Final Report

Risk-based Inspection

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16. Abstract

Construction inspection is a critical component of the quality assurance/quality control (QA/QC) program at the South Carolina Department of Transportation (SCDOT). A pressing challenge SCDOT has been facing is to balance the increasing demand to rebuild the statewide transportation systems with declining resources available for inspection. This project aims to address this critical issue by developing a risk-based inspection program that includes (1) the identification and assessment of risks associated with construction activities at SCDOT, (2) the development of inspection strategies that correspond to the level of risk, (3) the identification of quality requirements and inspection activities that are applicable to pay items, and (4) the design and implementation of a digital, risk-based inspection system. Two rounds of surveys were conducted to first identify and rank the risk factors and then assess the risks in aspects of likelihood, severity (cost, time, safety, and quality), and performance (short-/mid-/long-term). An aggregate risk score was calculated to categorize each pay item into high, medium, and low levels of risk. The inspection strategies (i.e., inspection priority and frequency and documentation frequency) were designed to correspond to the level of risk. The quality requirements and inspection activities for pay items were extracted from the corresponding sections in the standard specification, construction manual, supplementary specifications, supplementary technical specifications, and standard drawings. A database was designed to host the risk and inspection information. Tools were developed to assist project engineers and field inspectors in retrieving inspection activities in the digital form of checklists. The main deliverable is the resulting digital inspection system with tools. This system allows for the retrieval of all the related risk information, inspection strategy, and inspection activities/checklists for any given pay item. This system is expected to significantly enhance the efficiency of the construction inspection practice at SDCOT and reduce the workload for construction inspectors. The risk-based approach also enables SCDOT to focus on the most critical areas and can support the automation of construction inspection at SCDOT.

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Executive Summary

Construction inspection is a critical component at the South Carolina Department of Transportation (SCDOT) to ensure the quality and long-term performance of the resulting infrastructures. In the current practice, SCDOT has been facing the challenge of balancing the inspection resource shortage (attributed to staff downsizing and the retirement of experienced construction inspectors) with the increasing demand for rebuilding and maintaining the statewide infrastructures. The growing number of transportation projects and complexities in modern construction projects further aggravate the challenges. In order to help SCDOT effectively allocate limited resources to the most critical areas, this research aims to develop a risk-based inspection program by focusing mainly on risks associated with SCDOT's current construction activities. This project consists of four objectives: (1) identification and assessment of risks associated with construction activities at SCDOT, (2) the development of inspection strategies that correspond to the risk level, (3) identification of quality requirements and inspection activities associated with construction activities, and (4) the design and implementation of a digital, risk-based inspection system. This project consists of eight tasks.

Task 1 aims to identify construction activities and requirements at SCDOT by identifying pay items associated with construction activities, developing a work breakdown structure (WBS), and linking pay items to applicable sections and divisions in related construction documents (e.g., standard specification). As a result, a total of 7,024 pay items were identified and organized into the developed WBS, a hierarchy of "7 construction area – 142 construction activity groups – 1,276 construction activities". This linking enables the extraction of construction requirements and inspection activities for individual pay items.

Task 2 aims to understand the current inspection practices at SCDOT by conducting surveys and aligning pay items with construction processes. It was found that the construction inspection at SCDOT focuses on six areas, i.e., asphalt, earthwork, and concrete, traffic control, structures, and erosion control and survey. The inspection process mainly consists of 4 consecutive steps (notification, requirements retrieval/planning, inspection, and documentation). The most frequently used inspection documents were project plans/drawings, special provisions/contracts, and standard specifications. Inspection frequency and factors (e.g., nature of work, construction method, risk) contributing to the chosen inspection frequency were also identified.

Task 3 aims to identify the availability and cost of inspection resources at SCDOT by conducting surveys and analyzing materials provided by the SCDOT. It was found that SCDOT mainly uses in-house staff and CE&I contracts in the current inspection practice, and CE&I contracts have relatively higher average hourly rates on all the positions compared with in-house staff.

Task 4 aims to identify risks associated with construction activities and assess corresponding risk levels by compiling a list of risks, developing risk breakdown structure (RBS) and risk breakdown matrix (RBM), determining the risk likelihood and consequence severity, and computing the composite risk score based on risk assessment matrix (RAM). A total of 45 risk factors were identified and organized into the RBS, which consists of six categories (5M1E), i.e., Man, Machine, Method, Material, Money, and

External/Environmental. The RBS was integrated with the WBS, and the construction risks were identified for each construction activity and pay item using the resulting RBM. Two rounds of surveys were conducted to rank the risks and assess the risks in terms of likelihood, severity (cost, time, safety, and quality), and performance (short-/mid-/long term).

Task 5 aims to determine inspection priority, inspection frequency, and documentation requirements for construction activities based on the risk level. Three levels of inspection priority (high, medium, and low), three inspection frequencies (full-time, intermittent, and end of production), and three documentation requirements (daily/per segment, per pay item, and once per pay item) were proposed to correspond to the high, medium, and low levels of risk.

Task 6 aims to identify critical inspection information from construction documents and develop a digital inspection system by retrieving construction quality requirements from construction documents (e.g., standard specification) using deep learning approaches. A database system was designed and implemented to store quality requirements linked to construction activities and pay items. The deep learning-based tool can successfully extract inspection requirements from the standard specification with an average accuracy of 91% and the construction manual with an average accuracy of 90%.

Task 7 aims to summarize a list of inspection requirements based on four documents (standard specification, construction manual, supplemental technical specification, and supplemental specification). The resulting inspection summary contains risk at the section level, inspection objectives, and inspection activities at the section or grouped section level.

Task 8 aims to develop a toolbox to accompany the inspection system designed in Task 6. The resulting system can (1) automatically generate applicable check items for the selected pay item from standard specification and construction manual, (2) retrieve corresponding construction activity and group, (3) display associated risk information, (4) retrieve supplementary materials (e.g., standard drawing), and (5) generate inspection forms in a checklist format. Tutorials in the video and Word formats were developed to help inspectors effectively use the system.

The main deliverables of this research project are the digital, risk-based inspection system and the inspection summary document. They are expected to greatly reduce the workload of construction inspectors, facilitate the allocation of limited resources to most critical construction activities that carry high risk levels, ensure consistency in the QA/QC practice, and support the documentation of construction inspection. Inspectors can use the digital system as a single-stop, central location to retrieve applicable quality requirements for the pay items under inspection. The system generates easy-to-use checklists to guide field inspectors. There is no longer the need to manually go through lengthy construction documents to retrieve necessary information and quality requirements. As such, the digital inspection system can improve the efficiency of construction inspection by at least 25% and will reduce the risk to SCDOT in accepting or even overpaying low-quality construction results.

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1. Introduction

1.1. Background

Construction inspection is the practice of inspecting and overseeing the construction activities to ensure that procedures, materials, and installations comply with quality and quantity requirements stipulated in plans and specifications. Effective construction inspection is critical to ensuring the quality of infrastructure construction and warranting the long-term performance of infrastructure.

