# 구조물 진단에 있어 비파괴 시험법의 성능평가

# Performance Evaluation of NDE Methods in Condition Assessment of Structural Elements

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## Abstract

The relations between data from test methods and conditions in structural elements are considered. NDE(Nondestructive Evaluation) methods are joint application of a test and a basis for interpretation of data obtained in the test. Correct assessments of conditions of elements depend on the inaccuracy and variability in the test data and on the uncertainty of correlations 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 condition of elements. The quality of the test data itself is important, but equally important is the interpretation that occurs after the test. To make the decision of the performance of NDE methods, this paper presents mathematical basis to measure the reliability of NDE methods.

## 요　지

정밀한 구조물의 상태진단 혹은 안전성 평가는 비파괴 시험의 정밀성(Accuracy), 변이성(Variability) 등과 같은 여러 가지 요소에 의하여 좌우된다. 특히 비파괴 시험을 이용한 측정값과 구조물의 상태에 있어서의 불확실성(Uncertainty)은 정밀한 상태진단에 큰 영향을 미친다. 비파괴 시험을 활용함에 있어서의(간접조사) 신뢰할만한 비파괴 장비라면 현 구조물의 상태(피해면적)를 정확하게 나타낼 수 있어야 한다. 본 논문은 현재 사용이 증가되고 있는 비파괴 장비의 올바른 선택과 정확한 구조물의 안전 진단을 위하여, 비파괴 장비의 성능 평가에 있어 확률적 기초를 제공한다.

**Keywords :** NDE methods, NDE inspection, Interpretation of NDE data

**핵심 용어 :** 비파괴시험, NDE, 경계해석

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## 1. Introduction

The usefulness of NDE method depends on how well the method indicates the condition of an inspected element compared to its actual condition. The performance evaluation of NDE methods is performed by comparing indications of the condition made by the NDE method to the true condition of the element. The indications of conditions made by point-wise inspection methods are function of both the accuracy and the variability of the method and the uncertainty in correlation between attributes and conditions. Accuracy and variability here entail the performance of the device.

An outcome from NDE test can be expressed as a *Yes* or *No* indication of damage, or as a probability of the existence of damage. An assessment can be expressed as the percentage of area in an inspected element, which is damaged. The probable value of assessment is calculated through the several considerations. These include the location of tests, relation of physical quantity measured to existence of damage, accuracy and variability in measurements, and interpretation of individual tests. The term of "damage" in this study is considered to be binary. An element inspected is damaged or it is not damaged at any test location. There is no degree of damage. Uncertainly exists only in the detection of damage by an inspection method.

This paper develops the mathematical basis for the interpretation of NDE data and the performance evaluation of NDE methods. The approach developed in this paper is applicable to any instrument-based inspection method, which uses point applications of tests. A procedure for the calculation of an assessment and the evaluation of the performance of NDE methods is presented which uses the four steps: Application of test, Formation of probability density functions, Formation of populations, and Interpretation. This evaluation process will determine true and false indications of condition in an inspected element for instrument-based inspection methods.

For the clarity in understanding, several terms used in this paper are defined. NDE method is a means of measuring a physical quantity (attribute) in an inspected element for determination of the condition; Test is an individual, pointwise application of NDE method; Survey is an ensemble of tests; Outcome is an interpretation of a single test; Assessment is an ensemble of outcomes.

## 2. Interpretation of NDE Data

The condition assessment of an inspected element is the interpretation of measured attributes. Attributes here are employed as indicators of condition. They are the measurable physical quantity in an inspected element whose magnitude gives evidence of the existence or severity of damage in an element. Attributes are not in themselves a direct indication of damage. Attributes must be correlated with the existence or severity of damage. Voids in concrete, for example, affect sound velocity and scatter ultrasound waves passing through. Voids can also affect the nature of transmissions and reflection of radar pulses. Electrical potentials or electrical currents may be the evidence of corrosion of reinforcing steel which often leads to delamination of concrete. Attributes are useful for inspection, only if there is a correlation between the physical quantity measured and the condition of inspected element.

Interpretation of measured attributes follows simple, threshold-based interpretation. NDE measurements of attributes are either higher or lower than threshold, and so Yes or No determination on existence of damage can be made. Using thresholds, continuous NDE data are reduced to binary assessments.

