2012

# INDOT Construction Inspection Priorities

Ali Mostafavi
*Purdue*, amostafa@purdue.edu

Dulcy M. Abraham
*Purdue University - Main Campus*, dulcy@ecn.purdue.edu

**JOINT TRANSPORTATION RESEARCH PROGRAM**

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

# INDOT CONSTRUCTION INSPECTION PRIORITIES

**Ali Mostafavi**
Ph.D. Candidate
School of Civil Engineering
Purdue University

**Dulcy M. Abraham**
Professor of Civil Engineering
Purdue University
*Corresponding Author*

SPR-3400
Report Number: FHWA/IN/JTRP-2012/09
DOI: 10.5703/1288284314669

## RECOMMENDED CITATION

Mostafavi, A., and D. M. Abraham. *INDOT Construction Inspection Priorities*. Publication FHWA/IN/JTRP-2012/09. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012. doi: 10.5703/1288284314669.



## CORRESPONDING AUTHOR

Professor Dulcy M. Abraham
School of Civil Engineering
Purdue University
(765) 494-2239
dulcy@ecn.purdue.edu



## ACKNOWLEDGMENTS

The authors would like to thank the members of the Study Advisory Committee (SAC) for their support and insightful feedback during the course of this project: Greg Pankow (State Construction Engineer, INDOT), Samy Noureldin (Transportation Systems Section Manager—Division of Research and Development, INDOT), Joseph Novak (Construction Director, Crawfordsville District, INDOT), Ronald Walker (Manager, Office of Materials Management, INDOT), Bren George (Construction Program Oversight Manager, Federal Highway Administration, Indiana Division), and Kevin Hall (Construction Manager, Parsons Brinckerhoff).

The authors are also grateful of the following individuals for their help during the site visits and the data collection phases: Jay Harris (INDOT), Daniel Rogers (Indianapolis Testing Lab), Dallas Caudill (HNTB), Kenny Brooks and Michael Stair (Parsons Brinckerhoff), Stephanie Morse and Colleen Merkel (ACEC Indiana), and Jeffery Shapiro (Nevada DOT).


## JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure.
https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at: http://docs.lib.purdue.edu/jtrp/

TECHNICAL REPORT STANDARD TITLE PAGE

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| FHWA/IN/JTRP-2011/09 | | |

| | |
|---|---|
| **4. Title and Subtitle**<br>INDOT Construction Inspection Priorities | **5. Report Date**<br>May 2012 |
| | **6. Performing Organization Code** |
| **7. Author(s)**<br>Ali Mostafavi, Dulcy M. Abraham | **8. Performing Organization Report No.**<br>FHWA/IN/JTRP-2011/09 |
| **9. Performing Organization Name and Address**<br>Joint Transportation Research Program<br>Purdue University<br>550 Stadium Mall Drive<br>West Lafayette, IN 47907-2051 | **10. Work Unit No.** |
| | **11. Contract or Grant No.**<br>SPR-3400 |
| **12. Sponsoring Agency Name and Address**<br>Indiana Department of Transportation<br>State Office Building<br>100 North Senate Avenue<br>Indianapolis, IN 46204 | **13. Type of Report and Period Covered**<br>Final Report |
| | **14. Sponsoring Agency Code** |

**15. Supplementary Notes**

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

## 16. Abstract


In the last decade, the Indiana Department of Transportation (INDOT) has experienced an increase in their construction projects (e.g., INDOT's construction spending was $789 million in 2006 and increased to $1,081.4 million in 2010); while the level of its in-house inspection staff and resources has either remained the same or declined. There are different strategies to deal with the need for construction inspection resources and they may include strategies such as outsourcing the inspection of construction activities and using quality control and quality assurance certification programs to reduce the need for in-process inspection. One strategy that could reduce the inspection workload is prioritizing construction activities for inspection. However, reducing the number of inspections also has risks, such as functional failures and reduced design life, if defects are not identified before the work is covered. Thus, available inspection resources should be allocated to the activities with significant risk consequences due to reduced inspection.

The objective of this study was to: (1) evaluate the current inspection practices of INDOT and (2) develop a risk-based inspection protocol to facilitate efficient allocation of available inspection resources to minimize the risks associated with reduced inspection. First, the current inspection practices implemented by INDOT, other State Departments of Transportation, and consulting firms were identified and compared. The comparison between the inspection practices revealed that there is consistency between INDOT's and consultants' and other State Departments of Transportation's inspection practices.

To develop a risk-based inspection protocol, first, the risk consequences associated with reduced inspection were identified for different transportation construction activities, based on the data collected from 20 site visits to INDOT projects. These risk consequences include short and long-term functional failures, reduced design life, reduced safety, and increased maintenance cost. Based on data collected from 23 state Departments of Transportation, 58 engineers and inspectors from the Indiana Department of Transportation (INDOT), and 20 inspection consultants in the Midwest, the subjective perceived probabilities associated with the occurrence of each risk consequence were encoded using fuzzy analysis. Using these subjective probabilities, the risk impacts due to reduced inspection were derived. The construction activities subsequently were prioritized based on the risk impacts associated with reduced inspection into five priority levels: high, medium-high, medium, medium-low, and low. The greater the risk impacts were due to reduced inspection, the higher the priority would be for inspection of that activity. The study also included identification of value added of inspection and the critical items to be watched for different activities related to transportation construction.

Deliverables of this project include: (1) an inspection protocol, (2) an inspection staffing guide and (3) a list of pay items whose documentation requirements need to be modified to enhance the documentation process. The inspection protocol created in this study could assist INDOT in efficient allocation of inspection resources to construction activities.


| 17. Key Words | 18. Distribution Statement |
|---|---|
| construction, inspection, risks, prioritization, pay items, fuzzy analysis, resources | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 39 | |

Form DOT F 1700.7 (8-69)

## EXECUTIVE SUMMARY

# INDOT CONSTRUCTION INSPECTION PRIORITIES

## Introduction

In the last decade, the Indiana Department of Transportation (INDOT) increased the number of construction projects funded by capital made available through the leasing of the Indiana Toll Road. However, during the same time period, the level of personnel available for construction inspection either remained the same or declined. Insufficiency of inspection resources could lead to reduction in inspection and, thus, increased occurrence of potential risk consequences such as short- and long-term functional failures, reduced design life, increased maintenance costs, and reduced safety. The objective of this study was to (1) evaluate the current inspection practices of INDOT and (2) develop a risk-based inspection protocol to facilitate efficient allocation of available inspection resources to minimize the risks associated with reduced inspection.

## Findings

To develop a risk-based inspection protocol, first, the risk consequences associated with reduced inspection were identified for different transportation construction activities, based on the data collected from 20 site visits to INDOT projects. These risk consequences include short- and long-term functional failures, reduced design life, reduced safety, and increased maintenance cost. Based on data collected from surveys administered to 23 State Departments of Transportation (DOTs), 58 engineers and inspectors from INDOT, and 20 inspection consultants in the Midwest, the subjective perceived probabilities associated with the occurrence of each risk consequence were encoded, and risk analyses were performed.

The findings from the study indicated the following:

- Different state DOTs pursue different inspection practices. The results of the survey showed that that 74% of the DOTs that responded had experienced changes in their inspection staffing level over the last five years.
- The lack of experience and the differing expertise of the maintenance workforce have reduced the efficiency of construction inspections.
- Forty-four percent (44%) of the DOT respondents do not consider their current inspection practices to be “efficient,” implying that inspection resources are not necessarily allocated appropriately to the most critical activities.
- Seventy-four percent (74%) of the state DOTs indicated that they do not have a protocol for prioritizing the inspection of construction activities.
- Seventy-five percent (75%) of the INDOT inspectors who responded to the survey tend to implement full inspection for high-risk activities and random inspection for low-risk activities.
- The lack of training for new inspectors, limited overtime, and the current system for payment documentation were recognized to be the main causes of the inefficiency of current INDOT inspection practices.
- INDOT’s inspection practices are more conservative than those of other DOTs for some activities. Activities whose inspection is implemented more conservatively include bolting structural connections, post-tensioning, pipe placement, sub-grade treatment, retaining walls, aggregate base course, and embankment.
- The level of resources allocated for inspection of an activity is affected by the sequence of the work in a project, as well as the project schedule. In some cases, all available inspection staff may be allocated if there is only one activity in progress. This does not imply that the activity is a necessarily a high-priority activity.

## Implementation

The deliverables of this study include the following:

1. A protocol for inspection of construction activities
2. An inspection staffing guide
3. A list of pay items to enhance the documentation process

The inspection protocol could be used as a checklist for providing guidance to new inspectors. Using the inspection staffing guide, INDOT could enhance the current inspection practices by modifying the documentation requirements for the pay items whose contract value does not warrant the time required for documentation.

## Recommendations

1. The list of pay items for enhancement of inspection documentation could be used as a guide for allocation of inspection staff. Project engineers could use the inspection staffing guide to estimate the minimum of number inspectors for their projects.
2. The current documentation platform (SITEMANAGER) could be enhanced to reduce the required effort for inspection documentation.

CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

## 1. INTRODUCTION

State Departments of Transportation (DOTs) have experienced a growth in their funding for construction projects to restore and expand the aging transportation infrastructure in the U.S. The emergence of the Transportation Equity Act of 21st Century (TEA-21), State Infrastructure Banks, and the Transportation Infrastructure Finance and Innovation Act (TIFIA) enabled these agencies to expand the number of construction projects. For instance, the Texas Department of Transportation (TXDOT) experienced an increase of more than 44% in funding for construction during the last decade *(1)*.

In the last decade, the Indiana Department of Transportation (INDOT) increased the number of construction projects funded by capital made available through the leasing of the Indiana Toll Road. However, during the same time period, the level of personnel available for construction inspection either remained the same or declined. The limitation of available inspection resources is in part attributable to: (1) retirement of experienced inspectors, (2) departure of experienced inspectors to private firms, and (3) insufficient training of new inspectors *(2)*. To address this problem, "state Departments of Transportation are addressing their workforce challenges by outsourcing key project responsibilities that were previously performed by in-house state DOT forces and adapting their practices to perform construction administration more efficiently" *(1)*. In a search for strategies for inspection workload reduction, Jagers-Cohen et al. *(1)* identified the best strategy to be the creation of a checklist for prioritization of different construction activities that help inspectors prioritize inspection elements. This strategy seeks allocation of the available resources for the inspection of the most critical construction activities. However, currently there is no formal approach (e.g., checklists) to determine and to prioritize the most critical activities, and to identify whether or not the inspection efforts of the state DOTs are indeed focused on these activities.

## 2. PROBLEM STATEMENT

Insufficiency of resources could lead to reduction in inspection and, thus, increased occurrence of potential risk consequences such as short and long-term functional failures, reduced design life, increased maintenance costs and reduced safety. Therefore, available resources should be allocated to the construction activities whose risk consequences due to reduced inspection are significant. Prioritization of construction activities for inspection to effectively spend time, effort, and money on the inspection of these activities is a prudent approach in addressing inspection workload. Currently, there is no formal approach to determine whether or not INDOT's inspection efforts are focused on the most important activities to deal with insufficiency of current construction inspection resources.

## 3. OBJECTIVES

Failures in a construction project may arise due to design problems, improper implementation of construction practices, equipment-caused failures, or issues not directly linked to inspection. However, inspection may be able to help in the identification of poor construction practices and/or help in ensuring that materials not meeting specifications are not installed/ placed. If construction inspection is performed effectively, there is significant potential to reduce the probability of remedial actions downstream.

The objective of this study was to develop a risk-based inspection protocol that meets INDOT's need for efficient allocation of available resources for the expected increase in construction projects. The research focuses on construction inspection and documentation practices and does not assess materials testing. The current testing frequencies will be assumed as a means of integrating these activities with other inspection priorities. The key questions that were addressed are:

1. What items/activities should be inspected while there are more than two construction activities taking place concurrently on the jobsite and the resources for inspection are not sufficient to perform complete inspection of these activities?
2. What is the value-added of inspection of different construction activities?
3. What are the critical items to be inspected for different construction activities?
4. What are pay-items which take the most time for Final Construction Record (FCR) documentation and whose values do not warrant the time required for documentation?
5. What is the inspection staffing requirement for different construction activities to reduce the probability of missing the inspection of a critical item?

