비파괴 시험을 이용한 RC 구조물 상태진단

Inspection of Structural Elements Using NDE

심 형 섭*

Shim, Hyung-Seop

Abstract

Mathematical basis of interpretation of data from nondestructive evaluation (NDE) methods in condition assessment of structures is presented. In structural inspection with NDE methods, NDE data are not directly used for the condition assessment. Instead, NDE data must be interpreted as condition of inspected element. Correct assessments of conditions depend on many factors such as the inaccuracy and the variability in NDE measurements and the uncertainty in correlation between attributes (what is measured) and conditions (what is sought in the inspection). A full description of the performance of NDE methods considers the relation of test data to conditions of elements. The quality of the test itself is important, but equally important is the interpretation that occurs after the test. The effects of variability in test data and uncertainty in correlations of attributes and conditions are presented in three examples of field testing methods.

요 지

비파괴 시험을 이용한 RC 구조물의 진단에 있어서 비파괴 측정값의 적절한 해석을 통해서만 현 구조물의 상태진단이 가능하다. 보다 정확한 구조물의 상태진단은 비파괴 시험의 정밀성, 변이성 등과 같은 여러 가지 요소에 의하여 좌우된다. 특히 비파괴 시험을 이용한 측정값과 구조물의 상태에 있어서의 불확실성은 정밀한 상태진단에 큰 영향을 미친다. 본 논문은 현재 사용이 증가되고 있는 비파괴 장비의 올바른 선택과 정확한 구조물의 진단을 위하여, 비파괴 측정값의 확률적 해석법의 기초를 제공하고 있다.

Keywords : NDE Methods, NDE Inspection, Interpretation of NDE data

핵심 용어 : 비파괴시험, NDE, 경계해석

* 정회원, 경주대학교 철도건설환경공학과 부교수
E-mail : shimh@gju.ac.kr 054-770-5283

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1. Introduction

Nondestructive evaluation (NDE) methods are used to evaluate the conditions of structural elements, to assess remaining service life, and to identify needs for repairs. The significance of evaluations depends on the quality of data obtained in field tests and on the correlation of attributes measured in tests with the conditions of elements that are sought in the inspection. As a set, data quality and correlation of attributes with element conditions define the performance of NDE methods.

NDE methods measure attributes of materials or elements. These attributes may be electrical potentials or currents, temperature differences, dielectric constants, or aspects of transmission or reflection of stress waves. The accuracy of measurements of attributes in NDE tests can be determined. Usually, this involves the comparison of NDE data with data on the same quantity determined by an '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 indicate the probable value of an attribute. Bounds on attributes may be computed for desired levels of probability. The bounds are wide if variability in measurements is large.

Also important is the correlation of attributes with conditions of elements. Correlations may be uncertain. In such cases, attributes are related to the probability that conditions exist in elements. The significance of NDE methods then is a function of variability in measurements and uncertainty in correlations.

This paper considers mathematical basis for the interpretation of data from nondestructive evaluation (NDE) methods. The effects of inaccuracy and variability in NDE data and the uncertainty in correlation of attributes to conditions are mainly explored.

Examples of these effects in measurement of chloride ion content in concrete using a specific ion probe and detection of corrosion activity reinforcing steel using half-cell potential testing are presented.

2. Performance of NDE Methods

Performance of NDE methods is considered broadly here in terms of the quality of information on element condition that NDE methods deliver. The accuracy of NDE measurements is important, certainly. But a focus on element condition means that the accuracy of NDE measurements is combined with the significance of attributes that are measured. NDE methods that are accurate in their measurements may still be found to be poor methods if attributes are uncertain indicators of conditions of elements.

Three terms describing the performance of NDE methods are important. First, accuracy is the difference between NDE measurement of an attribute and the true value of the attribute. A Failure of accuracy in the mean can be corrected, if the inaccuracy is reproducible. Difference among individual readings is variability in NDE data. Known variability is used to determine the probability that attributes are at or beyond thresholds significant to element condition. Uncertainty in condition of elements or materials exists when attributes measured by NDE methods are correlated with conditions but are not direct proofs of condition. Uncertainty in correlation limits the significance of NDE data in some ranges.

3. Attirbutes of Materials or Elements

Attributes of materials or elements are em-ployed as indicators of condition. In reinforced concrete bridge decks, the concentration of chloride ion at the level of reinforcing steel is an indicator of possible initiation of corrosion. Often a concentration of 0.03% chloride ion by weight of concrete is taken as a threshold for identification of contaminated concrete. The simple interpretation of chloride ion content is shown in Fig. 1.