### 2.1 Probability Density Functions (pdf) of NDE Data

Measurements of attributes from NDE methods are variable, in addition to being inaccurate. Higher and lower data values are obtained, even for elements in identical condition. Each of attributes measured by NDE methods can be seen to follow a probability distribution of magnitude. For one NDE method seeking to the damage in element, two probability distributions can be formed. One distribution of magnitude of NDE data from inspected elements where elements are damaged, and a second distribution of NDE data from elements where elements are sound.

An attribute measured by NDE method is useful indicator, if the probability distributions from sound and from damaged elements are different. That is, if the probability distribution of NDE data from sound and damaged elements have different means and if two distributions do not overlap too much. To illustrate these points, consider two cases shown in Fig. 1. The first example distributions are well-separated, thereby unique interpretation of data is possible. However, the second distributions show considerable overlaps. In fact, this leads to an ambiguous interpretation of data.

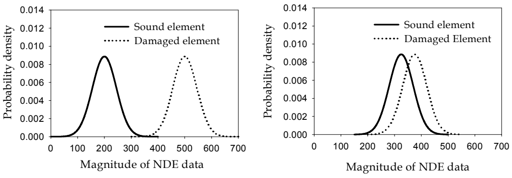

Fig. 1 Pdfs of magnitude of NDE data

The overlap of the distributions of a physical quantity in sound and in damaged elements is of primary importance in the performance of an NDE method. It should be possible to evaluate the performance of an inspection method based on the distributions of its magnitude in sound and in damaged elements. The amount of overlap of the distributions in sound and in damaged elements is indicated by β. Large values of β correspond to a little overlap of two distributions while small values of β correspond to a significant overlap of two distributions. β can be calculated as:

$$\beta = \frac{|\mu_S - \mu_D|}{\sqrt{{\sigma_S}^2 + {\sigma_D}^2}} \tag{1}$$

where, the subscripts "*S*" and "*D*"denote the parameters for the probability distributions of magnitude of NDE data in sound and in damage elements, respectively.

### 2.2 Populations of NDE Data

NDE tests are usually applied in point-wise manner in an inspected element. Moreover, methods are performed on evenly spaced grid line across the tested element. This fact can make the one possible assumption about assessment of tests that interpretation of number of tests results in an interpreted amount of damaged element. That is, the fraction of all tests interpreted as damaged element will equal the fraction of area, which is damaged. Even further, the populations of NDE data in sound and in damaged elements will be proportional to the fraction of element which are actually sound and damaged elements. Therefore, the population of NDE data can be obtained by multiplication of fraction of element which is in sound or in damaged elements to the probability distributions of NDE data in sound and in damaged elements.

Fig. 2 shows the example of populations from element which is damaged about 20% by area. These populations of NDE data are obtained from probability distributions multiplied by fraction of damaged portion and of sound portion of elements. The probability distributions and the populations of NDE data play important role when the performance of NDE methods are evaluated.

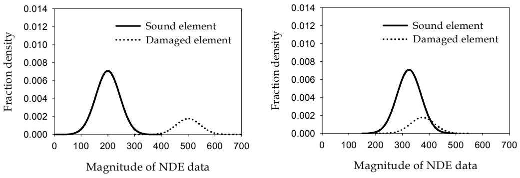

Fig. 2 Populations of NDE data

## 3. Performance Evaluation of NDE Methods

The performance evaluation of NDE methods is the measurement of difference between interpreted condition and true condition of inspected element. An useful NDE method should provide the small difference. That is, true condition of element should be detected with relative accuracy. For the performance evaluation of NDE method, two probability distributions of NDE data and simple, threshold-based interpretation are used throughout.