To accomplish these objectives, the following research tasks were implemented:

1. Seventeen site visits from five INDOT projects (Figure 3.1 and Table 3.1) were implemented to identify the current state of inspection practices on INDOT projects through interviews with INDOT inspectors and consultants who implement construction inspection for INDOT.
2. Three sets of surveys were deployed to state DOTs, consultants who implement construction inspection for INDOT, and INDOT area engineers and project engineers/supervisors to evaluate the inspection practices of INDOT and compare the responses from INDOT engineers and engineers with those of other state DOTs and consultants.
3. Quantitative risk analysis and probability encoding were implemented to evaluate the risk impacts due to missed inspection.
4. An inspection protocol was developed based on the risk impacts calculated from the risk analysis to prioritize construction activities for inspection.

**SIR-30843-A on SR 25**
**7-1-2010**

**SRS-31918-A on I-65**
**6-10-2010**

**SRS-31918-A on I-65**
**8-4-2010**

**SIR-30843-A on SR 25**
**7-1-2010**

**SB-28901-A US 52**
**Norfolk**
**8-12-2010**

**R-30576-A on SR 38**
**8-2-2010**

**Figure 3.1** Site visits for data collection.

TABLE 3.1
**Site Visits to INDOT Projects**

| No. | Project | Date of Site Visit | Organization Conducting the Inspection | Type of Interviews and Activities Observed |
|---|---|---|---|---|
| 1 | SIR-30843-A on SR 25 | 5-28-2010 | HNTB | Interviewing project inspectors regarding consequences of missed/ reduced inspection |
| 2 | SIR-30843-A on SR 25 | 6-22-2010 | HNTB | Interviewing project inspectors regarding consequences of missed/ reduced inspection |
| 3 | SIR-30843-A on SR 25 | 7-1-2010 | HNTB | Bridge construction, and base course earthwork |
| 4 | SRS-31918-A on I-65 | 6-3-2010 | Indianapolis testing lab | Interviewing project inspectors regarding consequences of missed/ reduced inspection |
| 5 | SRS-31918-A on I-65 | 6-10-2010 | Indianapolis testing lab | Base course earthwork, base stabilization, bridge construction, and culvert construction |
| 6 | SRS-31918-A on I-65 | 6-16-2010 | Indianapolis testing lab | Base course earthwork, base stabilization, bridge construction, and culvert construction |
| 7 | SRS-31918-A on I-65 | 7-08-2010 | Indianapolis testing lab | Base stabilization, asphalt paving, bridge construction, and culvert construction |
| 8 | SRS-31918-A on I-65 | 8-04-2010 | Indianapolis testing lab | Base stabilization, asphalt paving, and bridge construction |
| 9 | SB-28901-A US 52 | 6-1-2010 | PBWorld | Interviewing project inspectors regarding consequences of missed/ reduced inspection |
| 10 | SB-28901-A US 52 | 6-30-2010 | PBWorld | Base course earthwork and bridge construction |
| 11 | SB-28901-A US 52 | 8-12-2010 | PBWorld | Base course earthwork and bridge construction |
| 12 | SB-28901-A US 52 | 9-23-2010 | PBWorld | Base course earthwork and bridge construction |
| 13 | R-30576-A on SR 38 | 6-2-2010 | INDOT | Interviewing project inspectors regarding consequences of missed/ reduced inspection |
| 14 | R-30576-A on SR 38 | 6-18-2010 | INDOT | Base course earthwork and pipe installation |
| 15 | R-30576-A on SR 38 | 7-09-2010 | INDOT | Base course cement stabilization |
| 16 | R-30576-A on SR 38 | 8-02-2010 | INDOT | Concrete paving |
| 17 | R-31484-A on SR 38 | 6-24-2010 | INDOT | Interviewing project inspectors regarding consequences of missed/ reduced inspection |
| 18 | SRS-31918-A on I-65 | 5-05-2011 | Indianapolis testing lab | Validation of the protocol |
| 19 | SB-28901-A on US 52 | 5-10-2011 | PBWorld | Validation of the protocol |
| 20 | R-31651-A on US 52 | 5-26-2011 | INDOT | Validation of the protocol |

# 4. FINDINGS

The findings of this study include: (1) the current state of inspection practice by the state DOTs, consultants and INDOT, (2) risk assessment of transportation construction projects and prioritization of construction activities, (3) added value of inspection, and (4) the effects of work sequence and project schedule on the level of inspection.

## 4.1 Current State of Practice in State DOTs, Consultants, and INDOT

To evaluate the current state of practice regarding the inspection of construction activities, a survey was deployed by the research team of this study to all state DOTs in the summer of 2010, 23 of which responded (Table 4.1). The findings from the survey indicated that inspection practices are different in state DOTs. The results of the survey showed that 74% of the state DOTs that responded had experienced changes in their inspection staffing level over the last five years. On the other hand, the Ohio, Illinois, and North Carolina Departments of Transportation reported inspection staff growth. However, this growth was not proportional to the growth in the number of construction projects. None of the state DOTs that responded has a program or procedure for determining number of inspectors for construction activities.

For Departments of Transportation in states, such as Indiana and Texas, which experienced reduction of inspection workforce, the workforce typically assigned to maintenance activities were now performing construction inspection activities. Respondents to the survey stated that the lack of experience and the differing expertise of the maintenance workforce had reduced the efficiency of their construction inspections.

TABLE 4.1
**State DOTs that Responded to the Survey**

| | |
|---|---|
| Alaska | North Dakota |
| Arkansas | New Jersey |
| Colorado | Ohio |
| Georgia | Oklahoma |
| Illinois | Oregon |
| Iowa | Tennessee |
| Kansas | Utah |
| Louisiana | Vermont |
| Michigan | Washington |
| Nebraska | West Virginia |
| Nevada | Wisconsin |
| North Carolina | |

Eighty-three percent of the responding state DOTs stated that they implement their construction inspection using both in-house and outsourced inspectors. Forty-four percent of the DOT respondents do not consider their current inspection practices to be "efficient," implying that inspection resources are not necessarily allocated efficiently to the most critical activities. Sixty five percent of state DOTs seek full observation of certain construction activities and inspect other activities when resources are available; the remaining 35% require contractor certification with a quality control (QC) program and provide random inspection for quality assurance (QA). Also, 74% of the state DOTs indicated that they do not have a protocol for prioritizing the inspection of construction activities. Among the remaining 26%, Nevada DOT indicated having informal guidelines for prioritizing inspection of construction activities. The prioritization of construction activities for inspection is left to the experience and judgment of the inspectors on the construction site. With a high rate of retirement and departure of experienced inspectors from the state DOTs, the significant challenge facing new inspectors is prioritization of construction activities for inspection.

To evaluate the current state of practice regarding the inspection of construction activities by consultants which implement construction inspection for INDOT, a survey was deployed by the research team of this study to 83 consultants in the Midwest in the summer of 2010 (Table 4.2). The findings from the survey (based on 20 responses) indicate that 90% of the consultants who responded perceive their current construction inspection practices to be efficient. The comparison between the findings from the survey deployed to state DOTs with those of the surveys deployed to consultants reveals that: (1) there is consistency between consultants' and Departments of Transportation' inspection practices; and (2) consultant's inspection practices are more conservative compared to those of state DOTs. Activities whose inspection is implemented more conservatively by consultants include:

- Bolting structural connections
- Post-tensioning
- Drainage
- Traffic markings
- Pipe placement
- Sound wall post placement
- Sub-grade treatment
- Retaining walls
- Aggregate base course
- Embankment
- Reinforcement steel in structures

To evaluate the current state of practice regarding the inspection of construction activities by INDOT project inspection staff and area engineers, a survey was deployed by the research team of this study to project engineers/supervisors, and area engineers of INDOT districts in the Fall of 2010. Table 4.3 shows the number of responses per INDOT district. The findings from the survey indicated that 75% of the project engineers/supervisors who responded tend to implement full inspection for certain activities (high risk) and implement inspection for the other activities (low risk) if inspection staff are available. Only 57% of the project engineers /supervisors who responded consider their current inspection practices to be efficient. Lack of training for new inspectors, limited overtime and the current system for payment documentation were recognized to be the main causes of inefficiency of current INDOT inspection practices. Also, there is no consistent inspection approach for different activities among the INDOT project engineers/supervisors and area engineers.

The comparison between the findings from the survey deployed to INDOT project engineers/supervisors and area engineers with those of the surveys deployed to consultants and the state DOTs reveals that: (1) there is consistency between the inspection practices of INDOT, consultants, and other Departments of Transportation (Table 4.4); and (2) for some activities, INDOT's inspection practices are more conservative compared to that of other Departments of Transportation. Activities whose inspection is implemented more conservatively include:

TABLE 4.2
**Consultants Who Responded to the Survey**

| | |
|---|---|
| Murray, Smith & Associates, Inc. | R. W. Armstrong |
| PCS Engineers | Rowe PSC |
| Ayres Associates | Hatch Mott MacDonald |
| Bernardin Lochmueller & Associates, Inc. | Butler, Fairman & Seufert, Inc. |
| | URS Corporation |
| Mead & Hunt, Inc. | Johnson, Mirmiran & Thompson |
| RQAW Corporation | HNTB Corp. |
| Alfred Benesch & Company | Bollinger, Lach & Associates, Inc. |
| Wilbur Smith Associates, Inc. | United Consulting |
| Strand Associates | USI Consultants, Inc. |
| HWC Engineering | |

TABLE 4.3
**Responses from INDOT Districts**

| District | Number of Responses |
|---|---|
| Fort Wayne | 11 |
| Greenfield | 9 |
| Laporte | 10 |
| Seymour | 9 |
| Vincennes | 5 |
| Crawfordsville | 14 |
| Total | 58 |

TABLE 4.4
**Inspection Practices of INDOT (I), State DOTs (D), and Consultants (C)**

| Construction Activity | Full Supervision | Regular Supervision (High Priority) | Occasional Supervision (Low Priority) | Random Inspection | Inspection of Finished Product Only |
|---|---|---|---|---|---|
| Traffic control—set up | IC | ICD | | | C |
| Clearing site | | C | ICD | ID | D |
| Stripping | C | I | ICD | ID | D |
| Clearing site—bridge | C | IC | ICD | ID | I |
| Installing soil erosion/sediment control items | C | ICD | I | | |
| Excavation | | IC | ICD | D | |
| Blasting | ICD | ICD | C | | |
| Handling /removal of regulated waste | IC | ICD | | | |
| Aggregate base courses | IC | ICD | | | |
| Embankment | IC | ICD | D | | |
| Milling | | ICD | ICD | CD | D |
| Asphalt paving | ICD | ID | | | |
| Concrete paving | ICD | ID | | | |
| Concrete forms (structures) | | IC | ID | D | D |
| Reinforcement steel in structures | C | ICD | | D | |
| Placement of concrete in structures | ICD | D | | | |
| Structure rehabilitation (repairs to concrete deck) | ICD | ICD | | | |
| Drilled shafts | C | ID | | | |
| Driven piles | ICD | ID | | | |
| Sheet piles | IC | ICD | D | | |
| Cofferdams | C | ICD | I | | |
| Beam erection | IC | ID | | | |
| Bolting structural connections | IC | ICD | | | |
| Post-tensioning (pre-stressed structures) | IC | ID | | | |
| Painting steel | | ICD | ICD | D | |
| Guardrail/cable rail | | ICD | ICD | D | |
| Barrier curb | I | ICD | ICD | | |
| Sidewalk | | IC | ICD | D | |
| Drainage | C | ICD | ID | | |
| Traffic stripes/traffic markings | IC | ICD | IC | | D |
| Fence | | | ICD | ICD | D |
| Electrical conduit and wiring | | ICD | ICD | D | |
| ITS—fiber optic conduit and cable | | ICD | ICD | D | |
| Highway lighting (foundations and poles) | | ICD | ID | | |
| Traffic signals (foundations and poles) | | ICD | ID | | |
| Overhead sign structures | I | ICD | ID | | |
| Landscape plantings | | | ICD | ID | ID |
| Pipe placement | IC | ICD | | | |
| Seal coating | I | ICD | ICD | | |
| Sound wall post placement | C | ICD | ICD | | |
| Sound wall panel placement | | ICD | ICD | | |
| Placement of lighting features | | IC | ICD | D | |
| Sub-grade treatment | IC | ICD | D | | |
| Retaining walls | IC | ICD | | | |

- Bolting structural connections
- Post-tensioning
- Pipe placement
- Sub-grade treatment
- Retaining walls
- Aggregate base course
- Embankment

## 4.2 Prioritization of Construction Activities

To minimize the risks associated with reduced inspection due to insufficient resources, inspection of construction activities should be prioritized. Construction activities that present significant risks as a result of reduced/missed inspection should be given a higher priority for inspection. The decision regarding whether to inspect a construction activity now, later, or never should be made based on the subsequent risks. If the inspection of the activity cannot be implemented at a later time, there will be micro and macro risk consequences associated with the missed/reduced inspection as shown in Figure 4.1. Micro consequences are consequences such as longitudinal cracks in asphalt or soil settlement in an embankment. One or more micro consequences would lead to a macro consequences such as short-term functional failures or reduced design life. The results of the risk analysis are summarized in Table 4.5. The process of risk analysis and probability encoding used in this study, is described in detail in Appendix A.

