Bridge Inspection Practices Using Non-destructive Testing Methods for Concrete Structure

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ABSTRACT

Non-Destructive Testing (NDT) methods have been developed and employed as a means of rapid and effective structural inspection. Despite the various kinds of NDT methods developed for bridge inspection, not much study has been performed on their usage and effectiveness at a practical level. This paper presents an evaluation of NDT methods to identify how they are implemented in state agencies in the U.S. The findings and analysis presented herein were based on the results obtained from a survey questionnaire, targeted at Departments of Transportation (DOTs) in all U.S. states and territories. The survey questionnaire was initiated to clarify multiple issues regarding NDT implementation, such as identifying the types of inspection that involve NDT methods, effective methods of inspecting concrete structures, and so on. A total of 40 state agencies participated in the survey processing, and the major findings obtained from the states are explained in detail in this paper.

INTRODUCTION

According to the data from the Bureau of Transportation Statistics, there are more than 600,000 highway bridges in the U.S., among which around 25% are rated as either structurally deficient, functionally obsolete, or both (Bureau of Transportation Statistics 2009). The number of structurally deficient or functionally obsolete bridges by state can be found in Minchin et al. (2006). Some critical defects in a bridge can be missed and may eventually lead to catastrophic bridge collapses such as the Silver Bridge collapse in Point Pleasant, West Virginia (LeRose 2001). Over the last several decades, non-destructive testing (NDT) methods have been developed and employed as a means of rapid and effective structure inspections. The implementation of NDT methods has drastically impacted the time required to detect, analyze, and diagnose a host of structural problems such as cracks, voids, fatigue, delamination, corrosion, and loss of cross section. While some NDT methods are simple, many are very complicated and require significant operator training.

While research on the application of specific NDT methods can be easily found from multiple sources, a study on NDT usage by state DOTs for their bridge management programs has not been performed actively in the literature (Rens et al. 1997; Rolander et al. 2001). From the literature review, it was clear that there is a need to make a further study on the NDT usage in state agencies since previous
studies failed to deliver in-depth knowledge on the use or effectiveness and did not properly reflect currently available NDT methods.

The main objective of this paper is to clarify how, when, and where state DOTs utilize NDT methods specifically for highway bridge inspections. This was accomplished by developing and distributing a survey questionnaire to as many U.S. state DOTs as possible. The questionnaire was launched to accomplish several objectives: (1) to identify the circumstances that state DOTs contract out for bridge inspections, (2) to determine the types of inspections that involve NDT methods, (3) to identify bridge components that are most likely to be inspected with NDT, (4) to evaluate the degree of difficulty of each NDT method, and (5) to gauge the degree of effectiveness of each NDT method.

SURVEY QUESTIONNAIRE

Survey methodology

The objective of the survey questionnaire was to investigate how NDT technologies are being utilized in U.S. bridge inspection programs. Therefore, all 52 states and territories of the U.S. were initially targeted for survey distribution. The NDT technologies covered were chosen based on those covered in the Bridge Inspector’s Reference Manual published by the Federal Highway Administration in 2006 (Ryan 2006). The 2006 FHWA manual was chosen for several reasons: (1) It provides a comprehensive guide for all state agencies for conducting bridge inspections, (2) Many state DOTs widely use this document as a primary reference, and (3) It is the most recent publication of its type. From the reference manual, sixteen NDT methods were chosen for concrete structure inspection. These are: Acoustic emission, electrical method, delamination detection machinery, ground penetrating radar, electromagnetic methods, pulse velocity, impact-echo testing, infrared thermography, ultrasonic testing, laser ultrasonic testing, magnetic method, neutron probe, nuclear method, pachometer, smart concrete, and rebound and penetration.

Survey questionnaire design

The survey questionnaire was created using an online service to minimize the time required to take the survey, and for ease of distribution of the questionnaire. The questionnaire was designed to seek statistics on level of usage, perceived ease of use, perceived difficulty of operation, division of in house versus contractor work, and the most common applications of NDT technologies from each state department of transportation. Typically, bridge inspection personnel’s schedules are pretty tight, splitting their time between their regional office and the field. Thus, it was critical to keep the questionnaire as brief as possible to be taken in under an hour.

The questionnaire consisted of four major categories described in detail below. Despite its common use by bridge inspection units, the questionnaire did not consider visual inspections since they are well documented by previous studies.