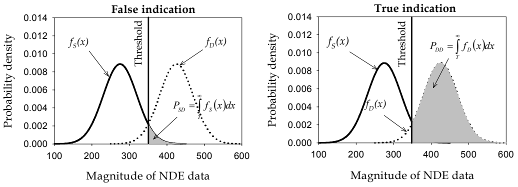

Fig. 3 True and false indications of damage

Consider NDE method with two probability density functions (pdfs) of NDE data in sound and in damaged elements. If the threshold value, *T*, for the interpretation is given, the probability that a test is interpreted as damage is equal to the probability that the measured value of the NDE data is greater than the threshold value. Both sound and damaged areas may have magnitudes of data which are greater than the threshold. Therefore, the probability that the measured data is greater than the threshold is the sum of two parts: True indications of actual damaged area and false indications of actual sound area. Fig. 3 shows true and false indications.

$$P_{DD} = \int_T^\infty f_D(x)dx \tag{2}$$

$$P_{SD} = \int_T^\infty f_S(x)dx \tag{3}$$

where, $f_D(x)$ is pdf of magnitude of NDE data in damaged element, $f_S(x)$ is pdf of magnitude of NDE data in sound element, $P_{DD}$ is probability of true indications of actual damaged area, and $P_{SD}$ is probability of false indications of actual sound area. Similarly, the probability that a measured data is interpreted as sound is the sum of two parts: True indications of actual sound areas and false indications of actual damaged areas. Fig. 4 shows the true and false indications.

$$P_{DS} = \int_{-\infty}^{T} f_D(x)dx \tag{4}$$

$$P_{SS} = \int_{-\infty}^{T} f_S(x)dx \tag{5}$$

where, $P_{SS}$ is probability of true indications of actual sound area, and $P_{DS}$ is probability of false indications of actual damaged area.

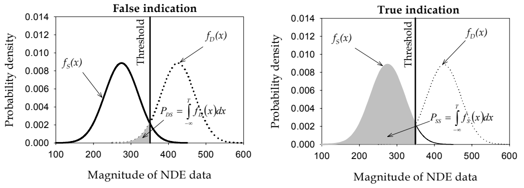

Fig. 4 True and false indications of sound element

In general, there are four possible outcomes in threshold-based interpretation. If NDE device is placed on damaged element, only Eq (2) and (4) are possible, whereas if NDE device is placed on sound element, only Eq(3) and (5) are possible. The sum of the probabilities of these two outcomes always equals one.

By making an assumption that the interpretation of number of tests results in interpreted amount of damaged area in an element, the interpreted percent area damaged is easily computed from populations of NDE data. Populations are obtained from pdfs and fraction of area in an element damaged.

$$\begin{aligned} P_S(x) &= (1-n)\times f_S(x) \\ P_D(x) &= n\times f_D(x) \end{aligned} \tag{6}$$

where, $P_S$ and $P_D$ are the populations of NDE data in sound and in damaged areas in an element and $n$ is the fraction of actual area damaged in an element. For given populations of NDE data and threshold value, $T$, for the interpretation, the interpreted percent area damaged in an element is calculated as:

$$A_D = \left[\int_{T}^{\infty} P_D(x)dx + \int_{T}^{\infty} P_S(x)dx\right]\times 100\% \tag{7}$$

where, $A_D$ is the interpreted percent area damaged in an element. Note that the first term in Eq. (7) is the true interpretation and the second term is the false interpretation of damage. For any NDE method seeking to the damage in an element, interpreted damage is the sum of two parts.

The false interpretation for NDE method is:

$$Err = \left[\int_{-\infty}^{T} P_D(x)dx + \int_{T}^{\infty} P_S(x)dx\right]\times 100\% \tag{8}$$

where, $Err$ is the false interpretation for NDE method. With the aid of Eq.(6) and (7), the interpreted percent area damaged in an element can be computed as a function of actual percent area damaged in an element. That is, for any given actual percent area damaged in an element, the interpreted percent area damaged is computed by formation of populations, Eq. (6) and calculation using Eq. (7). If the interpreted percent area damaged in an element is plotted in *xy* plane as actual percent area damaged in an element being *x* axis, the accurate NDE method should provide $45^{\circ}$ line in *xy* plane.