Nationwide, state Department of Transportations (DOTs) have been facing challenges caused by the decreasing number of experienced construction inspectors due to retirements, staff downsizing, and resignations to take jobs in the private sector, and increasing demand for construction to rehabilitate transportation infrastructure to function properly and develop new roads and bridges [1,2]. The data collected in a synthesis of staffing requirements in state highway agencies reveal that between 2000 and 2010, the in-house SHA personnel available to manage roadway infrastructure decreased by an average of 9.78%, whereas the total lane-miles in the systems increased by an average of 4.1% [3].

1.2. Challenges and problem statement

Considering the resource shortage, the South Carolina DOT (SCDOT) is facing the challenge to fully inspect all aspects of work with due attention and efforts in construction projects without causing project delays and cost overruns, as has traditionally been done in the past, to ensure the construction quality and the long-term performance of the infrastructure. This resource shortage is a major problem in balancing the increasing demand to rebuild the transportation system with declining resources available for inspection. The biggest problems of the existing highway system in South Carolina are aging transportation infrastructure, deadly roads, and structurally deficient bridges. The demand for rebuilding SCDOT's transportation system leads to increases in the number of construction projects. Secretary of Transportation Christy Hall said in 2018: *"SCDOT has experienced a record-breaking year in the first year of the agency's 10-year plan to Rebuild S.C.'s Roads. For the first time in the agency's history, the total amount of road and bridge work underway on the state's highways has exceeded $3 billion."* With the passing of the new infrastructure bill by Congress, the demand for construction and the need for the construction workforce will grow exponentially. However, despite the increasing demand for construction resources, SCDOT is exposed to threats of insufficient construction staff, following the same nationwide trend. According to the National Cooperative Highway Research Program (NCHRP) Synthesis 450, full-time equivalent staff for managing highway transportation systems decreased by more than 37% between 2000 and 2010. In 2017, SCDOT leadership identified the loss of key personnel and the inability to recruit or retain staff as potentially high impact and likelihood events. Even with its success in developing a competent workforce and contracting inspection staff, there is still a critical need for SCDOT to seek alternative strategies to more effectively allocate its limited inspection resources to ensure the construction quality and life cycle performance of infrastructure.

1.3. Goal and Research Objectives

This project aims to develop an effective risk-based construction inspection program for SCDOT to allocate limited resources to the most critical areas and ensure the construction quality and the lifetime performance of infrastructure by minimizing the risk to SCDOT. The objectives of this research are to identify and evaluate the level of risk and inspections associated with SCDOT's current construction activities, develop an inspection program that takes into account these risks, and develop tools for its implementation. Specific research objectives and associated questions are outlined as follows.

1. **Identify current SCDOT inspection practices to include the level of inspection for all construction activities.**
   a. What are the construction activities at SCDOT, and how are they defined?
   b. For each construction activity, what are the construction requirements as stipulated in the standard specification, supplemental specification, supplemental technical specification, standard drawing, and construction manual?
   c. For each construction activity, what is the current practice of construction inspection in aspects of timing, frequency, process, and check details to ensure the quality meets requirements?
   d. What inspection resources are available to SCDOT, and what are their costs?

2. **Identify and evaluate the level of risk associated with SCDOT's current construction activities.**
   a. For each construction activity at SCDOT, what is its likelihood/probability of failing to meet requirements?
   b. For each construction activity, what is the impact of its quality on the infrastructure service life, maintenance needs, performance, and consequence severity?
   c. How to combine the likelihood and consequence severity to quantify the risk associated with each construction activity?
   d. How to prioritize construction activities for inspection, and what is the best level, considering the nature of the construction activity, the associated risk, and cost?
   e. For each inspection activity, what data shall be collected and how to facilitate their documentation to support downstream applications and sharing?

3. **Develop an inspection manual that defines and strengthens the application of construction inspection. The expected benefits are to address maximum productivity combined with appropriate inspector staffing.**
   a. What are the inspection objectives and inspector activities?
   b. How to reduce the workload and improve the inspection efficacy via workshops, on-demand training materials, IT tools, and streamlining of the business process?

The work scope of this proposal includes:

1. Generating a comprehensive list of all SCDOT construction activities and corresponding standard specification section number(s), supplemental technical specification designation(s), standard drawing number(s), and construction manual division section number(s).
2. Assessing the level of risk for each construction activity and assigning a level of inspection (e.g., continuous inspection, intermittent inspection, and end of product inspection) corresponding to

the level of risk, inspection frequency, and necessary project documentation to each construction activity.

3. Developing an inspection manual that defines and strengthens the application of construction inspection, which will reduce the workload and improve the inspection efficacy in workload, manpower, costs, and/or other identified benefit.

2. Literature Review

Construction inspection is defined as the process of overseeing the construction activities to ensure that procedures, materials, and installations comply with requirements and qualifications stipulated in plans and specifications [4]. The literature review in this section provides concise background information on (1) the current construction inspection practice and processes at STAs, particularly at SCDOT, and (2) risk-based construction inspection, including risk-based inspection strategies adopted by STAs and in this research project.

2.1. Current Construction Inspection Practice

In the current practice, contractors and STAs share the responsibilities of quality assurance/quality control (QA/QC). According to the Federal Highway Administration (FHWA) manual, contractors mainly focus on QC activities, and STAs conduct QA and project acceptance [5]. The contractors are typically required to develop a plan for QC and monitor varying construction activities to control quality. STAs are tasked with approving the QC plan and verifying and accepting the activities/projects. However, the shared responsibilities among different parties (e.g., contractors and STAs) and lack of clear guidance on their tasks often lead to the acceptance of low-quality built infrastructure [6]. In addition, the shortage of experienced field inspectors, the manual inspection process, and the growing number of statewide transportation projects further aggravate the challenge to sustain the current practice. Developing advanced inspection strategies has become a strategic undertaking in many STAs to address the challenges and improve the efficiency of the current construction inspection practice [7,8].

In the current practice at SCDOT, contractors are responsible for QC, and SCDOT is responsible for QA. For instance, in the *SC 277 NB Bridge Replacement over I-77* project [9], the design-builder is responsible for QC as well as the requirements on sampling and testing to ensure all work and materials comply with the contract requirements; SCDOT is in charge of QA, including acceptance testing, independent assurance testing, and materials certification. SCDOT's field inspectors conduct sampling, testing, and inspection, referring to SCDOT's quality acceptance sampling and testing guide [10], standard specification [11], construction manual [12], supplemental specification [13], and supplemental technical specification [14] to determine the acceptability of the construction work.

