교량안전진단에 있어서 비파괴 시험자료의 통계적 해석방법

Probabilistic Interpretation of NDE Data in Condition Assessment of Bridge Element

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Abstract

Mathematical basis of interpretation of data from nondestructive evaluation (NDE) methods in bridge inspection is presented. In bridge inspection with NDE methods, NDE data are not assessments. NDE data must be interpreted as condition of element. Interpretation is then assessment. Correct assessments of conditions of bridge elements depend on the accuracy and variability in test data as well as on the uncertainty of correlations between attributes (what is measured) and conditions (what is sought in the inspection). Inaccuracy and variability in test data defines the quality of NDE test. The quality of test itself is important, but in view of condition assessment, the significance of uncertainty in correlations of attributes and conditions must be combined. NDE methods that are accurate in their measurements may still be found to be poor methods if attributes are uncertain indicators of condition of bridge elements. This paper reports mathematical presentation of inaccuracy and variability in test data and of uncertainty in correlation of attributes to element conditions with three examples of NDE methods.

1 Introduction

NDE methods measure attributes of material or bridge elements. These attributes may include electrical potential, chloride ion content, time of travel of ultrasound, temperature difference, and dielectric constant, etc. By relating attributes to conditions of elements, condition ratings can be assigned. There are several concerns in assigning condition ratings. First, NDE data are inaccurate as well as variable. The accuracy of measurements of attributes in NDE tests can be determined. This involves the comparison of NDE data with the data on the same quantity determined by 'exact' method. Inaccuracies in measurements may be corrected, if inaccuracies are reproducible. Separately, variability among individual measurement can also be determined. Where variability exists, NDE data indicates probable value of attribute.

Second, NDE data exist in a range of values that do not give clear indication of condition. This leads to an uncertain assignment of condition, even if accurate measurement of attribute is achieved. In such a case, attributes are related to the probability that condition exists in elements.

Third, NDE methods measure attributes in continuous scale. However, determination of condition is discrete. The conversion of continuous data into discrete determination of condition requires threshold-based interpretation. Threshold is the basis for interpretation of test data. Depending on variability in NDE measurements and on uncertainty in correlation, thresholds of NDE tests must be adjusted.

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2 Threshold-Based Interpretation

The assignment of condition ratings of bridge elements is the interpretation of measured attributes. As discussed, interpretation of NDE data follows simple, threshold-based interpretation. NDE data for elements are either higher or lower than threshold, and so condition ratings of elements can be assigned. Using thresholds, continuous NDE data are reduced to binary assessments.

In existing practice, thresholds are normally determined by performing companion tests. NDE and companion tests are carried out for the same specimens in lab or field. The true condition of elements and threshold for NDE method are determined by comparing results of tests. In this way, thresholds for NDE methods can be selected. Using thresholds for NDE methods, condition ratings of bridge elements are assigned as:

$$If\left(x_i > T\right) then\, Condition\, Rating\, is\, assigned$$

where, x_i is the NDE measurement of attribute and T is the threshold value for NDE method. Here *Condition Rating* is determined by NDE measurement of attributes such as chemical content, corrosion activity, discontinuity or section loss that may be identified or inferred on the basis of a particular NDE method.

3 Mathematical Basis for The Interpretation of NDE Tests

3.1 Mathematical Basis for Inaccuracy

Inaccuracy in NDE data can affect the identification of conditions based on attributes, such as concrete contamination, corrosion activity, etc. Inaccuracy is the difference between measurement of an attribute by NDE method, x_i, and the true value of attribute, X. Using the definition of inaccuracy, normalized percent error, ξ, can be defined as:

$$\xi = \frac{x_i - X}{X} \times 100\% \tag{1}$$

If inaccuracies, $(x_i - X)$, are reproducible, normalized percent error can be expressed as probability density function (pdf), $f(\xi)$. Then using pdf of normalized percent error, $f(\xi)$, the possible distribution of true values of attribute, $f(X)$, for a given measurement of attribute, x_i, may be formed with a mean value and a standard deviation as:

$$\mu_X = E(X) = E\left(\frac{x_i}{1+\xi}\right) = x_i \int_{-\infty}^{\infty} \frac{f(\xi)}{1+\xi} d\xi \tag{2}$$

$$\begin{aligned} \sigma_X^2 &= E\left(X^2\right) - E(X)^2 \\ &= x_i^2 \int_{-\infty}^{\infty} \left(\frac{1}{1+\xi}\right)^2 f(\xi) d\xi - E(X)^2 \end{aligned} \tag{3}$$

Once the distribution of true values of attribute, $f(X)$, is formed, the probability that a threshold is exceeded may be computed as:

$$P[X > T] = \int_T^{\infty} f(X) dX \tag{4}$$

Figure 1 shows an example of the probability that a threshold is exceeded. In this figure, initial NDE measurement of attribute, x_i, is lower than a threshold, so that test data is interpreted as good condition. However, due to the inaccuracy in NDE measurements, there is the probability that true values of attribute may be beyond a threshold value. This shows the misinterpretation of test data due to inaccuracy in NDE measurements of attributes.