## 4. Determination of Threshold

The choice of a threshold value for interpretation affects performance of NDE methods. Depending on threshold value, the interpreted percent area damaged and the false interpretation in an element is significantly affected. Possible criteria for the choice of a threshold may be to minimize the number of false interpretations of tests, or to insure that the actual amount of damaged area is accurately determined. To understand how the value of a threshold affects an assessment, four different criteria of choice of threshold are selected. The four different criteria are(5):

1) *Intersection of pdfs of magnitude of NDE data in sound and in damaged areas in an element.*
2) *Intersection of populations of magnitude of NDE data in sound and in damaged areas in an element.*
3) *Minimize the probability of falsely interpreted tests.*
4) *Insure that the actual amount of damage is accurately determined.*

The intersection of pdfs of magnitude of NDE data in sound and in damaged areas in an element leads to a unique threshold. This threshold can be obtained by following equation.

$$f_S(T) = f_D(T) \tag{9}$$

where, $T$ is the threshold at the intersection of pdfs. One limitation in using a threshold at the intersection of pdfs is that it does not respond to the change in sound and in damaged populations as an element becomes more damaged. To solve this problem, another criterion is to choose a threshold such that it lies on the intersection of the sound and damaged populations. Threshold at the intersection of populations is obtained from following equation.

$$P_S(T) = P_D(T) \tag{10}$$

If the primary concern of NDE inspection is that the location of damaged areas is accurately determined, it would be important that a threshold interpretation is chosen such that spatial errors are minimized. Spatial errors are minimized by minimizing false interpretations, which is the third criterion for choosing a threshold value. The threshold which minimizes the probability of false interpretations depends on the amount of actual damage. Therefore, the value of the threshold is a function of the actual area damaged. For any amount of damage, the threshold which minimizes false interpretations is identified by searching for the threshold which minimizes the sum of two equations, Eq. (3) and (4). It turns out that thresholds which minimize the false interpretations are identical to thresholds at the intersections of populations.

The goal of some NDE inspection is to accurately determine the amount of damaged area in an inspected element. For example, the decision of whether to replace a bridge deck is generally based on the total amount of damaged area. The locations of damage are not important. All that is needed is an accurate interpreted amount of damage is equal to the actual amount of damage. This is called interpretation accuracy and is the fourth criterion for choosing a threshold value.

To insure interpretation accuracy, a threshold must be chosen such that the number of falsely interpreted tests in damaged area in an element exactly equals the number of falsely interpreted tests in sound area in an element. In this manner, the damaged area falsely interpreted as sound is replaced by the sound area falsely interpreted as damaged, resulting in a correct interpretation of the total amount of damage. The number of tests falsely interpreted in sound and in damaged area in an element depends on the amount of actual damage. Since the location of the threshold determines the number of false interpretations of sound and of damaged areas, the threshold must also be a function of the amount of actual damage. The determination of a threshold, which insures interpretation accuracy is calculated from the following equation.

$$\int_{T}^{\infty} P_S(x)dx = \int_{-\infty}^{T} P_D(x)dx \tag{11}$$

where, $T$ is the threshold to insure interpretation accuracy.

## 5. Comparison of Thresholds

Four unique criteria upon which a choice of threshold can be based is introduced. To clearly understand how each of this criteria influences the performance of NDE method, these criteria are applied to example NDE of half-cell potential method. The performance of half-cell potential method using each of these criteria is evaluated in terms of the false interpretation.

Half-cell potential test 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, single point-in-time readings are collected, and corrosion activity is inferred from the magnitude of half-cell potential.

Hearn and Marshall(2) 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. Fig. 5 shows pdfs of half-cell potential in sound and in corroded areas. The β value of half-cell potential method is 1.38, which indicate large overlap of two distributions.

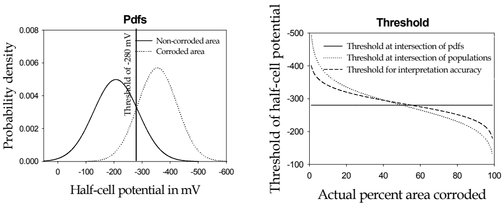

Fig. 5 Pdfs and thresholds of half-cell potential

Fig. 5 shows the threshold for half-cell potential method. Notice that threshold at the intersection of pdfs does not depend on actual amount of damage, whereas thresholds by other criteria do. Thresholds by other criteria approach negative and positive infinite as percent area corroded in an element approaches 0% and 100%.

Given threshold values for the interpretation of half-cell potential method and fraction of area corroded, interpreted percent area corroded can be plotted as a function of actual percent area corroded using Eq.(7). This kind of plot is recognized as performance curve for NDE method. Performance curve of half-cell potential method is shown in Fig. 6.

