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EXAMINING RISK-BASED INSPECTION APPROACHES TO HIGHWAY CONSTRUCTION PROJECTS

Mohamed, M.[1,2], Tran, D.[1,3]
[1]University of Kansas, USA
[2]mamdoh_ali@ku.edu
[3]daniel.tran@ku.edu

Abstract: State highway agencies traditionally rely on a quality control/quality assurance (QC/QA) to inspect the construction activities. Under this method, the contractor's QC test results are used as a basis of acceptance. However, this approach does not offset the shortage in inspection resources including experienced inspectors and inspection funding. During the last decade, the emerging state-of-the-practice approach, risk-based inspection, has been adopted in the acceptance of the Q/A construction and testing activities. Several highway agencies have implemented risk-based inspection in their highway construction projects. The risk-based inspection approach typically focuses on a core list of inspection items. This list is prioritized based on criticality of the QA test or inspection activities. This study aims to examine the current practices of the risk-based inspection approaches. Six departments of transportation (DOTs) of California, Florida, Texas, Washington, New York, and Indiana were selected and examined. The results show that acceptance protocols lay in one of two categories, material-based or test-based protocols. The core list of inspection activities varies. The typical criteria affecting the type and number of the core list activities include location, weather condition, and organizational structure. Based on these findings, this study provides a generic approach for other highway agencies interested in developing risk-based acceptance protocols. This generic approach involves four basic stages, comprehensive list development, core list development, risk assessment, and final protocol. This study enriches the construction body of knowledge and practices by shedding the light on the risk-based inspection in highway construction projects.

1. INTRODUCTION

Pavement construction is a manufacturing process that takes materials and workmanship as inputs and generates pavements as the end product. The quality of the pavement depends on both material properties and construction practice. To ensure the quality of the pavement, state departments of transportation (DOTs) allocate resources to test construction materials and inspect the construction items through QA acceptance process. Traditionally, DOTs adopted two acceptance systems (KDOT 2018). The first acceptance method is non QC/QA specifications where the DOT's test results are used as the only basis of acceptance for project materials. By this approach the contractor's test results are not considered as a basis for acceptance. In general, through this approach, the contractor is not required to conduct quality control testing. The second acceptance method is QC/QA specifications. Under this method, the contractor's QC test results are used as a basis of acceptance. In addition, DOT inspection staff verifies these results by comparing DOT's testing results with contractor's QC results. These verification and QC test results are statistically compared by the use of the F and T tests (LaVassar et al. 2009, KDOT 2018; Sillars et al. 2010).

During the last decade, state DOTs are facing the critical challenge of an increased demand for highway system construction work with reduced funding and staff. NCHRP Synthesis 450: Forecasting Highway Construction Staffing Requirements found that state DOTs are managing larger roadway systems with fewer in-house staff than they were 10 years ago(Taylor and Maloney 2013). The study found that staff constraints and the lack of needed skills are affecting virtually all DOT functions, with major impacts on construction inspection capabilities. As a result, state DOTs had to seek out effective approaches to accomplish construction inspection operations and optimize resource allocation. Incorporating risk-based inspection approaches into current practices with an emphasis on increasing the value of inspection has the potential to improve the QA process (Daniel 2017). The objectives of this study are to (1) examine the current practices of risk-based construction inspection and (2) provide a standard approach to highway agencies interested in developing risk-based acceptance protocols. This paper enriches the body of knowledge by identifying the risk-based inspection system. This paper also contributes to the construction industry by providing a guideline for state DOTs to adopt risk-based inspection system in their QA programs.

2. MOTIVATION

Anderson et al. (2012) conducted a study of transportation agencies staff recruiting and retaining issues throughout the 50 DOTs. The study pointed out that while many DOTs consider the process of operating and managing their system as an increasing priority, they still encounter a shortage of skilled staff. Retirement of transportation practitioners depletes the ranks of highly qualified professionals. Another study by Taylor and Maloney (2013) shows that between 2000 and 2010 the total lane-miles in the systems managed by DOTs increased by an average of 4.1%, whereas the in-house personnel available to manage these systems decreased by an average of9.78% over the same time period. By any measure, state DOTs are doing more work with fewer agency employees than they were 10 years ago. These statistics indicate that the allocation of human resources is critical in maintaining and improving the nation’s roadway infrastructure system. This is especially true for agency employees in the area of construction, because construction projects represent a significant portion of a transportation agencies’ total budget. Further, the study also found that 88% of state respondents to their survey used consultants to perform construction staffing functions.