The results presented in Table 4.5 are based on the responses of 101 experts from state DOTs, consultants, and INDOT. The values in the table indicate the average perceived risk impacts due to reduced inspection for different construction activities. For instance, for concrete paving, the average perceived risk impact due to reduced inspection is 64% based on all the responses. This result implies that if the inspection of concrete paving is reduced/missed, it is perceived that the likelihood of occurrence of macro consequences would be 64%. While these values do not reflect the actual risk impacts due to the existence of biases, they can be used to identify the construction activities with greater risk impacts due to reduced inspection.

To assess whether the obtained results are sensitive to the responses from different groups of experts, the analyses were performed separately for the responses of experts from the state DOTs, consultants, and INDOT. The results of the separate analyses are also shown in Table 4.5. The results indicate that the encoded probabilities from the different groups of experts are very close. For instance, for embankment activity, the encoded probabilities obtained from the state DOTs, consultants, and INDOT surveys are equal to 56%, 55%, and 58%, respectively. This result implies that (1) there is no significant difference in the risk attitude of the group of experts from the state DOTs, consultants, and INDOT; and (2) the methodology used in the study was successful in eliciting the beliefs of the experts.

In order to prioritize inspection activities based on the level of risks due to missed inspections, a risk-based inspection protocol can be created. The greater the average risk impact of a construction activity, the higher the priority of the activity for inspection. Initially, three categories of priorities of construction activities for inspection were defined: *High, Medium, and Low*. The boundaries of the different categories were set since an analysis of the survey results indicated that 95% of the average values of encoded perceived probabilities of risk outcomes were greater than 30% and less than 65%. Therefore, the range (i.e., 30% to 65%) was divided into three intervals (below 40%, between 40% and 55%, and above 55%). If

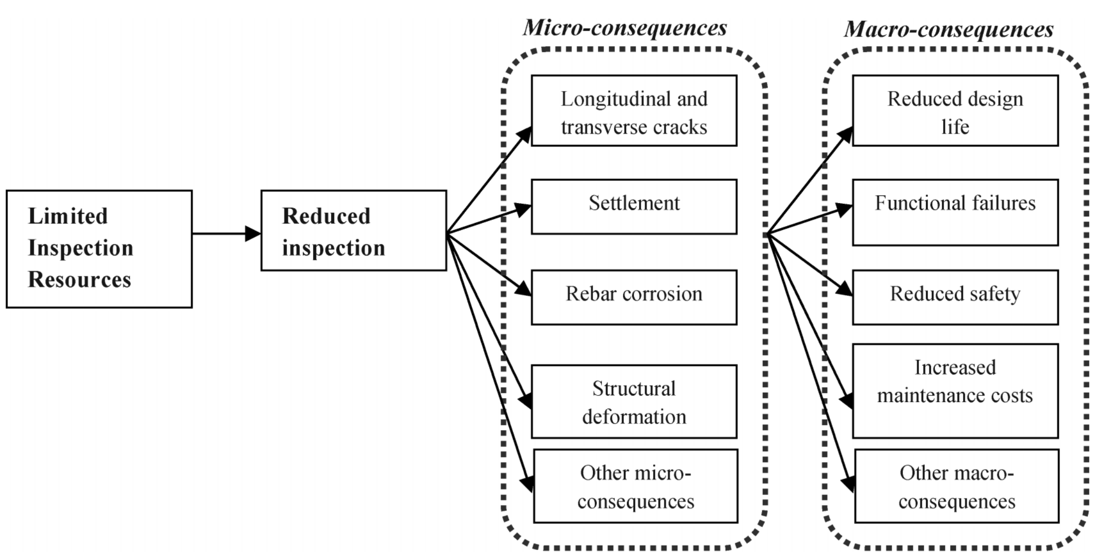


**Figure 4.1** Micro and macro risk consequences due to missed/reduced inspection.

TABLE 4.5
**Average Risk Impacts Due to Reduced/Missed Inspection**

| Construction Activity | All Responses | DOT | Consultants | INDOT |
|---|---|---|---|---|
| Traffic control—set up | 43% | 48% | 46% | 40% |
| Clearing site | 32% | 34% | 30% | 32% |
| Stripping | 37% | 38% | 34% | 38% |
| Clearing site—bridge | 34% | 37% | 31% | 34% |
| Installing soil erosion/sediment control items | 46% | 46% | 47% | 45% |
| Excavation | 46% | 46% | 46% | 46% |
| Blasting | 44% | 44% | 44% | 45% |
| Handling/removal of regulated waste | 45% | 42% | 46% | 47% |
| Aggregate base courses | 58% | 57% | 57% | 59% |
| Embankment | 57% | 56% | 55% | 58% |
| Milling | 42% | 41% | 39% | 44% |
| Asphalt paving | 63% | 65% | 58% | 64% |
| Concrete paving | 64% | 64% | 59% | 65% |
| Concrete forms (structures) | 49% | 45% | 48% | 52% |
| Reinforcement steel in structures | 57% | 55% | 56% | 58% |
| Placement of concrete in structures | 61% | 61% | 59% | 62% |
| Structure rehabilitation (repairs to concrete deck) | 60% | 61% | 57% | 60% |
| Drilled shafts | 51% | 57% | 52% | 49% |
| Driven piles | 58% | 57% | 56% | 60% |
| Sheet piles | 49% | 50% | 45% | 49% |
| Cofferdams | 45% | 44% | 37% | 48% |
| Beam erection | 54% | 52% | 51% | 56% |
| Bolting structural connections | 58% | 59% | 58% | 58% |
| Post-tensioning (pre-stressed structures) | 58% | 60% | 59% | 57% |
| Painting steel | 50% | 57% | 49% | 48% |
| Guardrail/cable rail | 50% | 56% | 50% | 49% |
| Barrier curb | 48% | 49% | 44% | 48% |
| Sidewalk | 46% | 44% | 44% | 47% |
| Drainage | 54% | 54% | 54% | 54% |
| Traffic stripes/traffic markings | 52% | 56% | 50% | 51% |
| Fence | 37% | 41% | 35% | 37% |
| Electrical conduit and wiring | 46% | 51% | 40% | 46% |
| ITS—fiber optic conduit and cable | 46% | 54% | 39% | 45% |
| Highway lighting (foundations and poles) | 49% | 50% | 47% | 50% |
| Traffic signals (foundations and poles) | 50% | 52% | 49% | 49% |
| Overhead sign structures | 49% | 55% | 47% | 48% |
| Landscape plantings | 37% | 43% | 38% | 35% |
| Pipe placement | 56% | 54% | 51% | 59% |
| Seal coating | 47% | 50% | 44% | 46% |
| Sound wall post placement | 46% | 47% | 42% | 47% |
| Sound wall panel placement | 45% | 46% | 40% | 46% |
| Placement of lighting features | 44% | 47% | 37% | 46% |
| Sub-grade treatment | 59% | 54% | 53% | 63% |
| Retaining walls | 57% | 56% | 56% | 58% |

the average probability of risk consequences was greater than 55%, the activity was considered to be *High Priority*; if the average probability of risk consequences was greater than 40% and less than 55%, the activity was considered to be *Medium Priority*; and if the average probability of risk consequences was less than 40%, the activity is considered to be *Low Priority.* Further analysis revealed that there are a number of activities whose average perceived probability of risk consequences due to missed inspection were close to the boundary values, which made it difficult to judge the priority category in which they could be placed.

Thus, two additional intermediate priority categories (i.e., *Medium-low* and *Medium-high*) were defined to address this issue. Table 4.6 summarizes the list of prioritized construction activities. The construction activities were then prioritized into five categories based on the risks associated with reduced inspection: *High, Medium-high, Medium, Medium-low, and Low*. The higher the priority of an activity for inspection, the greater the risk impacts due to reduced inspection would be. For instance, asphalt paving is categorized as a *High Priority* based on the aforementioned analysis. Asphalt paving requires a number of tests (e.g., asphalt core

TABLE 4.6
**List of Prioritized Construction Activities for Inspection**

| High Priority | Medium-High Priority | Medium Priority | Medium-Low Priority | Low Priority |
|---|---|---|---|---|
| Aggregate base courses | Beam erection | Barrier curb | Cofferdam | Clearing site |
| Asphalt paving | Pipe placement | Blasting | Electrical conduit and wiring | Clearing site—bridge |
| Bolting structural connections | Sub-grade treatment | Concrete forms (structures) | Fence | Stripping |
| Concrete paving | Drilled shafts | Drainage | ITS—fiber optic conduit and cable | |
| Driven piles | Guardrail | Excavation | Landscape plantings | |
| Driven piles | Guardrail | Handling/removal of regulated waste | Milling | |
| Embankment | Overhead sign structure | Highway lighting (foundations and poles) | Placement of lighting features | |
| Placement of concrete in structures | Painting steel | Installing soil erosion/sediment control items | Seal coating | |
| Post-tensioning (pre-stressed structures) | Traffic marking | Sound wall panel placement | Sheet piles | |
| Reinforcement steel in structures | | Sound wall post placement | Sidewalk | |
| Retaining walls | | Traffic control—set up | | |
| Structure rehabilitation (repair concrete deck) | | Traffic signals (foundations and poles) | | |

sampling, compaction testing, and mix temperature testing) that could not be performed after the completion of the activity. Not performing such tests could lead to lack of discovery of defects that could lead to potential cracks and eventually could lead to functional failures, reduced life of the facility, and increased maintenance costs. On the other hand, site clearing is categorized as a *Low Priority* based on the risk analysis. Site clearing only requires checking the clearing limits and underlying material and utilities. Failing to inspect these items is not likely to lead to lack of discovery of defects. Thus, there would be fewer risk impacts due to missing inspections of this activity.