2.2. Risk-based construction inspection

Risk-based construction inspection is one of the advanced inspection strategies which allows for optimizing the allocation of resources to the critical inspection items based on risk levels. Several STAs have developed inspection protocols and processes to incorporate risk in their QA practices. For example, Indiana DOT adopted a three-step protocol to prioritize critical inspection items based on associated risks [2]. They identified a list of core inspection items from specifications, linked each core inspection item to construction processes, and assessed the risk for each inspection item via surveys. Similarly, Ohio DOT, Washington DOT, Texas DOT, and New York DOT, to name a few, developed risk-based approaches to optimize material QA, considering both the probability of failure and the consequences. In 2019, a study in NCHRP aimed to develop an AASHTO guidebook for risk-based construction inspection and plan and conduct a workshop to introduce the proposed guidebook to an audience of DOT staff and other stakeholders.

The risk-based inspection typically involves the following three steps: (1) risk identification, (2) risk assessment and analysis, and (3) the development of a risk-based inspection strategy. Risk identification aims to determine specific risk factors that can reasonably be expected to affect project objectives. It describes the predisposing risk conditions that make the system vulnerable to threat events. Risk assessment and analysis focus on evaluating risks in terms of their likelihood and impact as a basis for determining how they could be managed. Developing a risk-based inspection strategy allows project managers, engineers, and inspectors to prioritize inspection activities and pay attention to high-risk construction tasks to ensure the quality of the resulting infrastructure.

Risk-based inspection has been adopted in many areas, such as examining the mechanical equipment, monitoring underground piping networks, and inspecting structural elements. Moura et al. [15] developed a multi-objective genetic algorithm to optimize the total risk level and inspection costs. The researchers first assessed the occurrence likelihoods and consequence severities of risks, built a decision tree to estimate the inspection costs and risk levels for two alternatives (inspection and no inspection), and identified the cost-efficient portfolios of item inspections using Portfolio Decision Analysis. De Carlo et al. [16] proposed an integral risk-based optimization method for inspections of structural systems. The study developed a heuristic strategy to formulate the optimization problem and adopted dynamic Bayesian networks to estimate the inspection cost. Shuai et al. [17] adopted risk-based inspection to quantitatively assess the risk of crude oil tanks using a risk matrix. Mohamed and Tran [18] developed a Fuzzy-Bayesian network model to evaluate risks on 12 critical inspection activities. Researchers first identified QA inspection activities with a three-step process, then estimated the risk impacts and occurrence probabilities using fuzzy sets, and calculated risk levels using the Bayesian Belief Network. Mostafavi et al. [19] applied the risk-based inspection approach to prioritize construction activities, which can assist project managers in better allocating their limited inspection resources while reducing the inspection risks. The study first encoded the subjective probabilities of undesirable consequence occurrence by fuzzy analysis and prioritized the inspection activities based on risk impacts on reducing inspections.

The comprehensive literature review indicated two chief limitations in current research on risk-based inspection for infrastructure projects. First, only a few studies focused on risk-based inspection for infrastructure projects due to their complexity and multifaceted characters. Second, it remains an open challenge to quantitatively evaluate qualitative and subjective risk perception through traditional surveys and expert interviews. To address these limitations, this project proposes a risk breakdown matrix (RBM) approach for risk-based inspection of transportation infrastructure projects. A large number of construction activities were organized into a hierarchical structure, work breakdown structure (WBS); the risks were organized into a hierarchical structure-risk breakdown structure (RBS); and a matrix of WBS-RBS was constructed to register top risks for each construction activity. A K-means clustering technique was developed to categorize occurrence probabilities, consequence severities, and risk scores, which reduced the effects of subjective perception and integrated the merits of both quantitative and qualitative data.

3. Research Approach

The overall goal of this project is to develop a risk-based inspection program, which can be used to help SCDOT balance the increasing demand for rebuilding the statewide transportation systems with declining resources available for inspection. To achieve the goal, this project adopts a research framework that consists of nine tasks. **Figure 1** illustrates the connection among these nine tasks, research questions, and specific deliverables.