For the identification of conditions of bridge elements, probability that an attribute is at or beyond threshold can be used as:

$$\textit{If } (P[X > T] > p), \textit{ then Condition Rating is assigned}$$

where, p is the probability selected for the identification of condition of a bridge element. Threshold for NDE method may be adjusted to recognize inaccuracy in NDE measurements using the desired probability, p.

$$p = \int_{T}^{\infty} f(T_l, \sigma_X) dX \tag{5}$$

where, T_l is the adjusted threshold for desired probability that threshold is exceeded and $f(T_l, \sigma_X)$ is the probability distribution of true values of attribute for a given measurement of attribute equal to T_l.

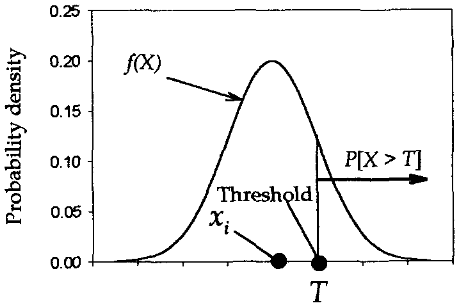

Figure 1 Probability of exceeding a threshold

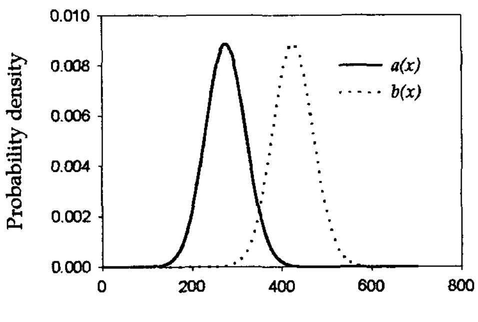

Figure 2 Probability distribution of NDE data

3.2 Mathematical Basis for Variability

Measurements from NDE methods are variable, in addition to being inaccurate. Higher and lower data values are obtained, even for bridge elements in identical condition. The variability of NDE data imposes an uncertainty in identification of conditions based on these data. Probability distributions of NDE data can be constructed. For one NDE method, seeking the identification of one condition, two probability distributions are obtained. One distribution of NDE data from elements where bad condition exist, $b(x)$, and a second distribution of data from elements where good condition exist, $a(x)$.

Figure 2 shows two distributions of NDE data with overlapped area. In overlapped area, the interpretation of NDE data is ambiguous. Only the probability that bad or good condition exists for a given NDE measurement, x_i, is computed. This probability is computed using conditional probability.

$$\begin{aligned} P[C|X = x_i] &= \frac{P[C \cap (X = x_i)]}{P[X = x_i]} \\ &= \frac{b(x_i)}{a(x_i) + b(x_i)} \end{aligned} \tag{6}$$

where, C is the event that bad condition exists in an element and $P[C|X = x_i]$ is the conditional probability that bad condition exists given a NDE measurement of attribute x_i. If the inaccuracy in NDE measurements of attributes is considered, $P[C|X = x_i]$ becomes:

$$P[C|X = x_i] = \frac{\int_{-\infty}^{\infty} b(x) f(X) dX}{\int_{-\infty}^{\infty} [a(x) + b(x)] f(X) dX} \tag{7}$$

The identification of condition requires a statement of probability as:

$$If\ (P[C|X = x_i] > p),\ then\ Condition\ Rating\ is\ assigned$$

A threshold for NDE method can be adjusted for a desired probability, p, as:

$$P[C|X = T_V] = p \tag{8}$$

where, T_V is the adjusted threshold for desired probability that bad condition exists in an element.

3.3 Mathematical Basis for Uncertainty

Some NDE measurements of attributes are the causes for deterioration of bridge element while others are the evidence of deterioration. For example, chloride ion content at the level of reinforcing steel is the cause for corrosion initiation while half-cell potential measurement of reinforcing steel is the evidence of corrosion activity. For NDE methods that measure causative attributes, test data are directly correlated with conditions of bridge elements. The correlation has uncertainty, and therefore the meaning of test data is uncertain. This uncertainty exists even if NDE data are perfectly accurate and reproducible.

Uncertainty may be expressed as probability density function. Consider bridge element which is in bad condition, the probability distribution of an attribute may be formed as $g(y)$, with mean value and standard deviation of the attribute. Given the true value X of an attribute, the probability that bad condition exists is:

$$P[Bad\ Conditon] = \int_{-\infty}^{X} g(y) dy \tag{9}$$

Uncertainty in correlation of attributes to element conditions can be combined with inaccuracy in NDE measurements. For a measurement x_i of an attribute obtained by NDE method, possible distribution of true values of attributes, $f(X)$, is combined with $g(y)$ as:

$$P[Bad\ Condition] = \int_{-\infty}^{\infty} f(X) \left[\int_{-\infty}^{x} g(y) dy \right] dx \tag{10}$$

The identification of condition requires a statement of probability as:

$$If\ (P[Bad\ Condition] > p)\ then\ Condition\ Rating\ is\ assigned$$

Also threshold for NDE method can be adjusted for desired level of probability, p, that bad condition exists.

$$p = \int_{-\infty}^{\infty} f(T_U, \sigma_X) \left[\int_{-\infty}^{x} g(y) dy \right] dx \tag{11}$$

where, T_U is the adjusted threshold for a selected probability, p and $f(T_U, \sigma_X)$ is the probability distribution of true values of attribute for a given measurement of attribute equal to T_U.