## 4.3 Value Added of Inspection

Efficient inspection of construction projects requires understanding the value added of inspection. The value added of inspection for different construction activities was identified and its relationship with the priority of inspection was evaluated. Table 4.7 summarizes the value added of inspection. Examination of Table 4.7 indicates that the existence of testing and safety requirements increases the perceived probability of macro risk consequences due to missed inspection. For instance, activities such as asphalt paving, concrete paving, aggregate base course, and embankment require testing. Activities such as structure rehabilitation and bolting structural connections entail safety considerations (e.g., safety of workers and the public during the construction phase and safety of facility users after the construction phase). Thus, these activities are perceived to experience greater risk impacts due to reduced inspection. In addition, activities such as installing reinforcement steel in structures in which the work is covered upon completion of the activity (it cannot be inspected later unless it is destroyed) are perceived to entail greater risk impacts due to missed inspection. The proposed risk-based inspection protocol could be used for resource allocation based on the risk impacts. The proposed list of prioritized construction activities could assist project and program managers to optimally allocate their limited inspection resources when a number of activities (whose inspection could not be performed at a later time regardless of the level of inspection required) are taking place concurrently on the jobsite.

## 4.4 The Effect of Work Sequence and Project Schedule on the Level of Inspection

During site visits to INDOT projects and interviews with INDOT inspection staff and area engineers, it was found that the level of resources allocated for inspection of an activity is affected by the sequence of the work in a project as well as the project schedule. In some cases, more resources are allocated since an activity is the only activity currently ongoing in the project; therefore, available inspection staff may be allocated to this activity. This does not imply that the activity is high priority. The protocol shown in Table 5.1 could assist allocation of inspection resources when: (1) there are multiple activities ongoing at the same time in a project and (2) available inspection resources are not sufficient to fully inspect ongoing construction activities.

TABLE 4.7
**Value Added of Inspection**

| Construction Activity | Priority | Value Added by Inspectors |
|---|---|---|
| Traffic control—set up | Medium | Ensuring that a correct sign is used and installed in accordance with specifications<br>Payment documentation |
| Clearing site | Low | Ensuring clearing limits<br>Checking for underlying hazardous material or utilities<br>Payment documentation |
| Stripping | Low | Ensuring stripping limits<br>Ensuring notice of bad spots<br>Payment documentation |
| Clearing site—bridge | Low | Identify any erosion control needed<br>Checking for buried utilities<br>Payment documentation |
| Installing soil erosion/sediment control items | Medium | Ensuring proper installation<br>Ensuring compliance with EC permits<br>Payment documentation |
| Excavation | Medium | Safety<br>Checking required undercuts<br>Payment documentation<br>Checking excavation limits |
| Blasting | Medium | Safety<br>Payment documentation |
| Handling/removal of regulated waste | Medium | Ensuring proper handling and removal<br>Payment documentation<br>Safety |
| Aggregate base courses | High | Running tests<br>Payment documentation |
| Embankment | High | Running tests<br>Ensuring specifications are adhered<br>Payment documentation |
| Milling | Medium-low | Ensuring proper depth and removal |
| Asphalt paving | High | Collecting tickets<br>Running tests<br>Payment documentation |
| Concrete paving | High | Collecting tickets<br>Running tests<br>Payment documentation |
| Concrete forms (structures) | Medium | Ensuring proper installation and placement |
| Reinforcement steel in structures | High | Ensuring proper installation |
| Placement of concrete in structures | High | Collecting tickets<br>Running tests<br>Payment documentation<br>Ensuring proper placement |
| Structure rehabilitation (repairs to concrete deck) | High | Safety<br>Ensuring proper removal depth |
| Drilled shafts | Medium-high | Ensuring proper placement and depth<br>Payment documentation |
| Driven piles | High | Ensuring bearing is reached<br>Ensuring proper placement |
| Sheet piles | Medium-low | Ensuring proper placement |
| Cofferdams | Medium-low | Inspect piling for defects<br>Verify locations<br>Verify depth |
| Beam erection | Medium-high | Safety<br>Proper placement |
| Bolting structural connections | High | Safety<br>Verify acceptable bolt tension |

TABLE 4.7
*(Continued)*

| Construction Activity | Priority | Value Added by Inspectors |
|---|---|---|
| Post-tensioning (pre-stressed structures) | High | Ensuring proper tensioning |
| Painting steel | Medium-high | Ensuring proper thickness |
| Guardrail/cable rail | Medium-high | Ensuring proper installation<br>Running tests<br>Payment documentation |
| Sidewalk | Medium-low | Payment documentation<br>Running tests |
| Drainage | Medium | Ensuring adherence to specifications<br>Checking underlying conditions |
| Traffic stripes | Medium-high | Ensuring adherence to specifications |
| Fence | Medium-low | Ensuring proper installation |
| Electrical conduit and wiring | Medium-low | Proper installation<br>Payment documentation |
| ITS—fiber optic conduit and cable | Medium-low | Proper installation<br>Payment documentation |
| Highway lighting (foundations and poles) | Medium | Ensuring proper placement |
| Traffic signals (foundations and poles) | Medium | Ensuring proper placement |
| Overhead sign structures | Medium-high | Ensuring proper installation |
| Landscape plantings | Medium-low | Proper placement |
| Pipe placement | Medium-high | Ensuring proper installation<br>Payment documentation |
| Seal coating | Medium-low | Ensuring proper placement<br>Payment documentation |
| Sound wall post placement | Medium | Ensuring proper installation and payment documentation |
| Sound wall panel placement | Medium | Ensuring proper placement<br>Payment documentation |
| Placement of lighting features | Medium-low | Ensuring proper placement and payment documentation |
| Sub-grade treatment | Medium-high | Running tests<br>Ensuring proper placement<br>Payment documentation |
| Retaining walls | High | Ensuring proper placement<br>Payment documentation |

# 5. DELIVERABLES

The deliverables of this study include the following:

1. A protocol for inspection of construction activities (Table 5.1)
2. An inspection staffing guide (Table 5.2)
3. A list of pay items to enhance the documentation process (Table 5.3)

## 5.1 Protocol for Inspection of Construction Activities

The findings of the study were used to create a protocol for the inspection of construction activities. The protocol related to inspection of construction activities is summarized in Table 5.1.

Activities that are deemed to be high priority for inspection and the critical items to be watched during inspection (as shown in Table 5.1) include:

- Construction activities that include buried work (such as rebar installation and pipe placement): In these cases, if inspection is not done constantly, it is likely that defects which are missed will not be detected since the work will be covered.
- Construction activities which require testing (such as aggregate base course and asphalt paving): In these activities, tests required by specifications should be implemented as needed. If a test is missed, the potential defects might not be discovered at a later time.
- Construction activities which include safety provisions (such as structure rehabilitation): Reducing inspection of such activities could result in missing defects that could endanger the safety of the workers and the public;
- Construction activities which include high cost items (such as pile driving): In such activities, the contract value of the pay item warrants full supervision.

## 5.2 Required Staff for Inspection of Construction Activities

Within INDOT, there has been no formal guideline for inspection staffing of construction projects using in-house resources. While inspection staffing is dependent

TABLE 5.1
**Protocol for Inspection of Construction Activity**

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| Traffic control—set up | Medium | Decreased safety | Type of signs | Frequently |
| | | | Location of signs | Frequently |
| | | | Correct placement and installation | Frequently |
| Clearing site | Low | — | Areas to and not be cleared | Randomly |
| | | | Clearing obstructions | Randomly |
| | | | Removal to adequate depth | Randomly |
| | | | Identify wet spots | Randomly |
| Stripping | Low | — | Removal of topsoil | Randomly |
| | | | Stay within removal depth limits | Randomly |
| | | | Correct removal area | Randomly |
| Clearing site—bridge | Low | — | Stay within removal depth limits | Randomly |
| | | | Correct removal area | Randomly |
| | | | Keep sufficient topsoil for finishing slopes | Randomly |
| Installing soil erosion/ sediment control items | Medium | Functional failure | Correct item | Randomly |
| | | | Correct location | Frequently |
| | | | Proper installation | Frequently |
| Excavation | Medium | Decreased safety, functional failures | Log and calculate areas excavated | Frequently |
| | | | Depth of excavation | Frequently |
| | | | Safety of operation | Frequently |
| | | | Elevation | Randomly |
| | | | Proper undercut | Frequently |
| | | | Test material for placement in other locations | Frequently |
| | | | Verifying hauling of waste to proper sites | Frequently |
| Blasting | Medium | Decreased safety, functional failures | Safety of operation | Frequently |
| | | | Lay out and spacing of holes | Randomly |
| | | | Measure and documentation | Frequently |
| Handling/removal of regulated waste | Medium | Decreased safety, increased user costs | Proper handling according to regulations | Frequently |
| | | | Complete removal | Frequently |
| | | | Safety | Frequently |
| Aggregate base courses | High | Functional failures, increased maintenance costs, decreased design life | Moisture and density control | Frequently |
| | | | Compactor passes | Constantly |
| | | | Depth of each lift | Constantly |
| | | | Documentation | Constantly |
| | | | Obtain tickets for materials (depending on payment method) | Frequently |
| Embankment | High | Functional failures, increased maintenance costs, decreased design life | Quality of the soil being placed | Constantly |
| | | | Moisture content | Constantly |
| | | | Density | Constantly |
| | | | Measure embankment area | Constantly |
| | | | Lifts height and width | Frequently |
| Milling | Medium-low | Increased maintenance costs | Milled surface | Randomly |
| | | | Depth and width of milled area | Frequently |
| | | | Check the ride behind milling machine | Randomly |
| | | | Proper debris removal | Frequently |
| Asphalt paving* | High | Decreased safety, functional failures, increased maintenance costs, increased user costs, decreased design life | Check for daily QC/QA sampling locations | Constantly |
| | | | Ensure that required tests are taken based on the QC/QA plan | Constantly |
| | | | Obtain tickets as they are placed to ensure that delivery was made | Constantly |

TABLE 5.1
*(Continued)*

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| | | | Calculate yield often to ensure that no overrun occurs | Constantly |
| | | | For HMA (Section 402), check that material is being rolled properly (pattern, number of passes, approved rollers) | Constantly |
| | | | Ensure that the quality control paving plan that was submitted by the contractor is being upheld | Constantly |
| | | | Check the temperature of the mix often to verify compliance with the spec | Constantly |
| | | | Observe the material behind the paver and check for defects that will affect the final product | Constantly |
| | | | Check that the tack is being properly applied | Constantly |
| | | | Total tickets at the end of the day; document, enter in SM, and update QC/QA totals for next day's test locations | Constantly |
| | | | Mark core locations and wait for contractor to cut them | Constantly |
| | | | Ensure samples and cores are hauled to testing lab on time | Frequently |
| Concrete paving* | High | Decreased safety, functional failures, increased maintenance costs, increased user costs, decreased design life | Check the base prior to paving for compliance with the specifications | Constantly |
| | | | Sample and test the concrete according to the frequency manual | Constantly |
| | | | Between tests inspect the concrete to ensure that concrete is uniform | Constantly |
| | | | Inspect the material behind the paver for defects | Constantly |
| | | | Inspect the finish and the tinning being applied by the contractor | Constantly |
| | | | Inspect the curing of the concrete and verify that it meets specifications | Constantly |
| | | | Inspect the placement and vibration of the plastic concrete making sure specifications are met | Constantly |
| | | | Test samples obtained for compliance with strength requirements | Constantly |
| | | | Measure and document | Constantly |
| Concrete forms (structures) | Medium | Increased maintenance costs, decreased design life | Check dimensions | Frequently |
| | | | Check that corners are chamfered according to the plans | Frequently |
| | | | Check for structural integrity | Frequently |
| | | | Check quality of the forms and fit | Frequently |
| Reinforcement steel in structures | High | Decreased safety, functional failures, increased maintenance costs, increased user costs, decreased design life | Check for bar placement according to the plans | Frequently |
| | | | Check for proper cover of the steel | Frequently |
| | | | Check for bar dimensions | Frequently |
| Placement of concrete in structures | High | Decreased safety, functional failures, increased maintenance costs, decreased design life | Make sure that concrete is placed and vibrated according to the specifications | Constantly |
| | | | Test and sample concrete according to the frequency manual | Constantly |
| | | | Between tests visually verify that the concrete is uniform from load to load | Constantly |
| | | | Inspect the finish being applied by the contractor | Constantly |

