points do not influence the center point, and S_e is a maximum, $\sqrt{2\gamma_r}$.

The weights given to the individual sample points depend on the semivariogram model and the values of its parameters, the location along the length of the timber pile, and the number of points within a range of influence of the point of interest along the pile. The weight at the location of a sample point is one, with all other sample points equal to zero. For points between sample points, the weight given to a sample point is inversely proportional to the distance from the point of interest to the sample point.

The preceding concepts were applied to the bridge piles used to calibrate the semivariogram model. Eqs. 6 and 10 were used for Denton bridge pile DD1 and Marshyhope bridge pile M3/1. The sample points were used with the model parameters to compute the kriged estimates, which are shown in Fig. 5. The variation between sample points is essentially linear. The standard errors, which are also shown in Fig. 5, were computed using Eq. 10 and the semivariogram model parameters of Table 1. The timber pile for Denton bridge had a radius of influence of 1.0 ft (0.31 m), with sample point measurements made at a spacing of 0.44 ft (0.13 m), which yields a $\Delta h/r$ ratio of 0.44. From Fig. 4, a maximum error ratio of S_e^2/γ_r is 0.32, which agrees with the computed values shown in Fig. 3. Because the timber

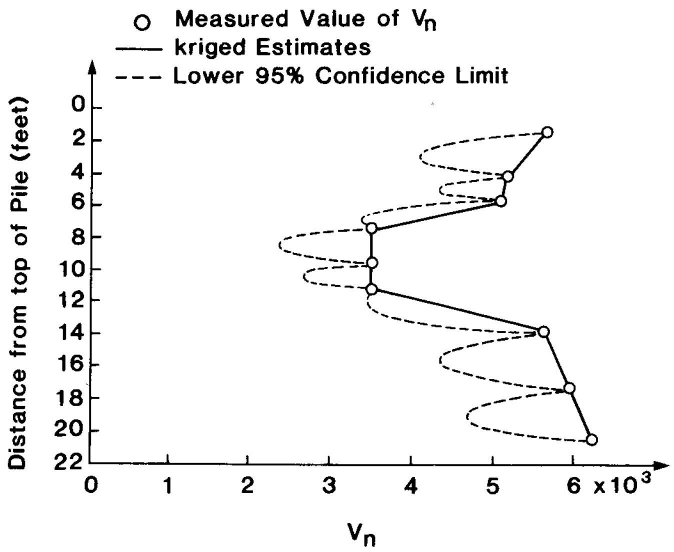

FIG. 5. Kriged Estimates of Wave Velocity (V_n) and 95% Lower Confidence Interval: Marshyhope Bridge Pile M3/1 (Note: 1 ft = 30.5 cm)

pile from Marshyhope bridge included a decayed wood fiber segment, it had a relatively large range of influence of 7.5 ft (2.29 m). The sample point measurements were made at a separation distance of 1.0 ft (0.31 m), which gives a $\Delta h/r$ ratio of 0.133. From Fig. 4, the maximum S_e^2/γ_r ratio between sample points is 0.14, which agrees with the values shown in Fig. 3.

The standard error is useful for establishing guidelines for sampling. Specifically, the standard error can be used to compute a confidence interval on the value estimated by the kriging procedure. A confidence interval provides a range of values in which the true value can be expected to lie. For the case of nondestructive testing, a one-sided lower confidence interval would indicate the probable lower limit of the true velocity, which could then be used with Eqs. 1 or 2 to place a lower limit expected in the compressive strength. The width of the confidence interval will be a maximum at a point half way between the sample points. While the estimated point gives the expected (most likely) value of the velocity, the limit of the confidence interval indicates just how much the true value can be expected to deviate from the best estimate. If the confidence interval is wide, then we can assume that the estimated value is not highly accurate, and the decision process may differ from the case where the confidence interval is relatively narrow.

A normal approximation can be used to compute one-sided lower confidence intervals on a kriged estimate of the velocity. Fig. 4 can be used to find the ratio S_e/γ_r for any value of $\Delta h/r$ and the location of the point between two points where the velocity was measured. The standard error can then be computed using the computed value of the sill, γ_r, since we are only interested in low velocities, the one-sided lower confidence interval is used; an upper limit is not of primary interest since this would reflect strength above the expected strength, while the lower limit on the expected strength would be the important decision criterion. The width of the interval would depend on the level of confidence desired, the kriged estimate of the velocity at the point of interest, and the computed standard error.

A one-sided lower 95% confidence interval was computed for the Marshyhope bridge pile M3/1. The interval and the kriged estimates are shown in Fig. 5 for all points along the length of the pile. The unequal spacing of the sample measurements produces a standard error that varies over the length of the pile. For example, between the pile depths of 7.5–9.75 and 9.75–11.25 the kriged estimate does not show much variation; however, the standard error at the center of the first interval is much greater than the standard error at the center of the second interval because the spacing of the points is wider. This is evident from the confidence interval shown in Fig. 5. Similarly, the maximum limit in the confidence interval between pile depths of 1.75–4.5 is lower than for the interval between depths of 4.5–6.0 even though the kriged estimate at a depth of 3.12 ft (0.95 m) is higher than that at a depth of 5.25 ft (1.6 m). The wider confidence interval reflects the greater uncertainty associated with the wider spacing between sample points.

The confidence interval provides for the assessment of the accuracy of the kriged estimates. The 95% confidence shows the lower limit above which we can be 95% certain that the true value of V_n lies. For the decayed part of timber pile M3 from the Marshyhope bridge, which lies between the distances 7.5 ft (2.29 m) and 11.25 ft (3.43 m) from the top of the pile, the kriged estimates of V_n were about 3,500. However, the true value for the unsampled parts of the pile that lie between the sampled points may be as low as 2,350. The confidence limit suggests that the compressive strength between sample points may actually be lower than that suggested by the measured values of V_n. Such variation can be important in making decisions about the action to be taken when nondestructive testing measurements suggest marginal or inadequate strength. The confidence limit is also useful in establishing guidelines for nondestructive testing.