4 Case Study for The Interpretation of Half-Cell Potential Test

Half-cell potential surveys detect corrosion activity of reinforcing steel in concrete. Electrical potentials of reinforcing steel in concrete shift abruptly to more negative values when corrosion begins. In laboratory studies, histories of electrical potentials over time exhibit jumps when corrosion begins. Jumps unambiguously reveal onset of corrosion. In field use, monitoring of potentials is not continuous and jumps in potential are not observed. Instead single point-in-time readings are collected, and corrosion activity is inferred from the magnitude of half-cell potential.

Hearn and Marshall [Hearn and Marshall, 1996] have collected data from half-cell potential surveys of reinforced concrete bridge decks in United States. In region of decks where reinforcing steel is not corroding, half-cell potential have a normal distribution with a mean value –207mV and a standard deviation of 80mV. In regions of decks where corrosion is active, half-cell potential value have a mean value of –354mV and a standard deviation of 70mV.

Interpretation of half-cell potentials according to recommendations of ASTM [*Annual*, 1992] identifies possible corrosion where potentials are more negative than –200mV, and probable corrosion where potentials are more negative than –350mV. The National Bridge Inventory (NBI) rating system in U.S uses only one threshold of –350mV to identify active corrosion. But pdfs show that among potentials in regions with no active corrosion, 50% will be more negative than –200mV and 5% more negative than –350mV. For potentials measured in regions with active corrosion, 50% of measurements will be more positive than –350mV.

Pdfs for potentials are plotted in Figure 3. The overlap of pdfs reveals a range where the interpretations of potentials are uncertain. This is caused from variability in individual measurements of half-cell potential. Note that the uncertainty exists in attribute, electrical potential, and not in measurements of the attribute.

Using pdfs of half-cell potential, probability of corrosion of reinforcing steel as a function of half-cell potential is computed by Eq. (6) and shown in Figure 4. In this figure, ASTM threshold of –350mV to identify corrosion activity has 84% of probability of corrosion. For different probabilities requires different half-cell potential readings.

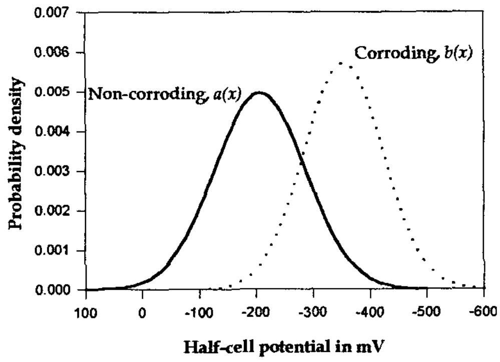

Figure 3 pdfs of half-cell potentials

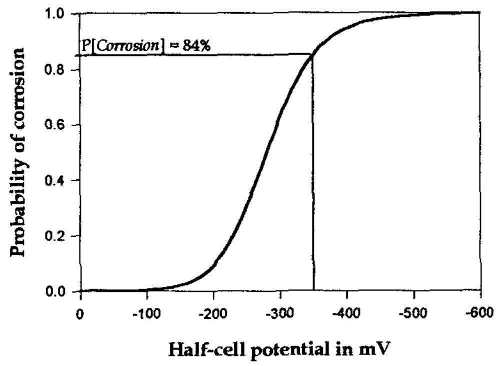

Figure 4 Probability of corrosion

5 Conclusions

Mathematical basis of interpretation of data from nondestructive evaluation (NDE) methods in bridge inspection is presented. The use of NDE methods in the inspection of highway bridges is the application of a test and of an interpretation. The performance of the method, overall, is determined by the accuracy and variability of measurements and by the uncertainty in the correlation between attributes that are measured in a test and conditions that are sought in elements.

Tests are reproducible. Characteristics such as inaccuracy in measurements and variability among individual readings can be established. Data can be corrected for inaccuracy. Variability can be recognized, but not corrected. Where readings are variable, the probability that bad condition exists can be computed instead. A result of inaccuracy is an adjustment of thresholds to achieve a desired probability that true values of attributes do not exceed specific values. In the same way, a result of variability is an adjustment of thresholds to achieve a desired probability that bad condition exists.

Attributes that are causes for deterioration can be directly correlated with conditions of bridge elements, and correlations can be uncertain. Thresholds that have been established for attributes do not offer definite determinations of condition, but merely a probability that a condition exists A better report for bridge elements is a report of the probability that a condition exists. A description of performance of NDE methods is the probability that conditions exist as a function of readings of the test. This approach recognizes variability in test readings together with uncertainty in correlations of attributes and conditions.

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