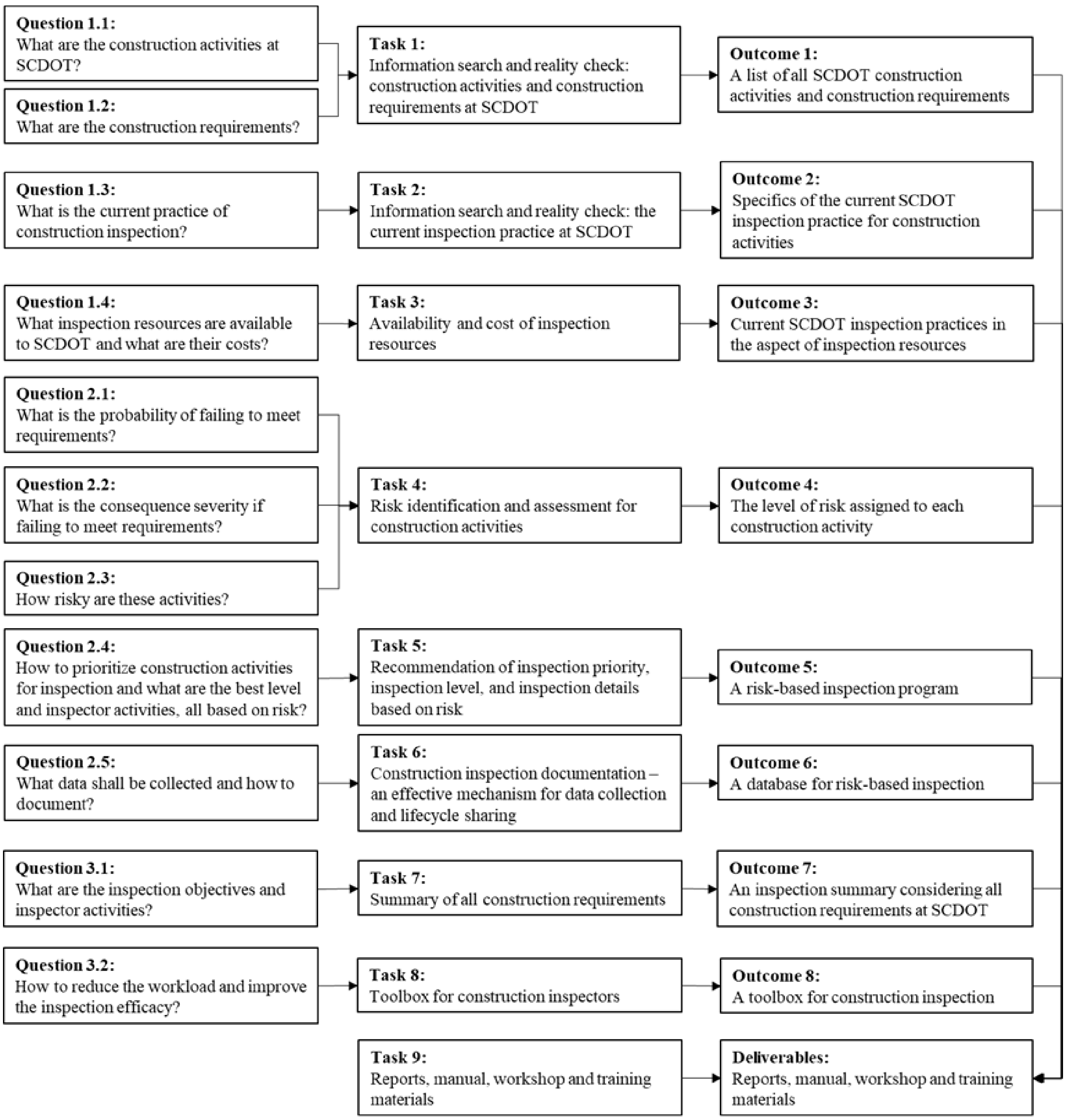

Figure 1. Overview of a research framework

4. Methodology and Results

4.1. Construction activities and construction requirements at SCDOT

In Task 1, a three-step approach was used to identify construction activities and construction requirements at SCDOT. First, pay items related to construction activities or infrastructure components were identified. Second, WBS was developed to organize these pay items into a hierarchy of "construction area – construction activity group – construction activity – pay item". This hierarchy serves as the bridge to connect pay items to divisions and sections in the standard specification and construction manual. It also sets the task context for risk assessment surveys in later tasks. Third, pay items were connected to the applicable sections and divisions in standard specification, construction manual, supplemental specification, supplemental technical specification, and standard drawing. As a result, corresponding construction requirements for each pay item were identified. The WBS enables the aggregation of construction requirements at all four levels.

4.1.1. Pay item categorization

The pay item list, available from SCDOT's website [20], contains a total of 7,307 pay items, each of which has an ID, description, and measurement unit, as illustrated in **Table 1**.

Table 1. Sample pay items

ID	Description	Units
2011001	CLEARING & GRUBBING WITHIN RIGHT OF WAY	ACRE
3011040	CEMENT MODIFIED SUBBASE (4" UNIFORM)	SY
3011060	CEMENT MODIFIED SUBBASE (6" UNIFORM)	SY
3011080	CEMENT MODIFIED SUBBASE (8" UNIFORM)	SY
3011100	CEMENT MODIFIED SUBBASE (10" UNIFORM)	SY
4011004	LIQUID ASPHALT BINDER PG64-22	TON
5010106	ROLLER COMPACTED CONCRETE PAVEMENT - 6" UNIFORM	SY
5010108	ROLLER COMPACTED CONCRETE PAVEMENT - 8" UNIFORM	SY
5010109	ROLLER COMPACTED CONCRETE PAVEMENT - 9" UNIFORM	SY
5010110	ROLLER COMPACTED CONCRETE PAVEMENT - 10" UNIFORM	SY
7010114	DRILLED SHAFT TEST-18"DIAMETER	EA
8111022	RED MAPLE - SEEDLING	EA

A thorough examination of the entire list of pay items resulted in the following observations. (1) Not all pay items were directly associated with construction activities that led to the delivery of infrastructure components. For example, *pay item 7010114 (DRILLED SHAFT TEST-18"DIAMETER)* is a testing item, which is a construction activity but does not directly lead to an infrastructure component; *pay item 8111022 (RED MAPLE – SEEDLING)* pertains to trees and plants, which is not relevant to construction activity. (2) Certain pay items are of the same construction activity. The only difference is the dimension. For example, *pay items* from *3011040* to *3011100* are *"CEMENT MODIFIED SUBBASE"* with different depths, which are of the same construction activity.

Based on these observations, the pay items were classified into three categories: category 1—pay items associated with construction activities that lead to infrastructure components (e.g., bridge deck, base course, and drainage structure); category 2—pay items that are construction activities but not directly relevant to infrastructure components; and category 3—pay items not related to construction activities. Category 1 pay items are the majority. A total of 6,943 pay items (95.0% of all pay items) are in this category. A total of 81 pay items (1.1%) are in category 2, and a total of 283 pay items (3.9%) are in category 3. Only category 1 and category 2 pay items were considered in developing WBS (*Appendix A*).

Deliverable: *Appendix A – Pay items categorization.xlsx*

4.1.2. Work breakdown structure (WBS)

WBS is a structure that decomposes a project into smaller components (e.g., construction activities) and defines the relationship between project units. WBS was developed by identifying four constituting layers (pay item, construction activity, construction activity group, and construction area) based on the standard specification and pay item list at SCDOT [11,20].

The standard specification has a hierarchy of "Division-Section-Subsection-(Subsubsection)-Paragraph" and includes eight divisions: Division 100—General Provisions, Division 200—Earthwork, Division 300—Bases and Subbases, Division 400—Asphalt Pavement, Division 500—Concrete Pavement, Division 600—Maintenance and Control of Traffic, Division 700—Structures, and Division 800—Incidental Construction. Pay items in category 1 and category 2 were further grouped into construction activities based on the similarity. As a result, 1,276 construction activities were identified from 7,024 pay items for developing the WBS. **Table 2** illustrates examples to group similar pay items into construction activities.

Table 2. Construction activities for similar pay items

Pay Item ID	Pay Item Description	Construction Activities
3011040	CEMENT MODIFIED SUBBASE (4" UNIFORM)	CEMENT MODIFIED SUBBASE
3011060	CEMENT MODIFIED SUBBASE (6" UNIFORM)	
3011080	CEMENT MODIFIED SUBBASE (8" UNIFORM)	
3011100	CEMENT MODIFIED SUBBASE (10" UNIFORM)	
5010106	ROLLER COMPACTED CONCRETE PAVEMENT - 6" UNIFORM	ROLLER COMPACTED CONCRETE PAVEMENT
5010108	ROLLER COMPACTED CONCRETE PAVEMENT - 8" UNIFORM	
5010109	ROLLER COMPACTED CONCRETE PAVEMENT - 9" UNIFORM	
5010110	ROLLER COMPACTED CONCRETE PAVEMENT - 10" UNIFORM	

Construction activities were examined, and relevant ones were further grouped into construction activity groups. This process generated 142 unique construction activity groups identified from the 1,276 construction activities. **Table 3** illustrates a few examples.

Table 3. Identification of construction activity groups

Construction Activities	Construction Activity Groups

CEMENT MODIFIED SUBBASE	Modified subbase
LIME MODIFIED SUBBASE	
PORTLAND CEMENT FOR CEMENT MODIFIED SUBBASE	
SOIL-AGGREGATE SUBBASE CR.	Aggregate subbase CR
AGGREGATE SUBBASE CR.	
SAND-CLAY BASE CR.	Sand-clay base
SCARIFYING, MIXING, REMIXING, SHAPING & RESHAPING	

The resulting construction areas were linked to applicable divisions in the standard specification. At this step, pay items comprising construction activity groups were used as a bridge to connect the specification division and construction activity group. For example, the *pay Item 2012000 (CLEAR.& GRUB. WITHIN RDWY.)* under the *construction activity (CLEARING & GRUBBING WITHIN ROADWAY)* belongs to the *construction activity group (Site preparation, clearing & grubbing)*, and this pay item is specified in the standard specification *(201.4.3 Clearing and Grubbing within Roadway, Division 200 Earthwork)*. Therefore, *division 200* was viewed as the corresponding construction area linked to the *construction activity group (Site preparation, clearing & grubbing)*. **Table** 4 summarizes the distribution of the 142 construction activity groups over the seven divisions/construction areas. Division 100 was excluded because all pay items in the division focused on design and project management, which are not directly related to construction activities.