Performance curve by threshold at the intersection of pdfs shows that half-cell potential method overestimates corroded area up to 56% actual damage (corroded area). Between 56 and 100 percent area actually corroded, this NDE method underestimates the damage. For a threshold at the intersection of populations, and which minimize the false interpretation, the interpreted and the actual amount of area corroded are equal at 0, 42, and 100 percent area actually corroded. The trend of slight over and under-estimations is also shown for this threshold. For a threshold of interpretation accuracy, interpreted amount of corroded area is exactly equal to actually corroded area as expected. However, notice that the interpretation by this threshold still contains spatial error.

Similar to the performance curve of half-cell potential method, false interpretation can also be plotted as a function of actual percent area corroded using Eq. (8). This is shown in Fig. 6.

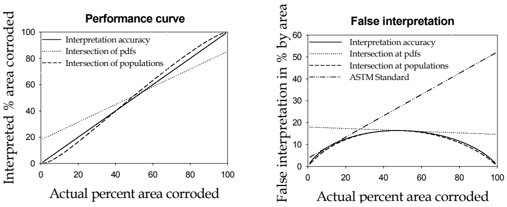

Fig. 6 Performance curve and false interpretation

The false interpretation for a threshold at the intersection of pdfs reaches the maximum values of 18% at 0 percent of actually corroded area and decreases to 15%. For a threshold at the intersection of populations and a threshold which insure interpretation accuracy are very similar, coinciding at zero, 100, and approximately 43 percent actually corroded area. For actual amounts of corroded area different from these, a threshold interpretation at the intersection of populations results in the least false interpretations. Since this type of threshold interpretation minimizes the false interpretations, this curve is essentially an envelop defining the lowest false interpretations which can be achieved for the half-cell potential method.

Interpretation of half-cell potentials according to recommendations of ASTM(1) identifies probable corrosion where potentials are more negative than -350mV. For this ASTM threshold, false interpretation increases linearly from 4% to 50%. This means that for an element severely corroded, there is a larger probability that a half-cell potential test will be falsely interpreted than correctly interpreted.

## 6. Conclusion

Mathematical basis for the performance evaluation of NDE method is presented along with simple threshold-based interpretation method. Procedure for the performance evaluation of NDE consists of four steps: Application of test, Formation of probability density functions, Formation of populations, and Interpretation. The results of this procedure is an interpreted percent area damaged in an inspected element, called assessment. Using assessment of condition, performance curve for NDE and false interpretation are plotted as a function of actual amount of damage.

Several criteria of selection of threshold value are proposed and applied for the example NDE of half-cell potential method to show the effect of threshold on the performance of NDE method. The results indicates the performance of NDE is significantly affected by choice of threshold value. For the same NDE methods, false interpretation is altered considerably depending on choice of threshold. When goal of NDE inspection is accurately determine total amount of damaged area, the threshold, which insure the interpretation accuracy is the best choice, whereas location of damage is the goal of inspection, the threshold at the intersection of populations should be used instead. When using the threshold at the intersection of pdfs, the practical limit can be set on the false interpretation which would lead to a lower bound of  value.

This paper considers performance evaluation of NDE method by threshold based interpretation. Opposed to this interpretation method, a continuous, probability-based interpretation method can also be proposed. Continuous interpretation method assigns probability of damage for a given NDE data as opposed to binary indication of damage obtained with threshold. This interpretation method produces continuous interpretation function for the assessment of element. With the better understanding of NDE and of elements inspected, continuous interpretation can be investigated in future.

## Reference

1. Annual book of ASTM standards. ASTM C876, Philadelphia, PA. 1992.
2. Hearn, G. and Marshall, S. "Damage assessment in bridge decks using half-cell potential measurements" in Nondestructive Evaluation of Civil Structures and Materials, M.P. Schuller, D.B. Woodham, eds., Boulder, CO, 1996, pp.259-306.
3. Recording and coding guide for the structure inventory and appraisal of the nation's bridges. , FHWA, Washington, DC. 1988.
4. Shim, H.S. "Nondestructive evaluation of reinforced concrete bridge elements subject to corrosion of reinforcing steel" Ph.D. thesis, University of Colorado at Boulder. 1998.
5. Standard specification for transportation materials and methods of sampling and testing. 16th ed., AASHTO, Washington, DC. 1993.

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