TABLE 5.1
*(Continued)*

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| | | | Inspect the curing and that it complies with the specifications | Constantly |
| | | | Test samples obtained according to strength requirements | Constantly |
| | | | Measure and document | Constantly |
| Structure rehabilitation (repairs to concrete deck) | High | Decreased safety, functional failures, increased maintenance costs, increased user costs, decreased design life | Inspect milling process for depth and damage | Constantly |
| | | | Mark areas to be repaired | Constantly |
| | | | Inspect removal of unsound concrete ensuring that reinforcing steel is not damaged and that depth requirements are met | Randomly |
| | | | Resound open patches to ensure that all unsound concrete has been removed | Randomly |
| | | | Inspect sandblasting and cleaning of the deck, ensuring that material is collected and properly disposed of | Randomly |
| | | | Inspect the covering and protecting of the deck until overplayed | Randomly |
| | | | Inspect wetting of the deck in preparation of the overlay | Constantly |
| | | | Calibrate overlay trucks to be used | Constantly |
| | | | Inspect that overlay placement is according to the specifications | Constantly |
| | | | Test overlay material according to the frequency manual | Constantly |
| | | | Check quantity during pour to avoid overrunning | Constantly |
| | | | Inspect curing of the overlay | Randomly |
| Drilled shafts | Medium-high | Decreased safety, functional failures, increased maintenance costs | Check location | Constantly |
| | | | Check for plumpness | Constantly |
| | | | Check depth to rock | Constantly |
| | | | Check depth in rock | Constantly |
| | | | Determine if shaft is dry | Constantly |
| | | | If shaft is not dry, require contractor to pump hole dry | Constantly |
| | | | Verify that shaft is clean before pouring | Constantly |
| | | | Make sure that concrete is placed and vibrated according to the specifications | Constantly |
| | | | Test and sample concrete according to the frequency manual | Constantly |
| | | | Between tests visually verify that the concrete is uniform from load to load | Constantly |
| | | | Measure and document | Constantly |
| Driven piles | High | Decreased safety, functional failures, increased maintenance costs, decreased design life | Verify locations | Constantly |
| | | | Verify straight or battered pile | Constantly |
| | | | Check piles for heat numbers and length | Constantly |
| | | | Document length placed in leads, length added, and length cut off | Constantly |
| | | | Document depth of penetration for each 20 blows | Constantly |
| | | | Direct contractor to stop driving when the bearing is reached according to information received from geotechnical tests | Constantly |
| | | | Measure and document | Constantly |
| Sheet piles | Medium-low | Decreased safety, functional failures | Verify locations | Constantly |
| | | | Verify straight or battered pile | Constantly |

TABLE 5.1
*(Continued)*

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| | | | Check piles for heat numbers and length | Constantly |
| | | | Document length placed in leads, length | Constantly |
| | | | added, and length cut off | Constantly |
| | | | Measure and document | Constantly |
| Cofferdams | Medium-low | Functional failures | Inspect piling for defects | Frequently |
| | | | Verify locations | Frequently |
| | | | Verify depth | Frequently |
| Beam erection | Medium-high | Decreased safety, functional failures, increased maintenance costs, decreased design life | Inspect beams for damage | Constantly |
| | | | Verify placement of beams | Constantly |
| | | | Observe placement watching for possible damage | Randomly |
| | | | Inspect that proper bracing is installed according to the shop drawings | Randomly |
| Bolting structural connections | High | Decreased safety, functional failures, increased maintenance costs, decreased design life | Verify that all bolts and welds shown on the plans are installed | Constantly |
| | | | Inspect the torque of the bolts according to the specifications | Randomly |
| Post-tensioning (pre-stressed structures) | High | Decreased safety, functional failures, increased maintenance costs, decreased design life | Observe the tensioning process being performed by the contractor ensuring that proper loading is applied | Constantly |
| Painting steel | Medium-high | Functional failures, increased maintenance costs, decreased design life | Inspect the removal of the old paint, ensuring that the paint and sand blasting grit is properly contained, stored, and disposed of | Randomly—as needed |
| | | | Inspect the cleaned surface for any areas that need further cleaning | |
| | | | Inspect the paint application to ensure that no overspray is happening and that the proper film thickness is obtained in both the primer and finish coats | Constantly |
| Guardrail/cable rail | Medium-high | Decreased safety, functional failures, increased maintenance costs, increased user costs, decreased design life | Inspect the post installation, ensuring that no posts are cut off for any reason | Frequently |
| | | | Inspect the hanging of the rail to ensure that all bolts are installed and properly tightened | Frequently |
| | | | Inspect the end treatment installation ensuring that all components are properly installed | Frequently |
| Barrier curb | Medium-low | Functional failures, increased maintenance costs | Sample and test the concrete according to the frequency manual | Constantly |
| | | | Between tests inspect the concrete to ensure that a uniform product is received | Frequently |
| | | | Check that the curing method chosen by the contractor meets specifications | Frequently |
| Sidewalk | Medium-low | Increased maintenance costs | Inspect and verify the dimensions of the sidewalk | Frequently |
| | | | Sample and test the concrete according to the frequency manual | Frequently |
| | | | Between tests inspect the concrete to ensure that we are receiving a uniform product | Frequently |
| | | | Check that the curing method chosen by the contractor meets specifications | Frequently |

TABLE 5.1
*(Continued)*

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| Drainage | Medium | Functional failures, increased maintenance costs, decreased design life | Check that ditches are constructed according to the plans | Randomly |
| | | | Verify that drainage elements being constructed will not leave or cause problems off of the right-of-way | Randomly |
| | | | Verify that the drainage shown in the plans will adequately drain | Constantly |
| Traffic stripes/traffic markings | Medium-high | Decreased safety, increased maintenance costs, decreased design life | Line width, color and type | Randomly |
| | | | Inspect the placement of the marking ensuring that requirements are being met | Frequently |
| | | | Inspect the installation of the lines making sure that they are straight, stopping the contractor if they are not | Frequently |
| | | | ensuring that all material is approved prior to use | Constantly |
| Fence | Medium-low | Increased maintenance costs | Check to see that all posts are properly installed | Randomly |
| | | | Check to see that the fence is being installed in the proper location | Randomly |
| | | | Check that the fence is stretched to the proper tension | Randomly |
| | | | Ensure that all material has been certified | Randomly |
| Electrical conduit and wiring | Medium-low | Functional failures, increased maintenance costs | Inspect the installation of the conduit and that it has been placed in the proper location | Frequently |
| | | | Inspect the installation of handholds and their location | Frequently |
| | | | Inspect the pulling of wiring to ensure that it is not damaged during the pulling process | Frequently |
| ITS—fiber optic conduit and cable | Medium-low | Increased maintenance costs | Inspect the installation of the conduit and that it has been placed in the proper location | Frequently |
| | | | Inspect the installation of handholds and their location | Frequently |
| | | | Inspect the pulling of wiring checking that it is not damaged during the pulling process | Frequently |
| Highway lighting (foundations and poles) | Medium | Decreased safety, functional failures, increased maintenance costs, decreased design life | Inspect the excavation of the foundation, checking for dimensions that are shown in the plans | Constantly |
| | | | Inspect that the reinforcement steel has been placed according to that plans | Frequently |
| | | | Make sure that concrete is placed and vibrated according to the specifications | Frequently |
| | | | Test and sample concrete according to the frequency manual | Constantly |
| | | | Inspect the curing and ensure that it complies with the specifications | Frequently |
| | | | Test samples obtained according to strength requirements | Frequently |
| Traffic signals (foundations and poles) | Medium | Decreased safety, functional failures, increased maintenance costs | Inspect the excavation of the foundation, checking for dimensions that are shown in the plans | Constantly |
| | | | Inspect that the reinforcement steel has been placed according to that plans | Frequently |

TABLE 5.1
*(Continued)*

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| | | | Make sure that concrete is placed and vibrated according to the specifications | Frequently |
| | | | Test and sample concrete according to the frequency manual | Frequently |
| | | | Inspect the curing and that it complies with the specifications | Frequently |
| | | | Test samples obtained according to strength requirements | Frequently |
| Overhead sign structures | Medium-high | Decreased safety, functional failures, increased maintenance costs, decreased design life | Inspect the excavation of the foundation, checking for dimensions that are shown in the plans | Constantly |
| | | | Inspect that the reinforcement steel has been placed according to that plans | Frequently |
| | | | Make sure that concrete is placed and vibrated according to the specifications | Constantly |
| | | | Test and sample concrete according to the frequency manual | Constantly |
| | | | Inspect the curing and that it complies with the specifications | Randomly |
| | | | Test samples obtained according to strength requirements | Constantly |
| Landscape plantings | Medium-low | Increased maintenance costs | Inspect that they have been placed as shown in the plans | Randomly |
| | | | Inspect to verify the types of plants installed | Randomly |
| | | | Verify that the plants have been installed according to the specifications | Randomly |
| Pipe placement | Medium-high | Functional failures, increased maintenance costs, decreased design life | Verify location, depth, direction of flow, and elevations | Constantly |
| | | | Inspect joining of the pipe and that it is performed according to the standards | Constantly |
| | | | Inspect backfilling to verify that compaction is being performed in the proper depth of lift | Constantly |
| | | | Test the density of the backfill according to the frequency manual | Constantly |
| Seal coating | Medium-low | Functional failures, increased maintenance costs | Obtain tickets for cover aggregate | Constantly |
| | | | Verify certification of oil | Constantly |
| | | | Calculate spread rates during placement to ensure proper chip embedment | Constantly |
| | | | Inspect spray pattern for uniformity | Constantly |
| | | | Check application rate of the cover aggregate to prevent over application | Constantly |
| Sound wall post placement | Medium | Functional failures | Check post lengths and verify depths | Constantly |
| Sound wall panel placement | Medium | Functional failures | Inspect panels for damage before and during placement | Frequently |
| | | | Inspect panel placement and verify elevations | Constantly |
| Placement of lighting features | Medium-low | Functional failure | Check lighting features, location, and height | Frequently |
| Sub-grade treatment | Medium-high | Functional failures, increased maintenance costs, increased user costs, decreased design life | Collection of tickets from aggregate, lime, or cement | Constantly |
| | | | Density testing for aggregate or soil | Constantly |
| | | | DCP testing for chemically modified soil | Constantly |

TABLE 5.1
*(Continued)*

| Construction Activity | Priority | Macro-Consequences Due to Missed/Reduced Inspection | Critical Items to Be Watched | Frequency of Inspection |
|---|---|---|---|---|
| | | | Proof rolling | Constantly |
| | | | Rolling to obtain density | Constantly |
| | | | Moisture testing | Constantly |
| Retaining walls | High | Decreased safety, functional failures, increased maintenance costs, increased user costs, decreased design life | Backfill density, lifts height, compaction, ties alignment and connections, wall segments location and alignment | Constantly |

*The critical items related to asphalt paving and concrete paving should be inspected constantly unless it is warranty payment.

TABLE 5.2
**Inspection Staffing Guide**

| Project Construction Activities | One Inspector Per Crew | One Inspector Per Two Crews | Two Inspectors Per Three Crews |
|---|---|---|---|
| Bridge construction and deck repair | × | | |
| Concrete paving | × | | |
| Earthwork | × | | |
| Asphalt paving | × | | |
| Pipe structures | × | | |
| Traffic item (signs, signals and lighting) | × | | |
| Bridge construction and deck repair + concrete paving or asphalt paving | × | | |
| Bridge construction and deck repair + earthwork | | × | |
| Bridge construction and deck repair + pipe structures | | × | |
| Concrete paving/asphalt paving + earth work | × | | |
| Concrete paving/asphalt paving + pipe structures | × | | |
| Earthwork + pipe structures | | × | |
| Bridge construction and deck repair + concrete paving/asphalt paving + earth work | | | × |
| Bridge construction and deck repair + concrete paving/asphalt paving + pipe structures | | | × |
| Bridge construction and deck repair + concrete paving/asphalt paving + pipe structures + earthwork | | × | |

upon the project characteristics (such as the activities, experience of the inspectors, testing requirements), there is a need for a protocol for specifying the minimum inspection staffing for a given project. The minimum inspection staff was identified through site visits and was also based on the findings from the surveys deployed to state DOTss, consultants, and INDOT.