Table 4. Identification of construction area

Construction Area	Associated Specifications Division	Number of Construction Activity Groups
Earthwork	200	13
Bases and Subbases	300	10
Asphalt Pavements	400	17
Concrete Pavement	500	15
Maintenance and Control of Traffic	600	18
Structures	700	44
Incidental Construction	800	25

As a result, the developed WBS consists of four layers: construction area, construction activity group, construction activity, and pay item. **Figure 2** illustrates the WBS developed in this research.

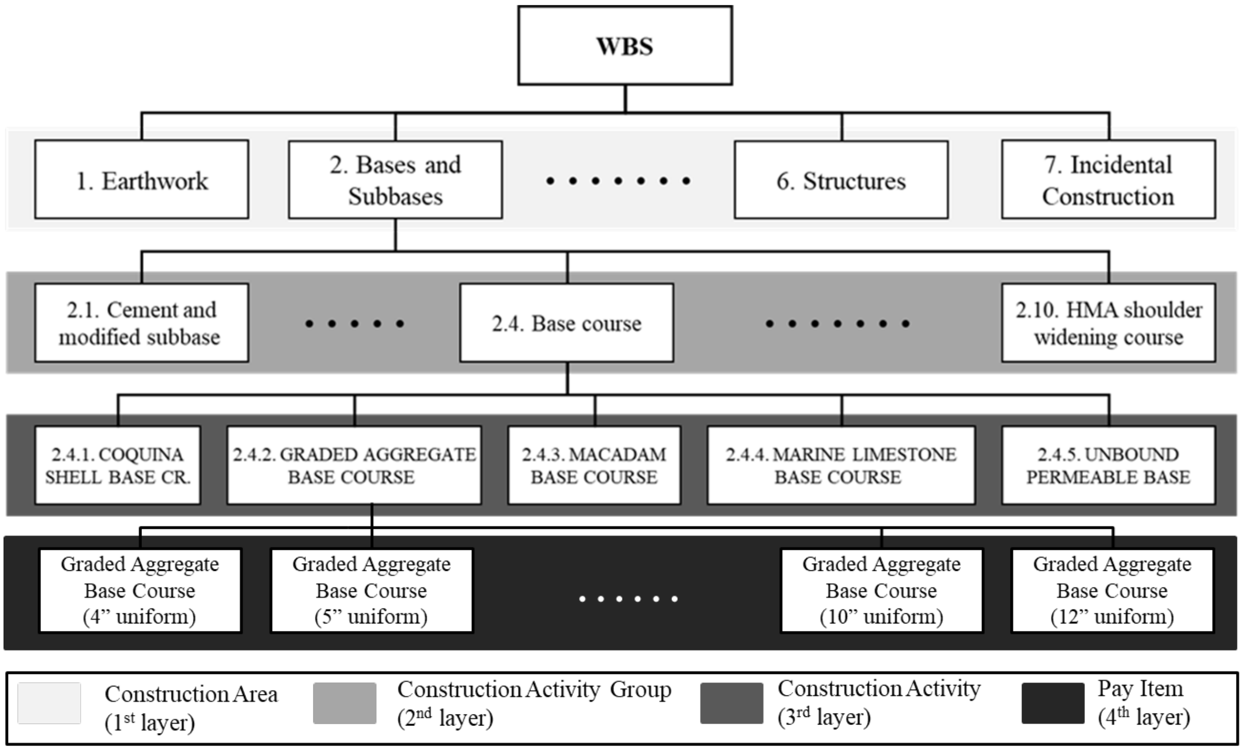

Figure 2. WBS for transportation infrastructure projects

Deliverables from this task include 1,276 construction activities identified from 7,024 pay items (*Appendix B*), 142 unique construction activity groups (*Appendix C*) identified from 1,276 construction activities, and 7 construction areas used to categorize the construction activity groups (*Appendix C*).

Deliverables: *Appendix B – Pay items-construction activities match table.xlsx*
Appendix C – Grouped Activities.xlsx

4.1.3. Construction requirements identification for each pay item

Construction requirements at SCDOT are specified in the standard specification [11], construction manual [12], supplemental specification [13], supplemental technical specification [14], and standard drawing [21]. All documents were downloaded from SCDOT's website. For any documents that have multiple versions, the latest version was used in this project.

To identify construction requirements for each pay item, the linking was established between the pay items and applicable documents or sections in the documents at three levels of detail (direct pay item, standard specification section number, and standard specification division number). At the "direct pay item" level, a pay item is explicitly specified in a document or section. For example, *pay Item 2011000 (CLEARING & GRUBBING WITHIN RIGHT OF WAY)* is listed in the standard specification *section 201,* and the linking is at the "direct pay item" level. At the "standard specification section number" level, the linking is based on the section number. For example, *"Geogrid Soil Reinforcement"* in the supplemental technical specification is linked to *section 203* in standard specification, which suggests the construction requirements in this document apply to all pay items linked to *section 203* in the standard specification.

At the "standard specification division number" level, the linking is based on the connection between a standard specification division and all sections underneath it. For example, the special provision *"Traffic Control"* is linked with *division 600* in the standard specification, which means the construction requirements in this document apply to all pay items linked with sections in division 600. **Figure 3** illustrates the linking mechanism, using *pay Item 2011000 (Clearing and Grubbing)* as an example. The applicable documents for this pay item are drawing *(Sediment Control Structure and Bases)*, construction manual *(Section 201 Clearing and Grubbing)*, standard specification (*section 201 Clearing and Grubbing*), and special provision (*Selected Clearing*).