1. **Who inspects highway bridges?** This category investigated what percentage of bridge inspection work was done in-house or contracted out to a third-party.
In which types of inspection is NDT being considered? The respondent was asked to rate each type of inspection based on how often an NDT technology was considered for that category. The types of inspections include: initial inspection, routine inspection, damage inspection, in-depth inspection, fracture-critical inspection, underwater inspection, and special inspection.

To which bridge components is NDT commonly applied? The respondent was asked to rate a list of bridge components based on how often an NDT technology was considered for that component. A wide range of bridge components were investigated, including superstructure and substructure.

What types of NDT methods are used for concrete structures, and how effective are those methods? The respondent was asked to rate a list of applicable NDT methods for concrete structures for effectiveness on a five degree scale ranging from very effective to not effective. Additionally, respondents were asked to rate the difficulty of application of NDT methods for concrete structures, on a five degree scale ranging from very difficult to very easy.

Process of survey questionnaire

The questionnaire was targeted at bridge inspection unit managers or a similar high level position within a state’s bridge inspection program. The respondents were contacted by looking up their contact information in their respective agency’s online directory. In cases where the bridge unit’s contact information was not listed, the main agency office had to be contacted.

Survey distribution began on February 14th, 2012. Since each agency’s target contact had to be found, the surveys were distributed to one respondent at a time. The distribution period was initially set from mid-February to mid-April, but was extended to May 1st. Of the 52 states and territories, a total of 40 responded, equivalent to a 76% response rate (Refer to Figure 1).

![Figure 1. Map of States Surveyed](image)

ANALYSIS AND RESULTS OF SURVEY QUESTIONNAIRE

The findings and results obtained from survey questionnaire on the ease of use and the level of effectiveness of NDT methods are presented below.

Allocation of state bridge inspection labor
The analysis of collected responses showed that state agencies conduct 74% of the total bridge inspection workload on average, while outside contractors are responsible for 26%. Six states, Connecticut, Florida, Nevada, New Jersey, South Dakota, and Texas, are exceptions, contracting greater than 60% of bridge inspection work to third parties. Alaska, Arizona, Hawaii, Minnesota, New York, North Dakota, Washington, and Wisconsin perform 100% of their general inspection work in house. California, Georgia, Idaho, Iowa, Kansas, Louisiana, Maine, Mississippi, and Ohio contract out less than 2% of their bridge inspection work.

**Application of NDT methods by inspection types**

Each respondent was asked to rate each inspection type on a five degree scale: very often considered, often considered, sometimes considered, rarely considered, and not considered. Table 1 shows the survey responses by percentage. The data shows that while there is some variability among the states surveyed, NDT methods are considered for every type of inspection. However, in the initial inspection category, 48% of states did not consider NDT methods for this inspection type. Also, 43% of states rarely or never use NDT methods for routine inspections. NDT usage in underwater inspections also appears to be very minimal.

Responses for damage and special inspections indicated that NDT methods are frequently used in these cases, with “Not considered” response percentages of 5% and 0%, respectively.

**Table 1. NDT Usage by Inspection Type**

| Inspection Type | Very Often Considered (%) | Often Considered (%) | Sometimes Considered (%) | Rarely Considered (%) | Not Considered (%) |
|-----------------|---------------------------|----------------------|--------------------------|-----------------------|-------------------|
| Initial         | 10                        | 5                    | --                       | 37                    | 48                |
| Routine         | 12                        | 12                   | 33                       | 23                    | 20                |
| Damage          | 20                        | 37                   | 38                       | --                    | 5                 |
| In-Depth        | 32                        | 17                   | 30                       | 13                    | 8                 |
| Fracture-Critical | 22                        | 32                   | 33                       | 5                     | 8                 |
| Underwater      | 7                         | 8                    | 35                       | 30                    | 20                |
| Special         | 25                        | 35                   | 30                       | 10                    | --                |

**Allocation of state bridge inspection labor when NDT is required**

Respondents were asked to describe the allocation of labor when NDT methods are required. They were asked to assign a percentage to either in house or contract work based on inspection types. Most types of inspections are performed by state agencies except underwater inspections. Underwater inspections heavily rely on outside contractors mainly because the inspections are inherently dangerous to inspectors and require special training, as indicated by Stromberg (2010).