This situation has motivated DOTs to seek out effective strategies to accomplish construction inspection operations and optimize resource allocation. There is a need to incorporate risk-based approaches into current practices for construction inspection with an emphasis on increasing the value of inspection and optimizing inspection frequency.

3. RISK-BASED INSPECTION

Using traditional inspection approaches such as QC/QA and declined frequency of inspection cannot reduce material and workmanship risks to acceptable level. Generally, risk cannot be reduced to zero level due to factors such as faults of design, natural disasters, and human errors. Uninspectable risk is a residual risk that is usually present (Soares et al. 2015). However, risk-based inspections aim to understand risk drivers in order to prioritize inspection-related activities. Typically, the risk-based inspection methodology requires assessing and evaluating seven main steps, including: data and information collection, risk assessment process composed of probability of failure rating and consequence of failure rating, risk ranking, inspection plan, mitigation (in case of need) and reassessment. The American Petroleum Institute pinpoints several benefits of using the risk-based inspection as following:

- Identifying critical inspection and maintenance activities;
- Facilitating the development of optimized inspection and mitigation plans;
- Understanding the current risk and providing an overall risk reduction;
- Allocating inspection resources properly; and
- Generating cost savings (API, 2016).

the risk-based inspection assessment process involves the two main components: (1) consequence of failure/risk and (2) probability of failure/risk. The risk impact can be estimated based on a product of the probability of an event and the associated consequences using Equation (1).

$$RiskImpact = ProbabilityofOccurancexRiskConsequencesEquation\ (1)$$

The probability of occurrence in Equation (1) is the likelihood of an adverse event or failure occurring during a given time period. The consequence is defined as a measure of the impact of the event occurring, which may be measured in terms of economic, social, safety, environmental, or other impacts. It is important to note that both the probability of risks and their possible consequences can be estimated quantitatively or qualitatively, depending on the considered project/system characteristics and the availability of inspection data. The quantitative estimating process often involves using probability of failure models and quantitative measures of consequences (e.g., cost impact of a risk event, the service interruption, or safety). Thequalitative estimating process involves using a risk matrix. For example, risk probability can be estimated based on whether the likelihood of a certain event is high, medium, or low. Similarly, the risk consequences can be expressed qualitatively as high, medium, or low. Researchers show that presenting risk qualitatively is a common and effective approach to assessing and evaluating risk (Washer et al. 2014). Figure 1 illustrates a simple sample of risk matrix.

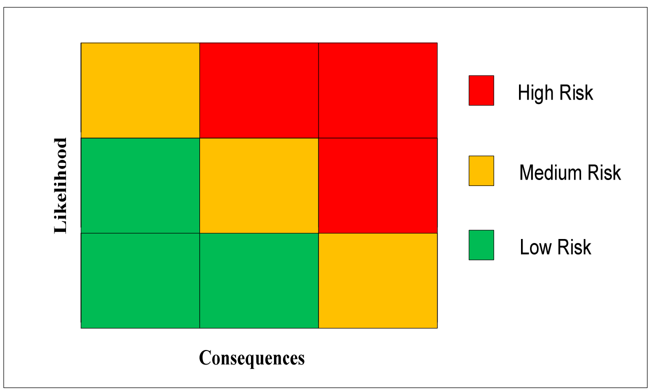

Figure 1: Risk matrix.

For decision makers, it is important to consider that high likelihood does not necessarily mean high risk, if the consequences are small. Similarly, high consequence does not necessarily mean high risk, if the likelihood is small. The level of risk can only be determined based on assessing both of these variables. Further, a risk-based inspection approach focuses attention not on the items that are most likely to fail, but rather those items whose failure is most important, by considering both the likelihood of failure and the associated consequences. For instance, some materials may not fail very often but failure would be catastrophic in case of occurrence. On the other hand, some materials often fail to meet production specifications, but the consequences are not risky.