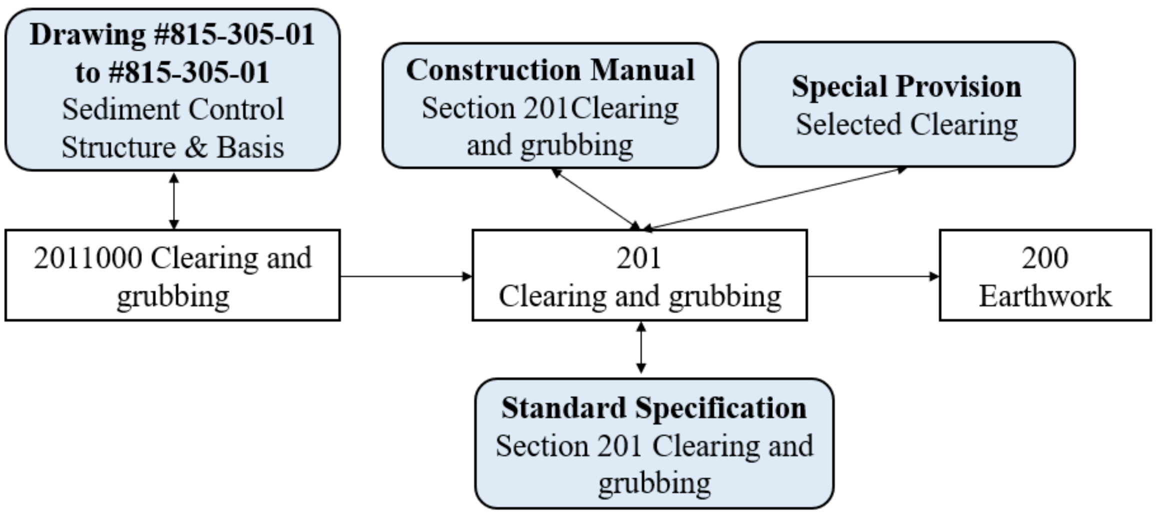

Figure 3. Linking applicable section in the documents with pay items at three levels of details

For different documents, pay items were matched with construction requirements as follows:

1. For standard specification, the sections were linked with pay items directly. The standard specification has corresponding pay items in each section. The standard specification was reviewed, and pay items were matched with associated sections in four cases as follows:
    a. Exact match (both ID and description match): the matched pay item can be found in some standard specification sections.
    b. Descriptions match, but IDs differ: the matched pay item can be found in some standard specification sections, but the matched pay item has a different ID.
    c. IDs differ with similar descriptions (match after examination): a similar pay item can be found in some Standard Specification sections, but the pay item has a different ID.
    d. No match: first three digits as the matched section number.
2. For the construction manual, the document was manually examined, and construction manual sections were linked with standard specification sections, which were connected with pay items.
3. For standard drawings, each drawing set was matched with pay items at two levels of detail:
    a. Pay item level: some drawing sets have pay items listed; those pay items and corresponding drawing ID were manually extracted.

    b. Section level: first three digits of the drawing ID were considered as the matched section in standard specification, which was linked with pay items.
4. For supplemental technical materials, each document was matched with pay items at two levels of detail:
    a. Pay item level: some materials have pay items listed at the end; those pay items and corresponding document ID/name were manually extracted.
    b. Section level: first three digits of the designation ID were considered as the matched standard specification section, which was linked with pay items.
5. For special provisions and supplemental materials, each document was matched with pay items at three levels of detail:
    a. Pay item level: some materials have pay items listed at the end; those pay items and corresponding document ID/name were manually extracted.
    b. Section level: some materials have section numbers indicated in the title; the sections in the title were considered as the matched Standard Specification sections, which were linked with pay items.
    c. Division level: some materials have division numbers in the title; the divisions in the title were considered as the matched standard specification divisions, which are linked with pay items.

Table 5, **Table 6**, and **Table 7** present some examples of matching documents at the pay item, section, and division level, respectively.

Table 5. Examples of construction requirements identification (at pay-item level)

Pay item ID	Pay item Description	Document Name	Document Type
2011000	CLEARING & GRUBBING WITHIN RIGHT OF WAY	Section201 Clearing and Grubbing	Standard Specification
2036020	GEOTEXTILE, SEPARATION	Geosynthetic Materials - Separation & Stabilization	Supplemental Technical Materials
2034000	MUCK EXCAVATION	EXCAVATION (MUCK)	Standard Drawings
2028100	REMOVAL & DISPOSAL OF EXISTING BRIDGE	Precast Reinforced Concrete Floorless Culvert 051910.doc	Special Provision

Table 6. Examples of construction requirements identification (at section level)

Section Number	Section Description	Document Name	Document Type
201	CLEARING & GRUBBING	CLEARING & GRUBBING	Construction Manual
203	ROADWAY AND DRAINAGE EXCAVATION	EXCAVATION (MUCK)	Standard Drawings
203	ROADWAY AND DRAINAGE EXCAVATION	Geosynthetic Materials - Separation & Stabilization	Supplemental Technical Materials
202	REMOVAL OF STRUCTURES AND OBSTRUCTIONS	Asbestos and Lead Inspections.docx	Special Provision

Table 7. Examples of construction requirements identification (at division level)

Division Number	Division Description	Document Name	Document Type
400	ASPHALT PAVEMENTS	HOT MIX ASPHALT QUALITY ASSURANCE	Special Provision
600	MAINTENANCE AND CONTROL OF TRAFFIC	SIGNAL SPECIFICATIONS	Special Provision
600	MAINTENANCE AND CONTROL OF TRAFFIC	AUTOMATED FLAGGER ASSISTANCE DEVICE SYSTEM (AFAD)	Special Provision

After establishing the linking between applicable documents or applicable sections in the documents with pay items, the construction activity was connected with applicable documents using the pay item as the focal point. The data model for matching construction activities, pay items, and applicable requirements from all the documents is illustrated in **Figure 4**. Based on the data model, applicable documents or applicable sections in the documents were identified for each pay item.