**Application of NDT methods on bridge components**

Each respondent was asked to rate each bridge component’s frequency of consideration on a five degree scale: very often considered, often considered, sometimes considered, rarely considered, and not considered. Three different
categories of bridge components were considered, bridge decks, superstructure components, and substructure components. The bridge components considered are: decks, beams and girders, truss members, cables, rivets bolts and welding, pins and hangars, bearings, paint, abutments, retaining walls, piers and bents, pile bents, dolphins and fenders, footings and foundations, and culverts as bridges. Tables 2 and 3 present the survey results by percentage for each component of the three categories. The data collected from this question indicate that NDT methods are frequently used to inspect components of bridge superstructure, and seldom used to inspect substructure components. However, there are exceptions in the superstructure, such as bearings and paint.

Table 2. NDT Usage for Bridge Deck and Superstructure Components

| Bridge Component          | Very Often Considered (%) | Often Considered (%) | Sometimes Considered (%) | Rarely Considered (%) | Not Considered (%) |
|---------------------------|---------------------------|----------------------|--------------------------|-----------------------|-------------------|
| Deck                      | 17                        | 18                   | 35                       | 15                    | 15                |
| Beams & Girders           | 10                        | 17                   | 60                       | 10                    | 3                 |
| Truss Members             | 17                        | 25                   | 50                       | 8                     | -                 |
| Cables                    | 12                        | 22                   | 33                       | 13                    | 20                |
| Rivets, Bolts, & Welding  | 20                        | 37                   | 33                       | 10                    | -                 |
| Pins & Hangars            | 50                        | 32                   | 18                       | -                     | -                 |
| Bearings                  | -                         | -                    | 22                       | 55                    | 23                |
| Paint                     | -                         | 10                   | 20                       | 37                    | 33                |

Table 3. NDT Usage for Bridge Substructure Components

| Bridge Component          | Very Often Considered (%) | Often Considered (%) | Sometimes Considered (%) | Rarely Considered (%) | Not Considered (%) |
|---------------------------|---------------------------|----------------------|--------------------------|-----------------------|-------------------|
| Abutments                 | -                         | -                    | 20                       | 35                    | 45                |
| Retaining Walls           | -                         | -                    | 12                       | 35                    | 53                |
| Piers & Bents             | -                         | -                    | 37                       | 35                    | 28                |
| Pile Bents                | -                         | -                    | 31                       | 33                    | 36                |
| Dolphins & Fenders        | -                         | -                    | 10                       | 45                    | 45                |
| Footings & Foundations    | -                         | -                    | 25                       | 37                    | 38                |
| Culverts as Bridges       | -                         | -                    | 7                        | 45                    | 48                |
Table 4 provides an overall look at the level of preference for NDT methods for bridge components. Each component was assigned a score from -2 to +2 to calculate preference scores \((P_s)\), as described by Equation 1, based on the number of responses corresponding to the frequency of consideration scale. Based on this scoring system, pins, hangars, rivets, bolts, welding, beams, girders, and decks are the most commonly inspected components using NDT methods. All substructure components received negative preference scores, indicating that they are rarely inspected using NDT.

\[
P_s = 2s_1 + 1s_2 + 0s_3 - 1s_4 - 2s_5
\]  

(1)

Where \(s_1\) = number of very often considered responses; \(s_2\) = number of often considered responses; \(s_3\) = number of sometimes considered responses; \(s_4\) = number of rarely considered responses; and \(s_5\) = number of not considered responses.

| Bridge Component         | NDT Preference Score \((P_s)\) | Bridge Component         | NDT Preference Score \((P_s)\) |
|--------------------------|-------------------------------|--------------------------|-------------------------------|
| Decks                    | 3                             | Abutments                | -50                           |
| Beams & girders          | 9                             | Retaining Walls          | -56                           |
| Truss Members            | 21                            | Piers & Bents            | -36                           |
| Cables                   | -2                            | Pile Bents               | -41                           |
| Rivets, Bolts, & Welding | 27                            | Dolphins & Fenders       | -54                           |
| Pins & Hangers           | 53                            | Footings & Foundations   | -45                           |
| Paint                    | -41                           | Culverts as Bridges      | -56                           |