3.1. Risk assessment methodologies for risk-based inspection

Risk assessment can be classified into three main categories: qualitative, quantitative, and mixed (e.g. semi quantitative) approach. All three risk assessment approaches share the same feature that involves identifying areas of concern and their associated risks, screening risks, and developing a prioritized list of inspection items for in depth analysis. These approaches can be defined as follow:

Qualitative Approach: This approach is the process of analyzing the probability and consequence of a risk event using descriptive information from subject matter experts based on their engineering judgment and experience (API, 2016; Mostafavi and Abraham 2012). The accuracy of this approach depends on the background, collective experience, expertise, and other defined quality of the participants. The result of this approach typically provides a qualitative terms such as “low,” “medium,” or “high” or numerical values (e.g., using Likert scale measurement such as a 1-5 scale). It is important to note that although the qualitative approach is less precise than the quantitative approach, it is effective and useful for screening and prioritizing risks and for developing appropriate risk mitigation and allocation strategies (API 2016). The qualitative approach may be used for any aspect of inspection plan development (API 2016). The qualitative analysis is often used to guide the quantitative risk assessment approach.

Quantitative Approach: The quantitative risk assessment approach relies on quantitative (or in-depth, detailed) data developed from probabilities models, databases of failure, past performance data such as deterioration rate models. The quantitative analysis involves quantifying the probabilities and consequences of the probable damage. For example, the likelihood of an inspection risk item can be assessed using the probability and effects of specific inspection or testing failure. Such analysis can be performed based on the history of failure probability for a type of testing or inspection items (Patel 2015; FHWA 2006).There are a series of statistical modeling techniques (e.g., Monte Carlo simulation, sensitivity analysis, and other stochastic methodologies) to determine the probabilities and the impact of inspection risk item. Event trees and fault trees also can be used to quantitatively model inspection risk items and inspection processes. It is important to note that although the quantitative assessment provides valuable insight, accurate and objective results, it has a number of limitations. In general, it is impractical to acquire the required data to be modeled effectively. For example, data on past performance are typically incomplete or inaccurate (Andersen et al. 2001).

Semi-quantitative Approach: This approach is referred to any approach that utilizes both qualitative and quantitative assessments. It aims at obtaining the main advantages of both approaches such as less available data required and level analysis (speed of qualitative assessment) (and more rigor and accuracy of quantitative assessment (API, 2016). Additionally, the qualitative data can be augmented with quantitative data for any inspection activities when available (Washer et al. 2014). It is recommended that the qualitative, quantitative, and semi-quantitative approaches should not be considered separately but rather as complementary (API, 2016). At the program level, a qualitative may be the suitable approach to screen the highest risk for further analysis. At the project level, a semi-quantitative approach may be suitable for the higher risk items. At the activity level, if the data available with enough quality, a quantitative approach may be the best approach to analyzing the risk. Washer et al. (2014) pointed out that quantitative analysis does not necessarily mean its results are more accurate than qualitative analysis unless the quality data supported the analysis is available.

Selecting a suitable risk assessment approach depends on various factors, including: number of inspection items required, available resources, nature, and quality of available data, complexity of inspection processes, and others. One of the outcomes from performing risk assessment in the risk-based inspection practice is knowledge and understanding to develop a prioritized list of inspection items (FHWA 2006). The prioritized list should be developed based on evaluating separately both the probability (likelihood) and consequence of risk (DOE 2011).

3.2 Key elements of risk-based inspection

The National Cooperative Highway Research Program (NCHRP) Report 782 includes three key elements for reliability-based bridge inspection practices: (1) occurrence factors, (2) consequence factors, and (3) assessment panel (Washer et al. 2014). While NCHRP Report 782focuses on reliability assessment of bridge elements, the concept can be applied to the inspection of highway projects. This section briefly discusses these three key elements in the light of risk-based inspection for highway construction projects.