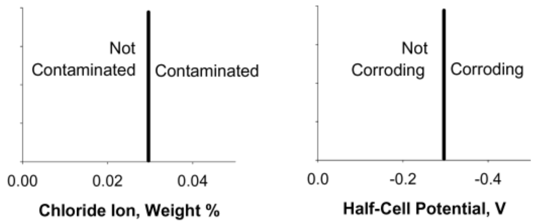

Fig. 1 Attributes of materials or elements

Electrical potential of reinforcing steel relative to a copper-copper sulfate half-cell is an indicator of active corrosion. Where there is active corrosion of reinforcing steel, disruption of concrete will soon follow. In US, the National Bridge Inventory(NBI)[(1)] rating system, half-cell potentials more negative than −0.35V indicate active corrosion (Fig. 1).

In above examples, attributes are correlated with conditions that are important to continuing service of structural elements. Chloride ion contamination indicates immanent corrosion of reinforcing steel. Cracks in steel members may grow and threaten structural strength. Half-cell potentials indicate active corrosion. More to the point, chloride ion content and half cell potentials are not, in themselves, corrosion of reinforcing steel. They are merely correlated with corrosion.

When decisions on maintenance of structures are based on measurement of attributes, limi-tations in the information are related to errors in measurements, variability in measurements, and uncertainty in correlations of attributes to element conditions.

4. Data from NDE Methods

Inaccuracy and variability of NDE data affect the identification of conditions based on attributes, such as concrete contamination and corrosion activity illustrated in Fig. 1. Inaccuracy is the difference between the measurement of an attribute by NDE method, μ_{NDE}, and the true value of the attribute, μ_{True}. For identification of concrete contamination, or corrosion activity, the attribute is compared to a threshold

$$\text{If } (\mu_{True} > Threshold), \text{ Condition exists} \quad (1)$$

where, condition represents contamination, corrosion activity, crack growth, or other material or element condition that is assessed on the basis of values of attributes.

Where NDE data are inaccurate, either NDE data or thresholds may be adjusted.

$$\triangle_{NDE} = \mu_{NDE} - \mu_{True}$$
$$\text{If } ((\mu_{NDE} - \triangle_{NDE}) > Threshold), \text{ Condition exists} \quad (2)$$
$$\text{If } (\mu_{NDE} > Threshold + \triangle_{NDE}), \text{ Condition exists}$$

where, $\triangle_{NDE}$ represents the difference between true values of attributes and values obtained from an NDE method.

The difference, $\triangle_{NDE}$, is specific to a NDE method. For each method, the value $\triangle_{NDE}$ is obtained.

Variability is expressed as the probability density of true values of an attribute for given mean, μ_{NDE}, and standard deviation σ_{NDE}, of NDE measurements. The mean value, μ_{NDE}, depends on the condition of the inspected element.

$$\mathrm{Prob}[\mu_{True} > T] = \int_T^{\infty} f(\mu_{NDE}, \sigma_{NDE})dx \quad (3)$$

where, T is a value of the attribute, usually a threshold, x is an integration variable for NDE readings and $f(\mu_{NDE}, \sigma_{NDE})$ is the probability density function for true values of the attribute, given the readings of an NDE method.

Using (3), the probability that an attribute exceeds the threshold may be computed. Or a tolerable NDE reading, μ_{NDE}, may be computed for a desired probability that the threshold for an attribute is not exceeded.

An examples of inaccuracy and variability in NDE methods are presented.

4.1 Specific Ion Probe for Chloride Ion Content in Concrete

A Strategic Highway Research Project(SHRP)[2] on rapid field determination of chloride ion content in concrete provides data on specific ion probes. Specific ion probes replace the titration methods of AASHTO T-260[3]. Inaccuracies in specific ion probe measurements are established through comparison of probe data with titration results for the same samples of concrete.

$$\triangle_{Probe} = Cl_{Probe} - Cl_{True} \quad (4)$$

where, Cl_{Probe} is the chloride ion content determined by specific ion probe, expressed as weight percentage of concrete and Cl_{True} is the chloride ion content determined by titration.

From data presented in the SHIP report, it is found that $\triangle_{Probe}$ has a mean value of 0.0023% and a standard deviation of 0.0071% for concrete with chloride ion content near the 0.03% threshold. The small value of $\triangle_{Probe}$ means that only a small correction of probe readings is needed. Concrete may, in fact, be at a 0.03% content when probe readings are 0.028%.