Table 5.2 shows the minimum inspection staff required for a project that consists different combination of construction activities. In developing this inspection staffing guideline it is assumed that all the inspectors are capable of implementing testing requirements and are capable of multi-tasking in the inspection. Also, the crews are linked to the activities and the location of the activity. If only one activity is underway on the jobsite, regardless of the priority of activity, the available inspection resources are allocated depending on the number of crews working on the activity. An example of *one inspector per crew* could be the allocation of one inspector assigned for the inspection of the earthwork activities performed by a crew working at the same location on the project. In cases where there are multiple activities underway on the jobsite, the inspection staff could be assigned to the inspection of multiple activities depending upon the distance between the locations of the activities. For instance, on a jobsite where bridge construction (that involves one crew) and embankment activities (that involves one crew) are performed concurrently in close proximity on the jobsite, one inspector could be allocated for inspecting both these activities. On the other hand, if a project includes bridge construction (including one crew), asphalt pavement (involving another crew), pipe placement and earthwork (performed by different crews) performed concurrently and at different locations on the jobsite, according to Table 5.2, two inspectors are required (i.e., one per two crews). However, concurrent inspection of multiple activities by a single inspector is not recommended when there are a number of high-priority activities being performed simultaneously. For instance, in cases when asphalt-paving (with one crew) and bridge construction (with another crew) occur simultaneously on the jobsite, one inspector per crew (i.e., two inspectors in total) is required since both activities are high priority.

The guideline presented in Table 5.2 is generic. Several factors affect the number of inspection staff required for a project. The level of experience of inspection staff, the skills and training required for the inspection staff to implement tests, the distances between the locations of activities that have to be inspected, and the project schedule are examples of factors which could affect the required number of inspectors on a project. In addition, the staffing guide presented in Table 5.2 does not take the resources required for documentation into account. These factors should be considered by area engineers while allocating inspection staff to the projects.

### 5.3 Reduction in Documentation Workload

One of the value added items of inspection of construction activities is payment documentation. However, there are pay items whose contract value does not warrant the time required for the documentation. This is one of the factors perceived by INDOT inspectors to be a major cause for the inefficiency of INDOT inspections. Identification of these pay items and modification of the documentation process could enhance the efficiency of inspection. Table 5.3 summarizes the pay items (1) that take the most time to document for the Final Construction Record (FCR) and (2) whose contract value does not seem to warrant the Final Construction Record (FCR) documentation time required.

A solution to enhance the efficiency of pay items documentation is to combine the pay items whose value does not warrant the time required for documentation with the other pay items. There are several individual pay items that rely on each other, that should be combined as one. For example, all rip rap placement requires geotextile, which leads to measurements, sketches and calculations. A solution to reduce documentation of this item would be including the geotextile in the rip rap item to avoid measuring per item.

TABLE 5.3
**Summary of Identified Pay Items to Modify the Documentation Proces**

| Pay items that take the most time to document for the Final Construction Record (FCR) | Pay items whose contract value does not seem to warrant the Final Construction Record (FCR) documentation time required |
|---|---|
| Concrete masonry | Pavement markings |
| Storm/sanitary sewer installation | Erosion control items |
| Earthwork | Bituminous prime coat |
| Traffic signal items | Driving piles |
| Pavement markings | Seal coat |
| Structural concrete/rebar | Tack coat |
| Pipe structures | Sidewalk items |
| PCC (Portland cement concrete) | Fence and gates |
| Sub-grade treatment | Sod |
| Sub-base | Signal loop wire |
| Sod | Signal wire items |
| | Under-drains |
| | Temporary traffic items |

## 6. CONCLUSIONS

The retirement of experienced inspectors, the departure of experienced inspectors to private firms, and insufficient inspection training have led to increased workloads due to insufficient resources for the inspection of construction projects for state DOTs in the U.S. This study proposes a risk-based inspection protocol for the inspection of transportation construction activities as a strategy for inspection workload reduction. The assumption behind the proposed protocol is that the activities that experience greater risks from missed/reduced inspection should be given a higher priority for inspection.

Risk analysis was performed to identify the risk impacts of missed/reduced inspection. The risk consequences (such as functional failures and increased maintenance costs) due to reduced inspection were identified through site visits and interviews with inspectors. Then, the subjective probabilities corresponding to the perceived probability of risk consequences due to reduced inspection were encoded. The subjective probability encoding process included deployment of three separate sets of surveys to state DOTs, consultants, and INDOT.

A total of 101 expert responses were elicited through a probability encoding approach, and the risk impacts for different construction activities were calculated. Based on the calculated risk impacts, transportation construction activities were prioritized for inspection. The list of prioritized construction activities was validated through discussions with three senior INDOT inspectors to ensure that such a list would be helpful in addressing the inspection challenges on the jobsites. The greater the risk impacts due to reduced inspection, the higher would be its priority for inspection. Thus, while facing limited inspection resources, state DOTs could allocate their available resources towards the inspection of their high priority activities.

The proposed protocol is intended for use by INDOT as a strategy to address their current challenges of inspection workforce reduction and construction inspection workload increase, while reducing the risks associated with missed/reduced inspection. In addition to the risk-based inspection protocol this study evaluated the inspection practices for different construction activities, value added of inspection and critical items to be inspected, inspection staffing requirements, and pay item documentation workload reduction. Using the proposed risk-based protocol along with the other components of the study, INDOT could more efficiently allocate the available inspection resources to more critical activities when two or more activities are underway on a project site.

## 7. RECOMMENDATIONS FOR IMPLEMENTATION

Construction inspection is critical to ensure delivery of a quality product. The findings of this study are intended to enhance the inspection of construction projects in the face of reduction in the available inspection resources within INDOT. The risk-based inspection protocol could be deployed to INDOT project engineers/supervisors and area engineers to assist them in prioritizing the construction activities.

Based on the findings, the report makes the following recommendations:

- The inspection protocol (Deliverable No. 1) could be used as a check list for educating the new inspection staff.
- Using Deliverable No. 2 (inspection staffing guide), INDOT could enhance the current inspection practices by modifying the documentation requirements for the pay items identified in this study (whose contract value does not warrant the time required for documentation).
- INDOT could adopt lump-sum contracts for combining certain pay items whose value does not warrant the time required for documentation with the other pay items.
- It is recommended that Deliverable No. 3 (enhancement of inspection documentation) be used as a guide for allocation of inspection staff. Project engineers could use the inspection staffing guide to estimate the minimum number inspectors for their projects.
- It is recommended that the current documentation platform (SITEMANAGER) be enhanced to reduce the required effort for inspection documentation.

## REFERENCES

1. Jagers-Cohen, C. A., C. L. Menches, Y. K. Jangid, and C. H. Caldas. Priority-Ranking Workload Reduction Strategies to Address Challenges of Transportation Construction Inspection. *Transportation Research Record*, Volume 2098, 2009, pp. 13–17, doi: 10.3141/2098-02.
2. Martin, C. Help Wanted: Meeting the Needs for Tomorrow's Transportation Work Force. *Public Roads*, Vol. 65, No. 1, 2001, pp. 2–12.

# APPENDIX A

## RISK ANALYSIS AND PROBABILITY ENCODING METHODOLOGY[1]

This appendix presents the methodology used in this study for risk-based assessment of transportation activities. Background information related to risk-based inspection, risk analysis, and probability encoding is provided. The appendix also presents the risk analysis steps through which construction activities were prioritized in this study.

## A.1. BACKGROUND ON RISK-BASED INSPECTION

Risk-based inspection is a widely used concept for pipe systems in oil and gas infrastructure. Reynolds *(1)*, Dey *(2)*, Nalli *(3)*, and Tien et al. *(4)* presented risk-based inspection frameworks for oil and gas infrastructure and Straub and Faber *(5)* discussed the computational aspects of risk-based inspection planning. The two components of risk-based inspection assessment are (1) risk consequences and (2) probabilities of occurrences of risk consequences. The risk impact is then calculated using Equation 1. Thus, the greater the risk consequences and the probability of occurrence of risk consequences, the greater the risk impact, leading to higher priority for inspection.

$$\textit{Risk Impact} = \textit{Risk Consequences} \times \textit{Probability of Occurrence} \quad (1)$$

The risk consequences and their likelihood can be recorded from historical data. Such data are not readily available in the transportation infrastructure domain. Data related to the defects (such as cracks) and the frequencies of the defects in the transportation infrastructure facilities are typically recorded. However, it is not known to what extent the consequences can be attributed to missed inspection, which could be an impediment to employing risk-based inspection for transportation infrastructure. An alternate approach to address the lack of appropriate data would be to obtain the information from subject matter experts based on their experience. To elicit the required data from subject matter experts, the level of detail should be limited to avoid the overestimation of risk consequences and their likelihoods *(6)*. Thus, it would be better to focus on the assessment of macro consequences due to missed/reduced inspection to limit the level of details and the number of events for which subject matter experts estimate probabilities. Figure A.1 shows the methodological framework of this study. As shown in Figure A.1, the risk-based assessment of inspection of construction activities can be implemented through the following steps: (1) identification of the macro consequences instead of micro consequences, (2) probability encoding to extract the "perceived (subjective) probabilities" of macro consequences instead of actual probabilities, (3) evaluation of risk impacts due to missed/reduced inspection, and (4) prioritization of construction activities based on risk impacts due to missed/reduced inspection.

## A.2. BACKGROUND ON PROBABILITY ENCODING

The concept of perceived (subjective) probability was introduced by De Finetti *(7)*. Perceived probability refers to the likelihood that one assigns to a particular uncertain consequence base. One of the characteristics of human reasoning is to form judgments from uncertain and incomplete evidence *(10)*. The process of extracting and quantifying individual judgment about the likelihood of an uncertain consequence is called probability encoding *(9)*. The encoded probability gets closer to the actual probability if: (1) the occurrence of the uncertain consequence is frequent, (2) the uncertain consequence is a result of few causes, (3) the individual has sufficient knowledge regarding the consequence, and (4) the individual is neither risk-averse or risk-taking.

The assessment of subjective probability is based on certain heuristics (i.e., experience-based mental models) such as availability, representativeness, and anchoring *(10,11,12)*. Availability refers to having memories of an event taking place, representativeness refers to making judgments based on the similarity of a sample of events to the population, and anchoring refers to having previous knowledge regarding the occurrence of an event *(9,10,13,14)*. Due to these heuristics, the encoded probability would not be equal to the actual probability and cognitive biases may exist. Nonetheless, probability encoding is useful in understanding which consequence is more likely to occur even when the order of magnitude of the likelihood is different from actual probabilities derived from historical data.

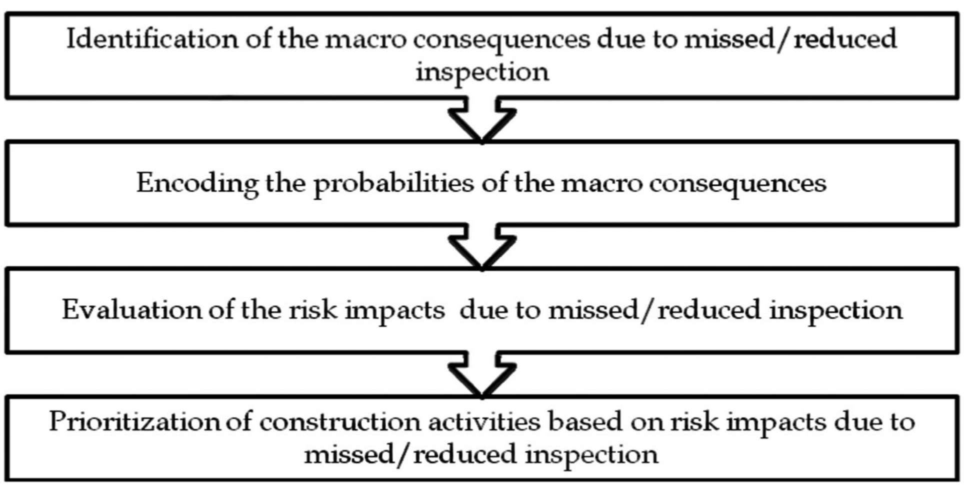


**Figure A.1** Methodological framework of the research.

[1]The majority of the material presented in Appendix A is also presented in the paper submitted by the authors to the Transportation Research Board annual meeting 2012.