Occurrence factor: The occurrence factor is an estimate of the likelihood of severe damage occurring in an inspection period by addressing the following question: "*What can go wrong, and how likely is it*?" All three risk assessment approaches (qualitative, quantitative, or semi-quantitative) discussed previously can be used for estimating the expected performance of components. A study by Washer et al. (2014) provided four-level scale ranging from "remote" when the likelihood is extremely small (e.g., unreasonable to expect failure) to "high" when the likelihood of the risk event is increased. Table 1 summarizes the rating scale using for estimating occurrence factors for the risk-based inspection practice.

Table 1: Rating scale for occurrence factor

Level	Category	Description
1	Remote	Remote likelihood of occurrence, unreasonable to expect failure to occur
2	Low	Low likelihood of occurrence
3	Moderate	Moderate likelihood of occurrence
4	High	High likelihood of occurrence

Consequence factor: The primary purpose of inspection is to ensure the safety and serviceability of highway elements. The consequence factor is used to categorize the consequences of failure of an element(s) based on the anticipated or expected outcomes (Washer et al. 2014). The consequence factor can be estimated based on the physical conditions, the materials involved, service interruption, safety issues, and other issues. Similar to the assessment of occurrence factors, three risk assessment approaches (qualitative, quantitative, or semi-quantitative) can be used to evaluate consequence factors. Washer et al. (2014) used a four-level scale ranging from “low” to “severe”. The “low” level is used to describe scenarios in which failure is very unlikely to have a significant effect on safety (short term consequences) and serviceability (long term consequence) while the “severe” level is used to describe the major consequences of safety or serviceability. Table 2 summarizes the rating scale using for estimating consequence factors for the risk-based inspection practice.

Table 2: Rating scale for consequence factor

Level	Category	Consequence on safety	Consequence on serviceability
1	Low	None	Minor
2	Medium	Minor	Moderate
3	High	Moderate	Major
4	Severe	Major	Major

Risk assessment panel: The critical component of the risk-based inspection practice is to establish a proper risk assessment panel. The individuals in the panel should offer experience relevant to the types of risks related to the inspection process such as design features, construction specifications and practices, materials, and operational environment. The process to elicit expert judgment from the panel is relatively simple. The purpose of the elicitation process is to provide a systematic framework that allows efficient, objective analysis, and comprehensive gathering insight into the probability of failure and its associated consequences (Washer et al. 2014).

4. RESEARCH APPROACH

To review and assess the multifaceted benefits and costs of risk-based inspection, the authors conducted a comprehensive literature review including academic, industry publications, state DOT websites, and government reports to find the most current trends and practices in risk-based inspection approach (see figure 2). The literature review was conducted by using academic database, general internet search engines, transportation research record (TRR), FHWA website, and the ASCE civil engineering database.

As shown in Table 3, six case studies of construction programs were investigated and analyzed in this paper. The DOTs were selected based on adopting risk-based inspection in their QA programs and availability of the documents of highway construction program. According to Yin (2009), case studies are the preferred research method when: the research problem is on a contemporary phenomenon within a real-life context; dealing with “how” and “why” research questions; and the researcher has little control events.