**Table 4. NDT Preference Score for Bridge Components**

**Degree of difficulty for application of NDT methods to concrete structures**

Each respondent was asked to rank how difficult each NDT method is to use on a five degree scale: very difficult, somewhat difficult, moderate, somewhat easy, and very easy. The results illustrate which NDT methods are the easiest for an operator to use in the field for a concrete structure and the exposure level of each NDT method. Surprisingly, every NDT method received a large number of “no experience” responses, indicating that state agencies use only a few NDT methods, and that there is a large degree of variability between agencies as to what NDT methods they use to inspect concrete structures. A lower value for the exposure percentage indicates that the NDT method has been used rarely by state agencies. The following methods received the lowest exposure percentages for concrete methods: laser ultrasonic testing (10%), neutron probe (5%), nuclear method (5%), and smart concrete (10%). These technologies require very expensive and complicated equipment and extensive training to be used properly.

Due to these constraints, it follows that these methods are more than likely to be operated by contractors when used for structural inspection. Table 5 illustrates the
difficulty of each NDT method \((D_f)\) for concrete inspection. A point system (Equation 2) was used to give each method a score, with a higher score meaning greater difficulty. “No experience” responses were not considered in the calculation of the score.

\[
D_f = \frac{5d_1 + 4d_2 + 3d_3 + 2d_4 + 1d_5}{N}
\]  

(2)

Where \(d_1\) = number of very difficult responses; \(d_2\) = number of somewhat difficult responses; \(d_3\) = number of moderate responses; \(d_4\) = number of somewhat easy responses; \(d_5\) = number of very easy responses; and \(N\) = total number of responses.

A score for a NDT method between 0 and 2 can be considered easy to use, between 2 and 4 moderately difficult to use, and greater than 4 difficult to use. The magnetic method, rebound and penetration and pachometer are the least difficult methods. Medium difficulty methods include electrical methods, delamination detection machinery, ground penetrating radar and ultrasonic testing. The most difficult methods to use are the nuclear method and acoustic emission.

Table 5. Concrete NDT Methods: Difficulty Score

| NDT Method                      | Degree of Difficulty \((D_f)\) | Standard Deviation | NDT Method                      | Degree of Difficulty \((D_f)\) | Standard Deviation |
|--------------------------------|-------------------------------|--------------------|--------------------------------|-------------------------------|--------------------|
| Acoustic Emission              | 3.75                          | 0.85               | Ultrasonic Testing             | 3.15                          | 0.86               |
| Electrical (Half-Cell) Method  | 2.89                          | 1.15               | Laser Ultrasonic Testing       | 3.50                          | 1.00               |
| Delamination Detection Machinery| 2.48                          | 1.12               | Magnetic Method                | 2.12                          | 0.93               |
| Ground Penetrating Radar       | 3.39                          | 0.88               | Neutron Probe                  | 3.00                          | 0.00               |
| Electromagnetic Methods (HERMES)| 3.25                          | 0.97               | Nuclear Method                 | 5.00                          | 0.00               |
| Pulse Velocity                 | 2.67                          | 1.15               | Pachometer                     | 2.21                          | 0.94               |
| Impact Echo Testing            | 3.50                          | 1.06               | Rebound and Penetration        | 1.38                          | 0.50               |
| Infrared Thermography          | 2.39                          | 1.14               | Smart Concrete                 | 2.00                          | 0.82               |

Effectiveness of NDT methods applied to concrete structures

Each respondent was asked to rank the effectiveness of defect detection of each NDT method on a five degree scale: very effective, somewhat effective, moderate, less effective, not effective, and no experience. The respondents were asked to evaluate sixteen NDT methods based on the five degree scale.
Based on the results of effectiveness, a point system (Equation 3) was used to give each method a score to calculate the degree of effectiveness \( E_f \), with a higher score being more effective. “No experience” responses were not considered in the calculation of the score.

\[
E_f = \frac{5e_1 + 4e_2 + 3e_3 + 2e_4 + 1e_5}{N}
\]  

(3)

Where \( e_1 \) = number of very effective responses; \( e_2 \) = number of somewhat effective responses; \( e_3 \) = number of moderate responses; \( e_4 \) = number of less effective responses; \( e_5 \) = number of not effective responses; and \( N \) = total number of responses.