## A.3. ANALYSIS OF TRANSPORTATION CONSTRUCTION ACTIVITIES

The research methodology discussed in the previous section was used to develop an inspection protocol for prioritization of transportation construction activities. The elaboration of the steps through which the protocol is obtained is presented in the remainder of this section.

### A.3.1. Identification of the Macro-Consequences Due to Reduced Inspection

To identify the macro consequences due to reduced inspection, the Delphi method was adopted. The Delphi method is a communication technique designed to obtain the insights of a panel of experts through a number of rounds of interviews. The results of each round of interviews are summarized and given to the experts in the next round of interviews so the experts could modify their judgment. The process stops when the panel of experts reaches a consensus on the subject under investigation. The interviews with the subject matter experts (i.e., construction inspectors) were conducted during 17 site visits to five construction projects in the state of Indiana between May and August 2011.

In the first round of interviews, the project engineers and inspectors on these projects were asked to identify the micro consequences due to reduced/missed inspection and the resulting macro consequences. They were asked questions such as "What would be the consequences of missing the inspection of asphalt compaction? And what would be its short- and long-term consequences?" Their comments were analyzed and the following macro consequences due to reduced inspection were identified: short-term functional failures, long-term functional failures, increased user costs, decreased design life, increased maintenance costs, and decreased safety. In the second round of the interviews, these macro consequences were re-evaluated by the project engineers and the inspectors of these projects who confirmed that the identified macro consequences are the major ones due to missed/reduced inspection. While in reality the identified risk consequences are not independent and mutually exclusive, for simplifying the risk analysis and the probability encoding process in this study, they are assumed to be independent.

### A.3.2. Encoding the Perceived Probabilities of the Macro-Consequences Due to Reduced Inspection

In this study, the individuals from whom the perceived probabilities were derived are inspectors, who have sufficient knowledge regarding the consequences of reduced inspection. However, the consequences of reduced inspection usually manifest after the project is completed and when the inspectors are no longer on the job. Thus, the frequency of observing the consequences of reduced inspection is low. In addition, the problems with functionality may be the result of other causes, such as problems due to poor design or severe weather condition. Furthermore, different inspectors have different risk attitudes (e.g., risk-averse, risk-neutral and risk-taking). Thus, the encoded perceived probabilities from different individuals would not be the same and may not reflect the actual probabilities. The objective of this study is not to obtain an accurate estimate of the probability distributions of the occurrence of risk consequences due to reduced inspection, but rather is to use the encoded probability estimates in order to identify the construction activities in which observing a risk consequence due to reduced inspection is more likely. Tversky and Koehler *(15)* refer to this as "the assignment of probabilities by experts to the description of an event rather than the event itself." Thus, probability encoding could be useful in understanding which consequence is more likely to occur even though the order of magnitude of the likelihood is different from the actual probabilities.

There are a number of approaches for probability encoding, and selecting an approach depends on the nature of the problem. For instance, if the nature of the problem requires evaluation of individual's risk attitudes and perception, direct interviews with the subjects as discussed by Spetzler and Von Holstein *(9)* are appropriate. However, if the problem requires assessment of the likelihood of the occurrence of a certain consequence based on the perception of a large population of experts, the use of direct interviews is not viable. The choice of experts is the most important step of subjective probability encoding *(16)*. In this study, to account for the different experiences and risk attitudes of experts, three sets of surveys were deployed to state DOTs, consultants that implement construction inspection for these agencies, and the Indiana Department of Transportation (INDOT) inspectors. These surveys were deployed in August 2010, September 2010, and January 2011, respectively. The data collected include responses from 23 state DOTs, 58 engineers and inspectors from Indiana DOT, and 20 inspection consultants, for a total of 101 expert responses. In the surveys, the experts were asked to comment on the typical inspection practices in their organizations as well as different inspection workload reduction strategies used by their organizations. These questions were asked to implement the *structuring* and *conditioning* stages of probability encoding as introduced by Spetzler and Von Holstein *(9)*. Structuring refers to clearly defining the uncertain variable for the experts, and conditioning refers to making the experts think about the uncertain variable. Then, the respondents were asked to assign subjective probabilities to the likelihood of risk consequences due to reduced inspection. The use of verbal expressions is an appropriate approach to elicit the perceptions of uncertainty from experts *(17)*. When subjective probabilities are collected using survey questionnaires from a group of experts in which experts communicate their perceptions regarding the likelihood of events using verbal expressions, probability encoding using fuzzy logic is viable. Fuzzy set theories are powerful mathematical tools for modeling uncertain systems. These tools facilitate probability encoding in the absence of precise and complete information. Figure A.2 shows the steps of the probability encoding process and risk analysis. In the following sections, the fuzzy probability encoding and the steps through which the risk impacts are derived are presented.

*Step 1: Fuzzification of the subjective probabilities* Linguistic terms such as "likely" or "probable" are acceptable ways to express the notion of uncertainty *(17)*. These terms carry meaning for communicating degrees of uncertainty. but they are less precise than numbers. These verbal expressions can be quantified using fuzzy numbers in order to assist in probability assessment *(17,18,19,20)*. A fuzzy number does not refer to one single value but rather to a continuous set of possible values, where each possible value has its own weight between 0 and 1. This weight is called the membership function *(21)*. A triangular fuzzy number is represented using three components as shown in Equation 2. Values less than the left-hand side component and greater than the right-hand side component have a membership function of zero. The values between the left and right-hand values have membership functions between 0 and 1. The middle component signifies the value with the membership function of 1.

$$P(\theta) : (\theta_1,\theta_2,\theta_3) \quad (2)$$

Van der Gaag et al. *(20)* proposed a scale for transforming probability linguistic terms to fuzzy numbers (Table A.1). The transformation is called fuzzification. The scale has not been proven to be context-specific *(17)*. In this study, the scale presented in Table A.1 was used for the fuzzification of the linguistic terms corresponding to the perceived probabilities of risk consequences due to reduced inspection. For instance, using Table A.1, it can be shown that 50% is the most representative probability corresponding to the "medium likelihood" probability linguistic term, and it has a membership value of 1 in the triangular fuzzy number. As probabilities move farther from 50%, they become less representative of the "medium likelihood"

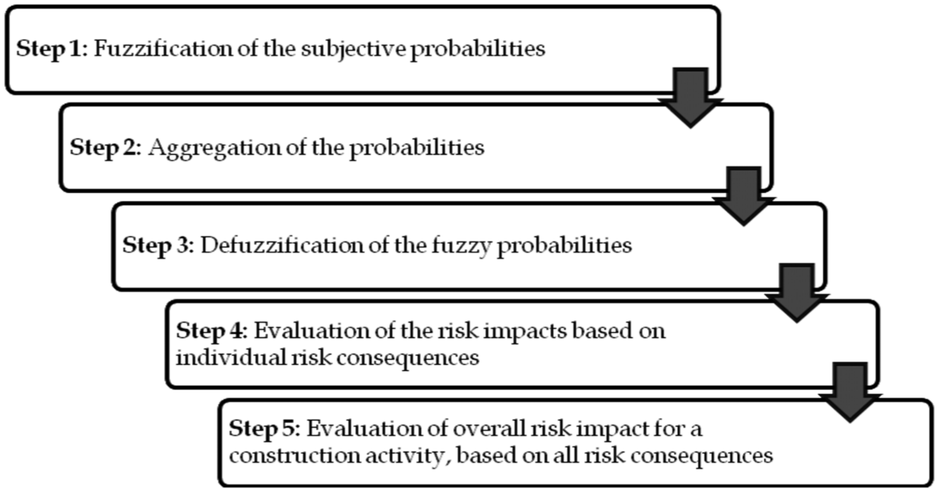


**Figure A.2** Steps in probability encoding.

TABLE A.1
**Fuzzy Numbers Corresponding to Probabilities**

| Linguistic Term | Fuzzy Number ($p(\theta)$:($\theta_1$, $\theta_2$, $\theta_3$)) |
|---|---|
| Very unlikely | (0.15,0.17,0.25) |
| Unlikely | (0.25,0.30,0.40) |
| Medium likelihood | (0.40,0.50,0.60) |
| Likely | (0.60,0.70,0.75) |
| Very likely | (0.75,0.83,0.90) |

probability linguistic term and their membership values decrease. As the probabilities become less than 40% or greater than 60%, they are no longer representative of the "medium likelihood" probability linguistic term. Thus, they have a membership value of 0. In the survey questionnaires, the experts were asked to assign probabilities of occurrence of risk consequences due to reduced inspection using verbal expressions. The assigned probabilities by each expert were fuzzified using the scale shown in Table A.1 and Figure A.3.

*Step 2: Aggregation of the probabilities* The assessments of several experts should be combined to capture the wisdom of the crowd and to normalize the differences in the risk attitudes of the experts *(22)*. There are various methods for aggregating the perceived probabilities of several experts *(23,24,25)*. One of the most commonly used approaches is the linear opinion pool *(26)*. Using the linear opinion pool, the aggregated probability was obtained using Equation 3:

$$P(macro\ risk\ consequences \mid missed\ inspection) = p(\theta) = \sum_{i=1}^{5} w_i p_i(\theta) \quad (3)$$

Where, $p_i(\theta)$ represents the probability fuzzy numbers (assigned by individual experts) presented in Table A.1, and $w_i$ is the percentage of experts who assigned $p_i(\theta)$ to the uncertain consequence $\theta$. $p(\theta)$ is the aggregated fuzzy number corresponding to the probability of consequence $\theta$ occurs due to reduced inspection of a construction activity ($P(macro\ risk\ consequences|missed\ inspection)$).

*Step 3: Defuzzification of the fuzzy probabilities* The probability fuzzy numbers need to be defuzzified so they can be used as probability point estimates for the risk analysis. Defuzzification refers to transforming a fuzzy number into a regular crisp number. The method used for defuzzification in this study is the centroid method. The centroid of a triangular fuzzy number is equal to the average of the three components of the fuzzy number (Equation 4).

$$Centroid[p(\theta) : (\theta_1, \theta_2, \theta_3)] = \frac{\theta_1 + \theta_2 + \theta_3}{3} \quad (4)$$

*Step 4: Evaluation of the risk impacts* As shown in Equation 1, the risk impact is the product of the risk consequence multiplied by the probability of occurrence of the risk

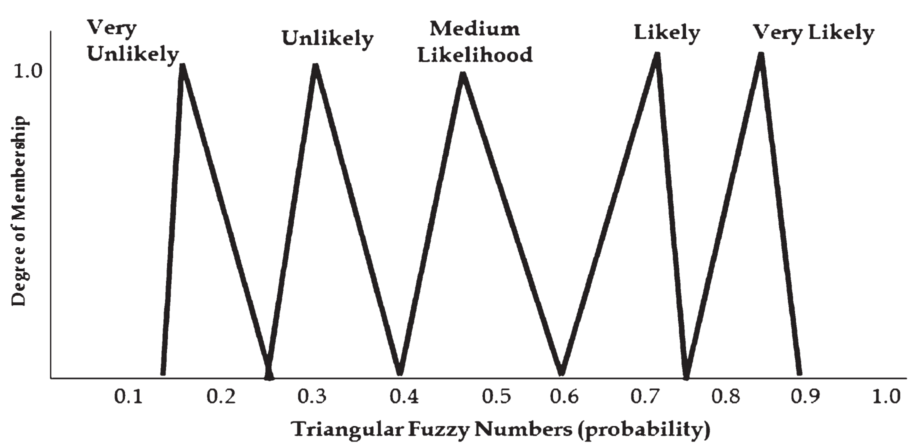


**Figure A.3** Fuzzy numbers corresponding to the probability linguistic terms.

consequence. Risk consequences are usually evaluated using dollar values; however, in this assessment of the macro consequences of reduced inspection, it was difficult to assign dollar values to the risk consequences. Thus, it is assumed that all the macro consequences are of equal significance (e.g., similar dollar values) so that the risk impacts are derived solely from the probability of occurrence of the risk consequences. Hence, the risk impacts for a given risk consequence in a construction activity can be represented by the value of the probability of risk consequences $p(\theta)$.