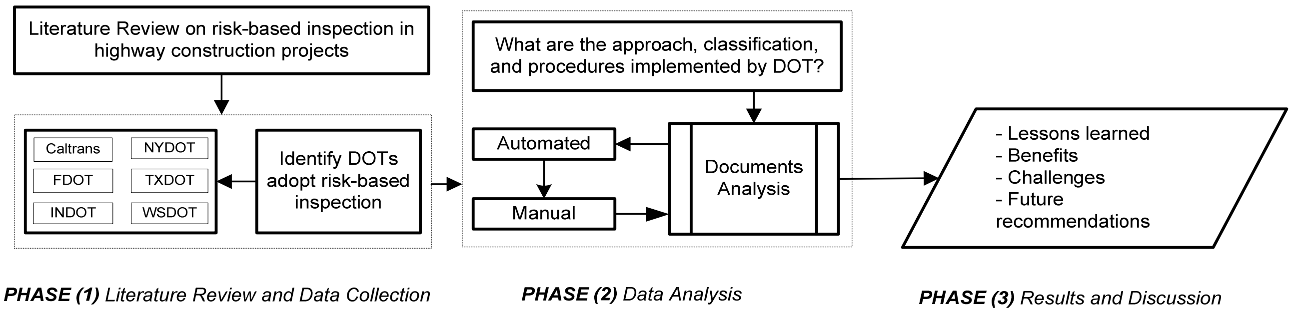

Figure 2: Research methodology

In addition, the case study approach is more explanatory in this research due to the lack of existing framework and guidance on risk-based inspection in highway construction field. As a result, the case study approach is a suitable research methodology and is a main research tool for this study.

Table3: Summaries of case study QA programs

Agency	QA Program
California DOT (Caltrans)	Quality Assurance Program (QAP) Includes an acceptance program for materials and workmanship, an independent assurance (IA) program and preparation of a project materials certification.
New York State DOT (NYSDOT)	Design QA Bureau develops and maintains most of the guidance for highway design functions. Materials Bureau determines the level of quality assurance required for each material item.
Texas DOT (TxDOT)	QAP consists of a Quality Control (QC) Program, an Acceptance Program, and IA Program.
Washington State DOT (WSDOT)	QAP includes Qualified Tester Program, Equipment Calibration/Standardization/Check andMaintenance Program, Qualified Laboratory Program, IA Program
Indiana DOT (INDOT)	QAP includes quality control office, material office, and field team.
Florida DOT (FDOT)	The central office at FDOT is responsible for general policy and QA procedures. Meanwhile, the eight districts are responsible for material QA on projects

In this step, a rigorous scan process was conducted for a large amount of documents. This process includes two stages:

- **Stage 1**:Automated Scan using a qualitative data analysis computer software package NVIVO. It has been designed for qualitative researchers working with very rich text-based and/or multimedia information, where deep levels of analysis on small or large volumes of data are required.
- **Stage 2:** Manual scan to confirm and validate the results obtained in stage 1.

The documents examined involve DOT bridge construction manuals, construction checklists, construction manuals, documentation manuals, specifications, and others. The six case study projects shown in Table 1 provide examples of how state DOTs organize their QA programs. Selection of these six programs covers different aspects such as geographical distribution among the U.S., considering weather effect, organizational structure, and levels of risk-based inspection implementation.

5. RESULTS

Table 4 provides a summary of different inspection optimization strategies by state DOTs. Examining inspection procedures of these state DOTs shows that five state DOTs are implementing explicit risk-based inspection principles. In addition, these five state DOTs adopt alternative project delivery methods as a strategy to minimize the number of required inspection resources.

Table 4: QA inspection strategies by DOTs

QA strategies	Caltrans	FDOT	TxDOT	WSDOT	NYSDOT	INDOT
1. Reduced frequency of testing for small quantities and large volumes of project-produced materials.	☑	☑		☑		
2. Consideration of material criticality	☑	☑		☑	☑	☑
3. Qualifications of producers or suppliers	☑	☑	☑	☑		
4. Alternative project delivery methods	☑		☑	☑	☑	☑
5. Explicit use of risk management principles	☑		☑	☑	☑	☑

Further, literature review and case studies including examining of acceptance procedures of six state DOTs led to the following key findings:

- With considering project delivery method, each state DOT has its own strategy for material or workmanship acceptance,
- All of these state DOTs acceptance methods do not provide a comprehensive acceptance approaches for their QA programs,
- Acceptance approaches focus on reducing inspection frequency rather than prioritizing inspection based on criticality,
- Cost saving is considered for transportation agencies that implemented risk-based inspection approach, and
- Extended highway service life for state DOTs that adopted risk-based inspection in their projects.

In addition, adopting new technologies will improve construction inspection and acceptance processes. These technologies help to fill the gap between increased number of highway construction projects and declination of inspection resources.