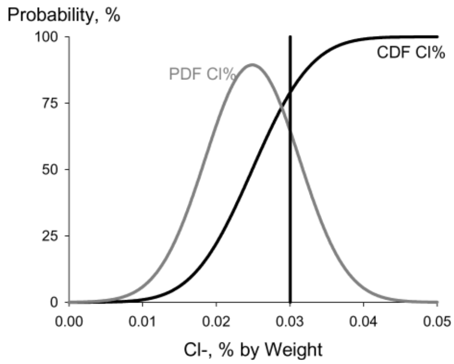

Fig. 2 Interpretation of Specific Ion Probe

Variability of probe readings has a greater influence. In Fig. 2, the PDF(Probability Density Function) of true Cl- content is shown for a (hypothetical) ion probe reading equal to 0.027%. Probe readings have already been corrected for $\triangle_{Probe}$. The variability in probe readings yields the PDF for true Cl- content. Also shown is the cumulative density function for true Cl- content. At an ion probe reading equal to 0.027%, there is a 22% probability that true Cl- content exceeds 0.03%. For this probability, a probe reading of 0.027% is, in effect, a new threshold. Different probabilities require different probe readings. Probe readings at probabilities of 10%, 50% and 90% are shown in Table 1.

Table 1 Readings for Specific Ion Probe

Probability Cl− % beyond 0.03%	Cl− % by Specific Ion Probe
10%	0.025%
50%	0.032%
90%	0.044%

Because probe readings are variable, lower probe readings become thresholds for lower probabilities that true chloride ion content is beyond 0.03%.

5. Attribute and Condition of Elements

Data and variability in data are only two in− fluences on interpretation of measured attributes of structural elements. Often, attributes obtained by NDE methods are not, themselves, direct measures of condition. Instead, attributes are correlated with conditions. Uncertainties in correlations affect the interpretation of NDE data.

Consider as an example the use of half−cell potential surveys to detect corrosion activity in reinforced concrete elements. Electrical potentials of reinforcing steel in concrete shift abruptly to more negative values when cor− rosion begins. In laboratory studies, histories of electrical potentials over time exhibit jumps when corrosion begins. Jumps unambiguously reveal onset of corrosion. In field use, mo− nitoring 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 potentials.

Hearn and Marshall[(6)] have collected data from half−cell potential surveys of reinforced concrete bridge decks in the United States. In regions of decks where reinforcing steel is not corroding, half−cell potentials have a normal distribution with a mean value −0.20V and a standard deviation of 0.08V. In regions of decks where corrosion is active, half−cell potentials have a mean value of −0.35V and a standard deviation of 0.06V.

Interpretation of half−cell potentials according to recommendations of ASTM[(7)] identifies possible corrosion where potentials are more negative than −0.20V, and probable corrosion where potentials are more negative than −0.35V. Most of corrosion inspections use only one threshold, −0.35V, to identify active corrosion. But PDFs show that among potentials in regions with no active corrosion, 50% will be more negative than −0.20V and 5% more negative than −0.35V. For potentials measured in regions with active corrosion, 50% of measurements will be more positive than −0.35V.

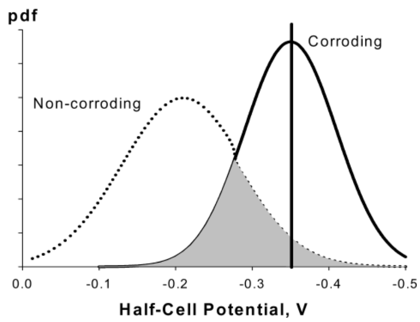

Fig. 3 PDFs of Half−cell Potential in RC Structures

PDFs for potentials are plotted in Fig. 3. The overlap of PDFs, shaded in the Fig., reveals a range where the interpretations of potentials are uncertain. The uncertainty exists in the attribute, electrical potential, and not in me− asurements of the attribute.

Given the PDFs for potentials, the threshold at −0.35V seems misplaced. The threshold is well placed, however. if it yields accurate assessments of total area of decks where re-inforcing steel is corroding. In Fig. 4, populations of measurements in corroding and non-corroding regions are shown for a deck that has active corrosion over about 8% of its surface area. Since all potentials more negative than −0.35V are interpreted as evidence of active corrosion, about 50% of the readings in corroding regions, and about 4% of the readings in non-corroding regions are interpreted as corroding. Mis-interpretation of many potentials in corroding regions is offset by misinterpretation of some readings in non-corroding regions.