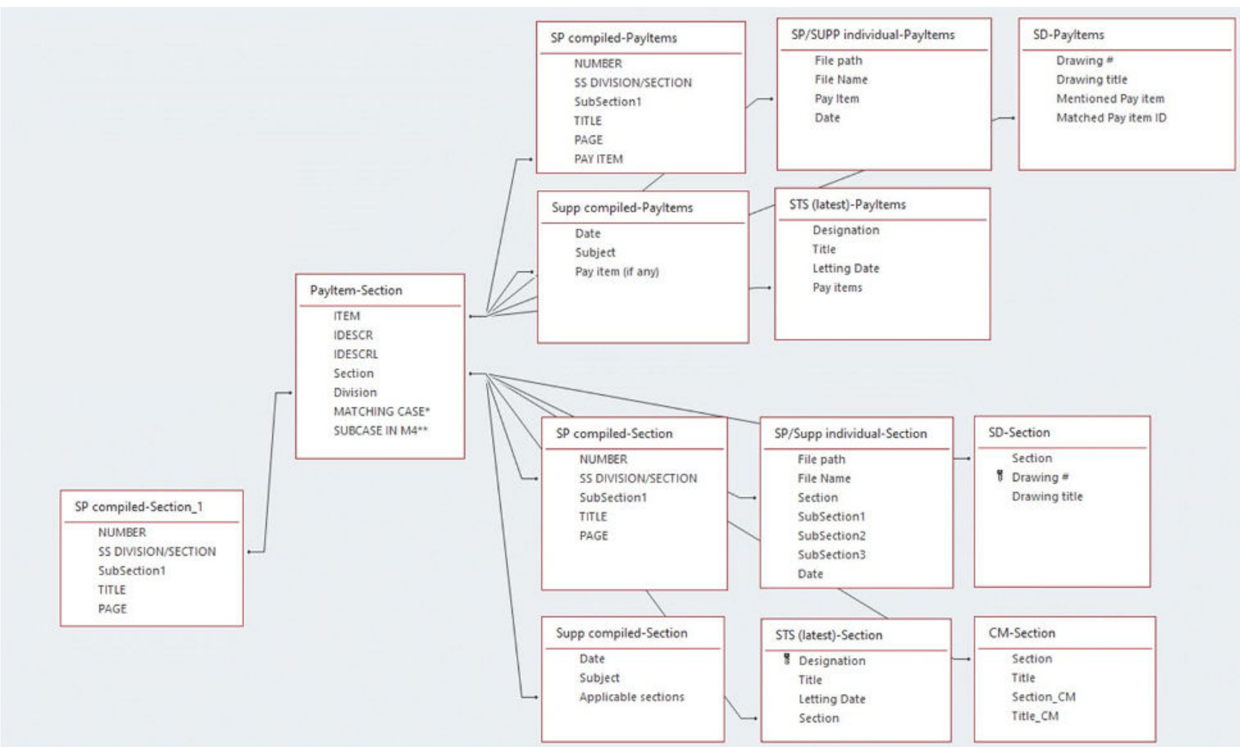

Figure 4. Data model for matching pay items and applicable requirements from all the documents

As a result, for each construction activity, construction requirements in standard specification (Appendix D), construction manual (*Appendix E*), standard drawings (*Appendix F and G*), supplemental technical specification (*Appendix H and I*), special provisions (*Appendix J-N*), supplemental materials (*Appendix O and P*) were identified.

Deliverables: *Appendix D – Pay Item-Std Section based on matched pay item.xlsx*
Appendix E – Pay Item-CM based on matched section.xlsx

Appendix F – Pay Item-SD based on matched pay item.xlsx *Appendix G – Pay Item-SD based on matched section.xlsx* *Appendix H – Pay Item-STS (latest) based on matched pay item.xlsx* *Appendix I – Pay Item-STS (latest) based on matched section.xlsx* *Appendix J – Pay Item-SP compiled based on matched pay item.xlsx* *Appendix K – Pay Item-SP compiled based on matched section.xlsx* *Appendix L – Pay Item-SP compiled based on matched division.xlsx* *Appendix M – Pay Item-SP_Supp ind based on matched pay item.xlsx* *Appendix N – Pay Item-SP_Supp ind based on matched section.xlsx* *Appendix O – Pay Item-Supp compiled based on matched pay item.xlsx* *Appendix P – Pay Item-Supp compiled based on matched section.xlsx*

4.2. Current inspection practice at SCDOT

In Task 2, the current inspection practice at SCDOT was identified to ensure the construction results comply with requirements as described in specifications and manuals in terms of timing (when), responsibility (who) and procedure, level of inspection (how often), and inspection details (what is being checked and how). This task includes two steps. First, the current inspection practice at SCDOT was investigated via surveying, focusing on the inspection process, time spent on different stages, the use frequency, and referred construction requirement documents. Second, pay items were aligned with construction processes to determine the best time to perform an inspection with maximum effectiveness.

4.2.1. Survey for current inspection practice

A survey was designed and distributed to SCDOT construction engineers and inspectors with questions on inspection practice for each construction activity, covering the following aspects: (1) what is the current construction inspection process at SCDOT (shown in **Figure 5**), (2) what is time distribution of different steps of inspection, (3) what is the sequence of construction documents usage, (4) what documents are frequently used for gathering information, (5) how often is the inspection and when, (6) what factors are considered in determining the inspection frequency, and (7) how is the inspection documented. The survey was conducted through Qualtrics—an web-based platform that allows for efficiently conducting surveys and collecting results—as shown in **Figure 6.** The word version of the survey is attached in *Appendix Q*.