*Step 5: Evaluation of the average risk impact for a construction activity* $p(\theta_j)$ is the probability of occurrence of risk consequence $j$ due to reduced inspection in a construction activity. Since in the previous step it was assumed that all the risk consequences are of equal significance, the average risk impact (considering all risk consequences) due to reduced inspection in a construction activity is equal to the average of the probabilities of occurrences of the six identified risk consequences (i.e., short-term functional failures, long-term functional failures, increased user costs, decreased design life, increased maintenance costs, and decreased safety) and can be evaluated using Equation 5. In other words, the average risk impact is equal to the average probability of risk impacts.

$$Average\ probablity\ of\ risk\ impacts = \frac{\sum_{j=1}^{6} p(\theta_j)}{6} \qquad (5)$$

## A.4. PRIORITIZATION OF CONSTRUCTION ACTIVITIES FOR INSPECTION

The results of the risk analysis performed using steps 1–5 of the probability encoding process are summarized in Table 4.5. The results presented in Table 4.5 are based on the responses of 101 experts from state DOTs, consultants, and the Indiana DOT (INDOT). The values in the table indicate the average perceived risk impacts due to reduced inspection for different construction activities. For instance, for concrete paving, the average perceived risk impact due to reduced inspection is 64% based on all the responses. This result implies that if the inspection of concrete paving is reduced/missed, it is perceived that the likelihood of occurrence of macro consequences would be 64%. While these values do not reflect the actual risk impacts due to the existence of biases, they can be used to identify the construction activities with greater risk impacts due to reduced inspection. To assess whether the obtained results are sensitive to the responses from different groups of experts, the analyses were performed separately for the responses of experts from the state DOTs, consultants, and INDOT. The results of the separate analyses are also shown in Table 4.5 in the main report. The results indicate that the encoded probabilities from the different groups of experts are very close. For instance, for embankment activity, the encoded probabilities obtained from the state DOTs, consultants, and INDOT surveys are equal to 56%, 55%, and 58%, respectively. This result implies that (1) there is no significant difference in the risk attitude of the group of experts from the state DOTs, consultants, and INDOT; and (2) the methodology used in the study was successful in eliciting the beliefs of the experts.

In order to prioritize inspection activities based on the level of risks due to missed inspections, a risk-based inspection protocol can be created. The greater the average risk impact of a construction activity, the higher the priority of the activity for inspection. Initially, three categories of priorities of construction activities for inspection were defined: *High, Medium, and Low*. The boundaries of the different categories were set based on the fact that an analysis of the results indicated that 95% of the average values of encoded perceived probabilities of risk outcomes were greater than 30% and less than 65%. Therefore, the range (i.e., 30% to 65%) was divided into three intervals (below 40%, between 40% and 55%, and above 55%). If the average probability of risk consequences was greater than 55%, the activity was considered to be *High Priority*; if the average probability of risk consequences was greater than 40% and less than 55%, the activity was considered to be *Medium Priority*; and if the average probability of risk consequences was less than 40%, the activity is considered to be *Low Priority*. Further analysis revealed that there are a number of activities whose average perceived probability of risk consequences due to missed inspection were close to the boundary values, which made it difficult to judge the priority category in which they would be appropriate.

Thus, two additional intermediate priority categories (i.e., *Medium-Low* and *Medium-High*) were defined to address this issue. Table 4.6 in the main report summarizes the list of prioritized construction activities. The construction activities were then prioritized into five categories based on the risks associated with reduced inspection: *High, Medium-High, Medium, Medium-Low, and Low*. The higher the priority of an activity for inspection, the greater the risk impacts due to reduced inspection would be. For instance, asphalt paving is categorized as a *High Priority* based on the aforementioned analysis. Asphalt paving requires a number of tests (e.g., asphalt core sampling, compaction testing, and mix temperature testing) that could not be performed after the completion of the activity. Not performing such tests could lead to lack of discovery of defects that could lead to potential cracks and eventually could lead to functional failures, reduced life of the facility, and increased maintenance costs. On the other hand, site clearing is categorized as a *Low Priority* based on the risk analysis. Site clearing only requires checking the clearing limits and underlying material and utilities. Failing to inspect these items is not likely to lead to lack of discovery of the defects. Thus, there would be fewer risk impacts due to missing inspections of this activity.

Examination of the list of prioritized activities (Table 4.6 in the main report) reveals that the existence of testing and safety requirements increases the perceived probability of macro risk consequences due to missed inspection. For instance, activities such as asphalt paving, concrete paving, aggregate base course, and embankment require testing. Activities such as structure rehabilitation and bolting structural connections entail safety considerations (e.g., safety of workers and the public during the construction phase and safety of facility users after the construction phase). Thus, these activities are perceived to experience greater risk impacts due to reduced inspection. In addition, activities such as installing reinforcement steel in structures in which the work is covered upon completion of the activity (it cannot be inspected later unless it is destroyed) are perceived to entail greater risk impacts due to missed inspection. The proposed risk-based inspection protocol could be used for resource allocation based on the risk impacts. The proposed list of prioritized construction activities could assist project and program managers to optimally allocate their limited inspection resources when a number of activities (whose inspection could not be performed at a later time regardless of the level of inspection required) are taking place concurrently on the jobsite.

## REFERENCES


1. Reynolds, J. T. The Application of Risk-Based Inspection Methodology in the Petroleum and Petrochemical Industry. *ASME PVP*, Vol. 336, 1996, pp. 125–134.
2. Dey, P. K., S. O. Ogunlana, and S. Naksuksakul. Risk-Based Maintenance Model for Offshore Oil and Gas Pipelines: A Case Study. *J Qual Maint Eng*, Vol. 10, No. 3, 2004, pp. 169–183, doi: 10.1108/13552510410553226.
3. Nalli, K. Risk-Based Inspection—An Efficient Maintenance Tool. *Journal of Hydrocarbon Processing*, Vol. 86, No. 12, 2007, pp. 91–94.
4. Tien, S-W.,W-T. Hwang, and C-H Tsai. Study of a Risk-Based Piping Inspection Guideline System. *ISA Transactions*, Vol. 46, 2007, pp. 119–126, doi: 10.1016/j.isatra.2006.06.006.

5. Straub, D. and M. H. Faber. Computational Aspects of Risk-Based Inspection Planning. *Computer Aided Civil Infrastructure Eng*, Vol. 21, No. 3, 2006, pp. 179–192.
6. Anderson, J. L. Embracing Uncertainty: The Interface of Bayesian Statistics and Cognitive Psychology. *Conservation Ecology*, Vol. 2, No.1, 1998. Available at: http://www.ecologyandsociety.org/vol2/iss1/art2/
7. De Finetti, B. Foresight: Its Logical Laws, Its Subjective Sources. In *Studies in Subjective Probability*, H. Kyburg and H. Smokler, Eds. John Wiley & Sons, Inc., New York, 1964.
8. Duda, R. O., P. E. Hart, and N. J Nilsson. Subjective Bayesian Methods for Rule-based Inference Systems. *Proceedings of the AFIPS National Computer Conference*, Vol. 45, 1976, pp. 1075–1082.
9. Spetzler, C. S., C. S. Staël Von Holstein. Probability Encoding in Decision Analysis. *Management Science*, Vol.22, No 3, 1975, pp. 340–358, doi: 10.1287/mnsc.22.3.340.
10. Tversky, A., and D. Kahneman. Judgment under Uncertainty: Heuristics and Biases. *Science*, Vol.185, 1974, pp. 1124–1131, doi: 10.1126/science.185.4157.1124.
11. Tversky, A., and D. Kahnemann, Belief in the Law of Small Numbers. In *Judgment under Uncertainty: Heuristics and Biases*, D. Kahneman, P. Slovic and A. Tversky, Eds. Cambridge University Press, Cambridge, 1982, pp. 23–31.
12. Von Winterfeldt, D., and W. Edwards. *Decision Analysis and Behavioral Research*. Cambridge University Press, New York, 1986.
13. Barnes, J. H. Cognitive Biases and Their Impact on Strategic Planning. *Strategic Management Journal*, Vol. 5, No. 2, 1984, pp. 129–137, doi: 10.1002/smj.4250050204.
14. Kahneman, D., and A. Tversky. On the Reality of Cognitive Illusions. *Psychlogical Review*, Vol. 103, No. 3, 1996, pp. 582–592, doi: 10.1037/0033-295X.103.3.582.
15. Tversky, A., and D. A. Koehler. Support Theory: A Nonextensional Representation of Subjective Probability. *Psychological Review*, Vol. 101, No. 4, 1994, pp. 547–567, doi: 10.1037/0033-295X.101.4.547.
16. Daneshkhah, A. R. (2004). *Uncertainty in Probabilistic Risk Assessment: A Review*. The University of Sheffield, August 9, 2004. http://www.shef.ac.uk/content/1/c6/03/09/33/risk.pdf. Accessed Spring 2011.
17. Clark, D. A. Verbal Uncertainty Expressions: A Critical Review of Two Decades of Research. *Current Psychology: Research and Reviews*, Vol. 9, No. 3, 1991, pp. 203–235, doi: 10.1007/BF02686861.
18. Beyth-Marom, R. How Probable is Probable? A Numerical Translation of Verbal Probability Expressions. *Journal of Forecasting*, Vol. 1, 1982, pp.257–269, doi: 10.1002/for.3980010305.
19. Bonissone, P. P., S. S. Gans, and K. S. Decker. RUM: A Layered Architecture for Reasoning with Uncertainty. *Proceedings of the 10th International Joint Conference of Artificial Intelligence* (IJCAI-87), Milan, Italy, August 23–28, 1987, pp. 373–379.
20. Van der Gaag, L. C., S. Renooij, C. L. M. Witteman, B. M. P. Aleman, and B. G. Taal. Probabilities for a Probabilistic Network: A Case-study in Esophageal Cancer. *Artificial Intelligence in Medicine*, Vol. 25, No. 2, 2002, pp. 123–148, doi: 10.1016/S0933-3657(02)00012-X.
21. Hanss, M. *Applied Fuzzy Arithmetic: An Introduction with Engineering Applications*. Springer-Verlag, Berlin, 2005.
22. Winkler, R. L., S. C. Hora, and R. G. Baca. The Quality of Expert Judgment Elicitations. In *Nuclear Regulatory Commision Contract NRC-02-88-005*. Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas, 1992.
23. Lindley, D. V., A. Tversky, and R. V. Brown. On the Reconciliation of Probability Assessments. *Journal of the Royal Statistical Society: Series A*, Vol. 142, 1979, pp. 146–180, doi: 10.2307/2345078.
24. West, M. Modelling expert opinion. In *Bayesian Statistics*, J. M. Bernardo, J. O. Berger, A. P. Dawid, and A. F. M. Smith, Eds. Oxford University Press, Oxford, 1988.
25. Clemen, R. T. and R. L. Winkler. Combining Probability Distributions from Experts in Risk Analysis. *Risk Analysis*, Vol. 19, No. 2, 1999, pp. 187–203.
26. Stone, M. The Opinion Pool. *Annals of Mathematical Statistics*, Vol. 32, 1961, pp. 1339–1342.

# APPENDIX B

## SURVEY INSTRUMENT

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=3&article=2974&context=jtrp&type=additional