In terms of risk-based inspection, the case studies show that there are two risk-based acceptance strategies implemented by DOTs to prioritize inspection effort by QA staff:

- Test-based acceptance : Emphasizing on test properties that are more indicator of performance, where tests lay in level 1 have a priority for inspection than those in next levels (see Table 5-a). TxDOT and NYSDOT have used this approach.
- Material-based acceptance: Emphasizing on the prioritized list of materials and QA activities (see Table 5-b). This approach is implemented by several state DOTs such as WSDOT and INDOT. Materials lay in highest level are more critical than the others in the lower levels.

Table 5-a:Test risk-based inspection

Level	Description	Example
1	Strong indicators of performance	Compressive strength for structural concrete
2	Secondary measures of performance	Concrete slump test
3	Does not affect long-term performance	Removal of structures and obstructions

Table 5-b: Material risk-based inspection

Level	Description	Example
Highest	Acceptance testing	Field statistical (PWL or other)
Medium	Certification with quality system plan/visual inspection	Manufactured Products from Certified Suppliers
Medium low	Certification or catalog cut	Qualified/Certified Products
Low	Visual inspection	Shop or source inspection

Based on these findings, the authors proposed an approach that may be adopted for developing risk-based acceptance protocols. Examination of the case studies revealed that there is a series of typical procedures to create risk-based inspection protocol for highway construction activities (see Figure 3 for more details). This approach involves four basic stages, comprehensive list development, core list development, risk assessment, and final protocol.

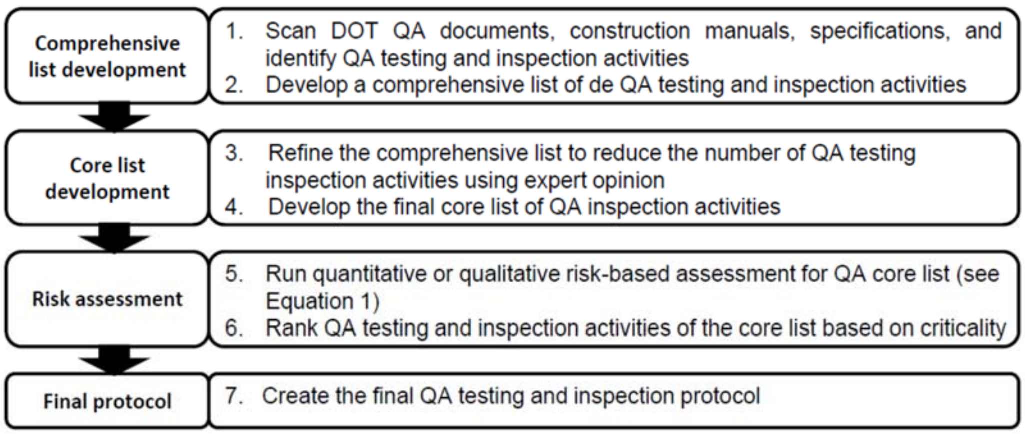

Figure 3: Procedures to develop risk-based inspection protocol

6. CONCLUSIONS

Risk-based inspection for highway construction projects is performed by one of two approaches. The first approach is material-based where the materials are classified into four levels. The highest inspection priority level is for the materials that require testing. Meanwhile, the lowest level is for materials that requires visual inspection. The second approach is test-based, where the highest priority is for tests with Strong indicators of performance. And the lowest inspection priority is for the materials that do not affect long-term performance. Further, the core list of inspection activities varies from agency to other depending on factors such as weather conditions and project delivery methods. Cost saving is considered for state DOTs that implement risk-based inspection approach in their QA programs. State DOTs that adopted risk-based inspection have extended highway service life than DOTs that implement traditional QA acceptance. However, risk-based acceptance protocols for highway construction activities should cover both of material inspections and workmanship. The later includes quality inspection for labour and equipment production. The philosophy of risk-based inspection is built upon prioritizing inspection activities based on material or test criticality rather than the traditional way of reducing inspection frequency.

Based on examination of the case studies, the authors proposed an approach that can be adopted by state DOTs interested in implementing risk-based acceptance protocols in their QA programs. This approach involves four basic stages, comprehensive list development, core list development, risk assessment, and final protocol. These stages are divided into seven steps from scanning DOT QA related documents to developing the final risk-based QA testing and inspection protocol.

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