An NDT method with a value for \( E_f \) between 0 and 2 can be considered not effective, between 2 and 4 moderately effective, and greater than 4 very effective. The results displayed in Table 6 show a high degree of variability in the perceived effectiveness of each NDT method, with many of the methods displaying a high standard deviation. Comparing these findings with those found in Table 5, no one NDT method is a “silver bullet” when inspecting concrete. Generally, most of the methods were reported to be somewhat difficult to use and somewhat effective. There was very little variability for the degree of effectiveness for each technology, with scores ranging from 2 to 4.

| NDT Method                        | Degree of Effectiveness \( (E_f) \) | Standard Deviation | NDT Method                        | Degree of Effectiveness \( (E_f) \) | Standard Deviation |
|-----------------------------------|-------------------------------------|--------------------|-----------------------------------|-------------------------------------|--------------------|
| Acoustic Emission                 | 2.85                                | 1.14               | Ultrasonic Testing                | 3.04                                | 1.32               |
| Electrical Method (Half-Cell)     | 3.11                                | 1.01               | Laser Ultrasonic Testing          | 2.00                                | 0.82               |
| Delamination Detection Machinery  | 3.71                                | 1.01               | Magnetic Method                   | 2.59                                | 1.23               |
| Ground Penetrating Radar          | 3.29                                | 1.01               | Neutron Probe                     | 4.00                                | 0.00               |
| Electromagnetic Methods (HERMES)  | 2.33                                | 0.78               | Nuclear Method                    | 2.50                                | 0.71               |
| Pulse Velocity                    | 2.42                                | 0.67               | Pachometer                       | 3.45                                | 0.91               |
| Impact Echo Testing               | 3.18                                | 1.01               | Rebound and Penetration           | 3.19                                | 0.83               |
| Infrared Thermography             | 3.11                                | 0.96               | Smart Concrete                    | 3.00                                | 0.00               |
Efficiency of concrete NDT methods

Based on Tables 5 and 6, an efficiency ratio can be calculated (Equation 4) for each concrete NDT method to illustrate which technologies are the “best”.

\[ \text{Efficiency Ratio} = \frac{E_f}{D_f} \]  

(4)

A high efficiency ratio indicates that the NDT method is more effective and less difficult, while a low efficiency ratio indicates the method is less effective and more difficult. The minimum and maximum possible values for the efficiency ratio are 0.2 and 5, respectively. The technologies were ranked from high to low. This study calculated efficiency ratio values from only two factors, the degree of difficulty and the degree of effectiveness of each technology. The results of this analysis are displayed in Table 7. By a wide margin, rebound and penetration has the highest efficiency ratio of all the concrete NDT methods. Fifty percent of concrete NDT methods had an efficiency ratio less than 1.0.

Table 7. Efficiency Ratio of Concrete NDT Methods

| NDT Method                        | Efficiency Ratio | NDT Method                        | Efficiency Ratio |
|-----------------------------------|------------------|-----------------------------------|------------------|
| Rebound and Penetration           | 2.32             | Ground Penetrating Radar          | 0.97             |
| Pachometer                        | 1.56             | Ultrasonic Testing                | 0.96             |
| Delamination Detection Machinery  | 1.50             | Pulse Velocity                    | 0.91             |
| Smart Concrete                    | 1.50             | Impact Echo Testing               | 0.91             |
| Neutron Probe                     | 1.33             | Acoustic Emission                 | 0.76             |
| Infrared Thermography             | 1.30             | Electromagnetic Methods (HERMES)  | 0.72             |
| Magnetic Method                   | 1.22             | Laser Ultrasonic Testing          | 0.57             |
| Electrical Method (Half-Cell)     | 1.08             | Nuclear Method                    | 0.50             |

CONCLUSIONS

The main contribution of this paper is an in-depth study on the usage of NDT methods in the U.S. at a practical level. In conclusion, major findings from this study can be described as follows.

- **Exposure**: it was surprising that only a few NDT methods are utilized in the field while a variety of methods have been studied and developed by researchers. Only four methods out of 16 showed higher than 60% exposure rate.
- **Difficulty**: it was found that state agencies consider most NDT methods difficult to use. This may be one of major reasons why NDT is not used actively. The only NDT method with a difficulty score less than two is rebound and penetration.
Effectiveness: Only one method in concrete, neutron probe, showed an effectiveness score higher than four, but it has very limited exposure.

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