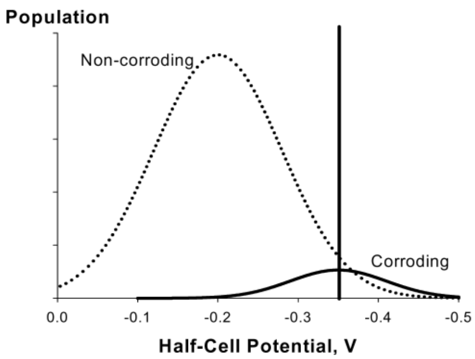

Fig. 4 Half-cell Potential in V

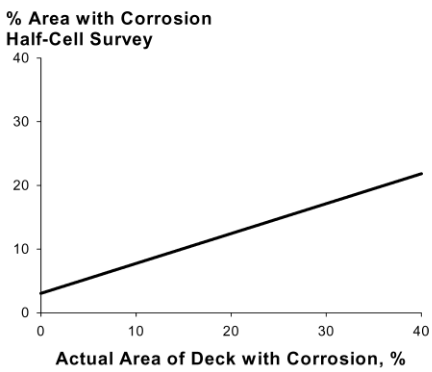

Fig. 5 Performance of Half-cell Potential Survey

The ability to get accurate determinations of extent of regions of corroding rebars, while misinterpreting about half of the potentials in regions with corrosion, illustrates the difference between accuracy of individual test applications and accuracy of survey using the test. For the PDFs of half-cell potentials and the threshold set at −0.35V, outcomes of surveys are shown in Fig. 5 for a range of true extent of corrosion. Because of the overlap in PDFs and the unavoidable misinterpretation of some tests, half-cell surveys are expected to indicate corrosion in at least some regions of decks, even when decks have no corrosion activity, and to underestimate the extent of regions with corrosion when decks have corrosion over large areas.

5.1 Threshold for Chloride Ion Contamination

In the same way that a threshold of −0.35V for half-cell potential misinterprets corrosion activity in some regions of elements, the threshold of 0.03% for chloride ion content does not always identify contaminated concrete.

Using data in the literature on chloride ion content in concrete at the onset of corrosion [(6)(7)], a first estimate of the probability density function of chloride ion content for contamination is formed. The distribution of chloride ion content has a mean value of 0.035% and a standard deviation of 0.012%. The threshold at 0.03% corresponds to a 34% probability that corrosion will begin. Here is a direct statement of the correlation of an attribute with a condition sought by inspection. A threshold of 0.03% chloride ion content does not identify contaminated concrete. Instead, a 0.03% content indicates a 34% probability that concrete is contaminated.

Concrete and reinforcing steel might tolerate this Cl− content without harm, or concrete with lesser Cl− content may suffer corrosion of rebars. Of course, corrosion activity depends on many other factors including availability of oxygen and water, temperature of the concrete, etc. The PDF for chloride ion content proposed here is for average concrete quality and average service conditions in highway bridges. This PDF will not apply to other structures, to other materials or material quality, or to other types of service.

The performance of the specific ion probe can be revisited using the PDF for chloride ion contamination in place of the 0.03% threshold. Using $\triangle_{Probe}$, σ_{Probe}, and the PDF, the probability that corrosion will occur for concrete with a probe reading Cl_i is

$$Prob[Corrosion] = \int_0^{\infty} f_{Cl_i}(c) \left\{ \int_0^{c} f_{Corr}(i)\, di \right\} dc \quad (5)$$

where $f_{Cl_i}(c)$ is the PDF for true chloride ion content corresponding to a ion probe reading equal to Cl_i and $f_{Corr}(i)$ is the PDF for corrosion initiation at true chloride ion content i.

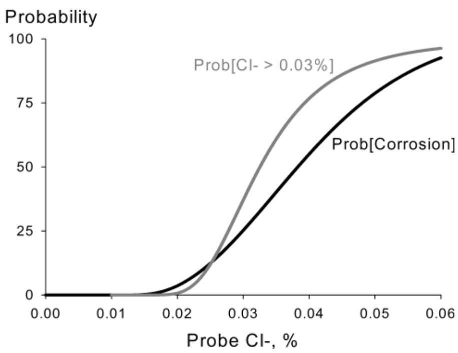

Fig. 6 Probability of Corrosion

The probability of initiation of corrosion is plotted as a function of probe readings in Fig. 6. Also shown for comparison is the plot of probability that true chloride ion content exceeds 0.03% as a function of probe reading.

Table 2 Cl− Content and Corrosion Events

Prob	Event [Cl−Probe > 0.03%]	Event [Cl−True Initiates corrosion]	Event [Cl−Probe Initiates corrosion]
10%	0.025%	0.020%	0.024%
50%	0.032%	0.035%	0.038%
90%	0.044%	0.050%	0.058%

In Table 3, probe readings are shown for a set of events and probabilities of events. First is the simple event that true Cl− content exceeds 0.03%. The probe readings for this event are listed for three probabilities of oc− currence. Next, the event that corrosion begins as a function of Cl− content is considered. The Cl− contents here are true contents, not probe readings. The third event is the probability that corrosion will begin as a function of probe reading. Here, probe readings are slightly higher than true Cl− content. This is caused by the uncertainty in the relation between Cl− content and initiation of corrosion and inaccuracy and variability in application of test.

6. Summary

The use of NDE methods in the inspection of structural elements 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 mean values and variability among individual readings can be established. Data can be corrected for inaccuracy in the mean. Variability can be recognized, but not corrected. Where readings are variable, the probability that an attribute is at or beyond a threshold can be computed. A result of variability is an adjustment of thresholds to achieve a desired probability that true values of attributes do not exceed specific values.

Attributes are correlated with conditions in materials or 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 structural inspection 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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