Guidelines for Test Point Spacing

There are two elements in establishing guidelines for test point spacing in nondestructive testing of timber piles. First, the minimum point strength must be established; this should be based on the requirements of the structural element in question. The minimum strength required can be transformed into a velocity V_n using the relationships between the compressive strength and the velocity V_n (Eqs. 1 and 2). However, the velocity obtained from Eqs. 1 or 2 is the mean value expected at a sampling point. The regression line does not reflect either the sampling variation of the computed relationship at the location of a sample point or the variation that can be expected at points located along a timber pile between point measurements. The first source of variation, i.e., sampling error, is expected to be relatively small compared with the error variation between sample points; this is true because Eqs. 1 and 2 explained a large portion of the total variation, with R^2 values of 97 and 87%, respectively. However, the second source of variation should not be neglected in establishing sampling guidelines.

The second element of the sampling program is to decide on the number of points to be sampled and the spacing of the points. If a timber pile is assumed to be homogeneous in strength along the length of the pile, then the optimum sampling plan would provide the minimum expected error. Since a nonhomogeneous pile is easier to detect because of the larger variance in the measurements, then the spacing established using the assumption of homogeneity will actually be conservative, with decay more likely to be detected. The second requirement in deciding on a sampling program is to specify the number of points. This decision depends on the assumed semivariogram model and the required accuracy. As indicated in the discussion of Fig. 5, the accuracy, which is suggested by the width of the confidence interval, improves as the spacing of the points is decreased. For a spherical semivariogram, Fig. 4 can be used to indicate the relative change in accuracy as the spacing of the V_n measurements is changed. By setting the value of relative error, S_e/γ_r, the spacing ratio, $\Delta h/r$, can be obtained. Unless site specific values of the semivariogram parameters γ_r and r are available, the critical values C_γ and C_r of 400,000 and 1.9 ft (0.58 m) can be used for γ_r and r, respectively. For example, if a relative accuracy of 50% is required, i.e., $(S_e/\gamma_r)^2 = 0.5$, at the centerline between measurements, then Fig. 4 can be entered with a value of $S_e/\gamma_r = 0.7$, which yields a value for $\Delta h/r$ of 1.0; this would yield a spacing of 1.9 ft (0.58 m) if the value of C_r is used for r. For a relative accuracy of 80%, then $(S_e/\gamma_r)^2 = 20\%$ (or 0.2) and $S_e/\gamma_r = 0.45$. Fig. 4 yields a value of $\Delta h/r$ of 0.65, which corresponds to a spacing of 1.2 ft (0.37 m). If there were restrictions, either physical or cost related, on the number of sample measurements that could be taken, then the relative accuracy of the kriged estimates along the length of the timber pile could be evaluated using Fig. 4.

In establishing the lower limit of V_n that is considered acceptable, the value obtained from Eqs. 1 or 2 represents the mean value rather than an expected lower limit. The confidence interval approach could be used to establish the critical value of V_n that is used to decide whether or not to provide restoration. This would require setting the lower limit of the compression strength σ_{cr} and using Eqs. 1 or 2 to estimate the corresponding value of V_n, which is denoted as V_{n1}; this value of V_n would represent the confidence interval value. The value to be used for decision making could then be computed by:

$$V_n = V_{n1} + zS_e \quad (17)$$

in which V_{n1} = the lower 95% confidence interval value obtained with the minimum compressive strength; z = the standard normal deviate for a 95% level of confidence, and S_e = the standard error. The resulting value V_n should be used to decide whether or not to provide restoration of the pile. Using the confidence interval approach rather than the mean value provides assurance that the expected strength between the sample point measurements is adequate.

Summary and Conclusion

Nondestructive testing techniques are being used increasingly for the evaluation of the strength of timber piles. Ultrasonic testing is a more accurate and less costly alternative to the conventional practice of visual inspection. Because of the cost and time required to perform such tests, minimizing the number of measurements to be made in order to obtain a specified degree

of accuracy is of importance. This paper provides a methodology for such a determination.

Analyses of data obtained from testing timber piles, which included both decayed piles and piles in good condition, thus covering a wide range of compressive strengths, were used to develop spacing guidelines. The data base consisted of yellow pine timber piles from four bridges in the state of Maryland. Two of the bridges had piles with wood decay while the piles from the other two bridges were structurally sound. The ultrasonic testing measurements were analyzed using semivariogram analysis, with a spherical semivariogram calibrated to represent the stochastic character of the ultrasonic wave velocity. The results of the semivariogram analyses provide a relationship between the relative accuracy and the relative spacing of point measurements of the wave velocity. Confidence intervals that reflect the stochastic character of the wave velocity, and therefore the compressive strength, can be applied to account for between-point error variation. Therefore, the spacing guidelines provided can ensure the specified level of accuracy of the estimate of the strength of timber piles even at points where measurements are not made. Semivariogram modeling, the statistical procedure for characterizing the stochastic properties, can also be used for providing spacing guidelines for the nondestructive evaluation of other structural components.

A number of statistical approaches could have been applied in developing sampling guidelines. Semivariogram analysis and kriging estimation are the most appropriate tools because of the importance of the stochastic properties of a timber pile. Even a new timber pile will have nonconstant structural properties along its length, and as the pile ages and is subject to weathering, as well as dynamic loading conditions, the variation of the structural properties will probably increase. Thus, establishing spacing guidelines requires a method, such as semivariogram analysis, that can characterize the stochastic variation of the strength of timber piles as a function of the distance between sample points.

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