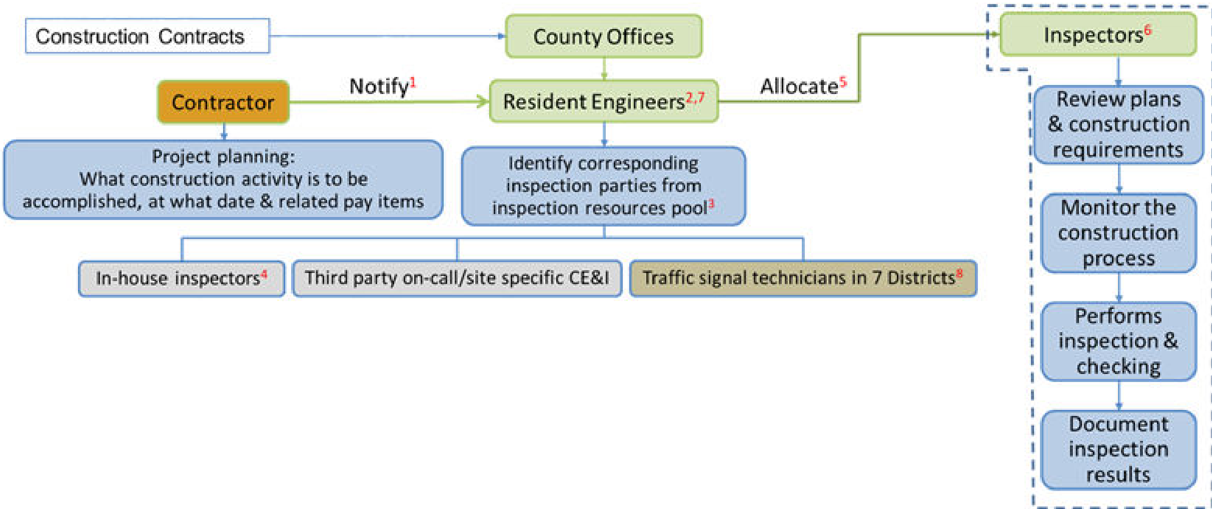

Figure 5. Current inspection practice flowchart

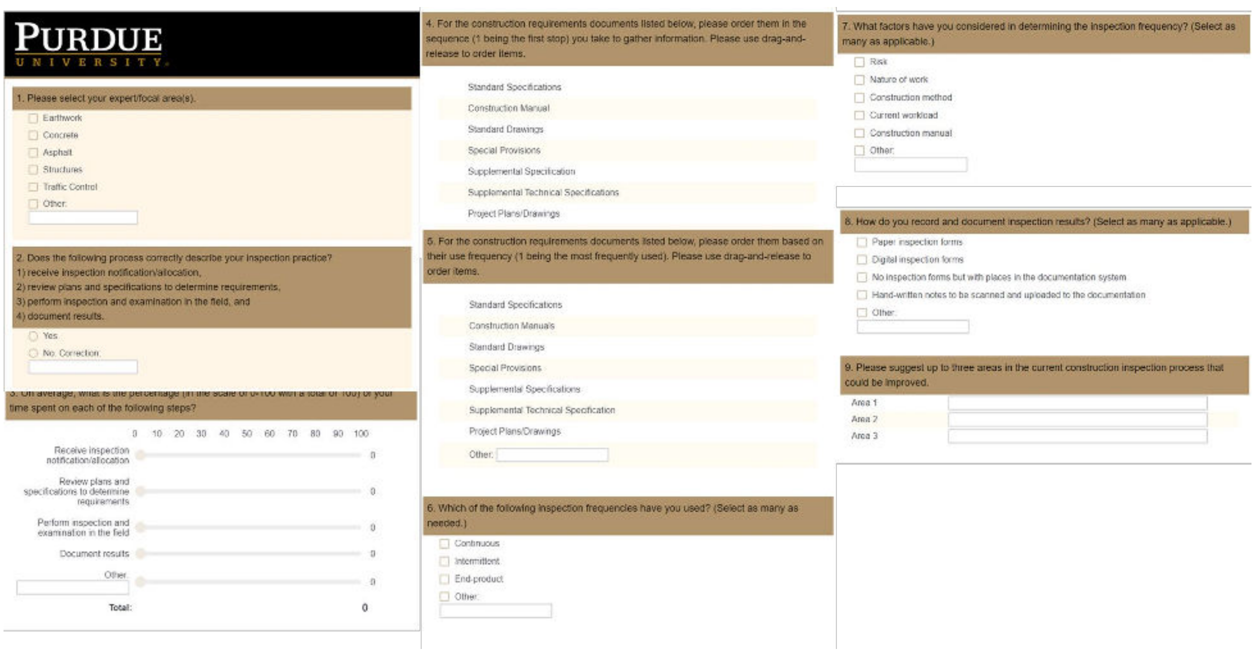

Figure 6. Survey for current inspection practice

The responses were statistically analyzed to identify the current inspection practice at SCDOT in aspects of the construction inspection process, time spent on different stages, document usage, inspection frequency, and documentation. The number of total responses was 516, and the number of completed responses was 441; incomplete responses were excluded for the analysis. The survey results are shown in *Appendix R*. The observations and findings are as follows:

1. Expert/focal areas:
    a. Asphalt-earthwork-concrete-traffic control-structures, relatively even distribution.
    b. Erosion control and survey could be two additional expert areas.

2. General inspection process
    a. (1) Notification → (2) review plans and specs to determine requirements → (3) perform an inspection (notify the contractor of noncompliance) → (4) document results.
    b. Some complaints on NOT receiving notifications.
3. Time distribution on the four-step inspection process
    a. An inspection takes about 50%.
    b. A significant amount of time on retrieving requirements and documentation.
    c. Notification time may be further reduced.
    d. A significant amount of time on project management and administration, and scheduling and providing technical support for field inspection staff (this might be relieved by a digital inspection system).
4. A sequence of documents accessed
    a. Order of documents: (1) project plans/drawings → (2) special provisions/contract → (3) standard specifications → (4) standard drawings → (5) supplemental specifications → (6) supplemental technical specifications → (7) construction manual → (8) other.
    b. SCDOT's hierarchy: special provisions/contract → project plans/drawings → standard drawings → supplemental technical specifications → supplemental specifications → standard drawings. CM is guidance only.
    c. The discrepancies between the two orderings indicate that more education is needed on the hierarchy of the governing inspection documents.
5. Frequency of use
    a. (1) project plans/drawings → (2) special provisions/contract → (3) standard specifications → (4) standard drawings → (5) supplemental specifications → (6) construction manual → (7) supplemental technical specifications → (8) other.
    b. This order is expected: project-specific requirements → standard requirements → supplemental (might not apply to all projects).
    c. Generally aligns with the order of use sequence.
6. Inspection frequency
    a. Continuous: 408
    b. Intermittent: 317
    c. End-product: 264
    d. Most people picked more than one type of inspection frequency: Among 441 respondents, 382 (87%) picked more than one type of inspection frequency. 233 (53%) picked all three types of frequency.
7. Factors considered to determine the inspection frequency
    a. Nature of work > construction method > risk > construction manual > current workload
    b. The construction manual is important as it provides an inspection frequency chart
    c. The risk seems to be considered
    d. Not a good practice to let workload determine the inspection frequency

Deliverables: *Appendix Q – Survey_inspection practices.docx*
Appendix R – Survey Analysis_With Observations and Question.pptx

4.2.2 Aligning pay items with the construction process

Aligning pay items with the construction process is important because this alignment determines the best time to perform the inspection with maximum effectiveness. Sample construction schedules were collected from SCDOT to extract construction phases for roadway and bridge projects. **Figure 7** and **Figure 8** illustrate a bridge and a roadway sample, respectively.

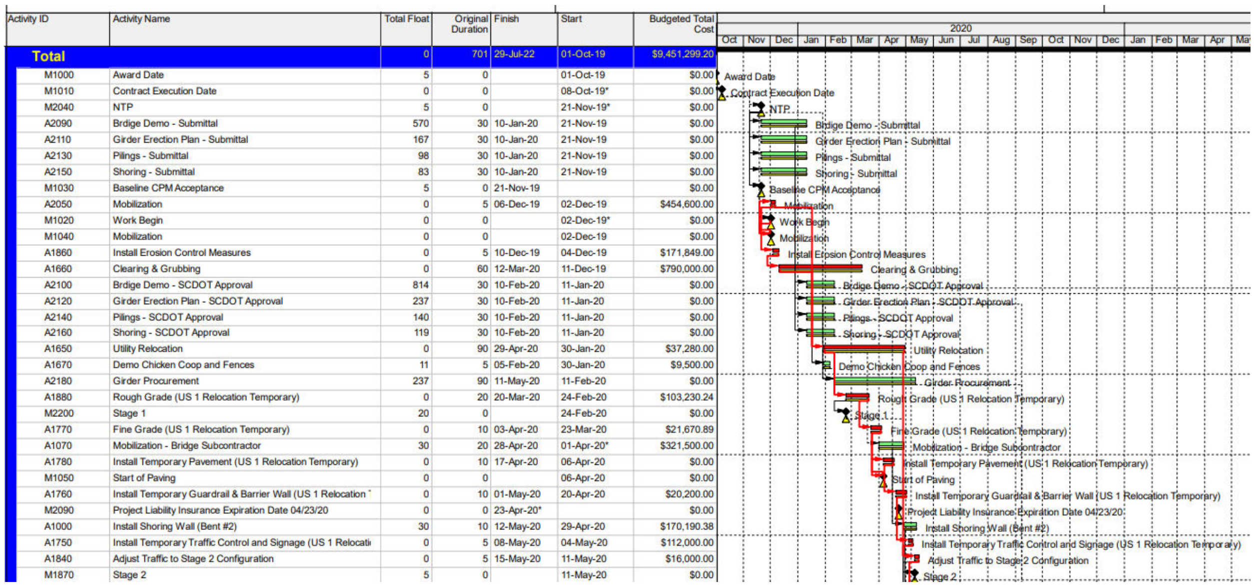

Figure 7. Example schedule from SCDOT – Bridge Job 1

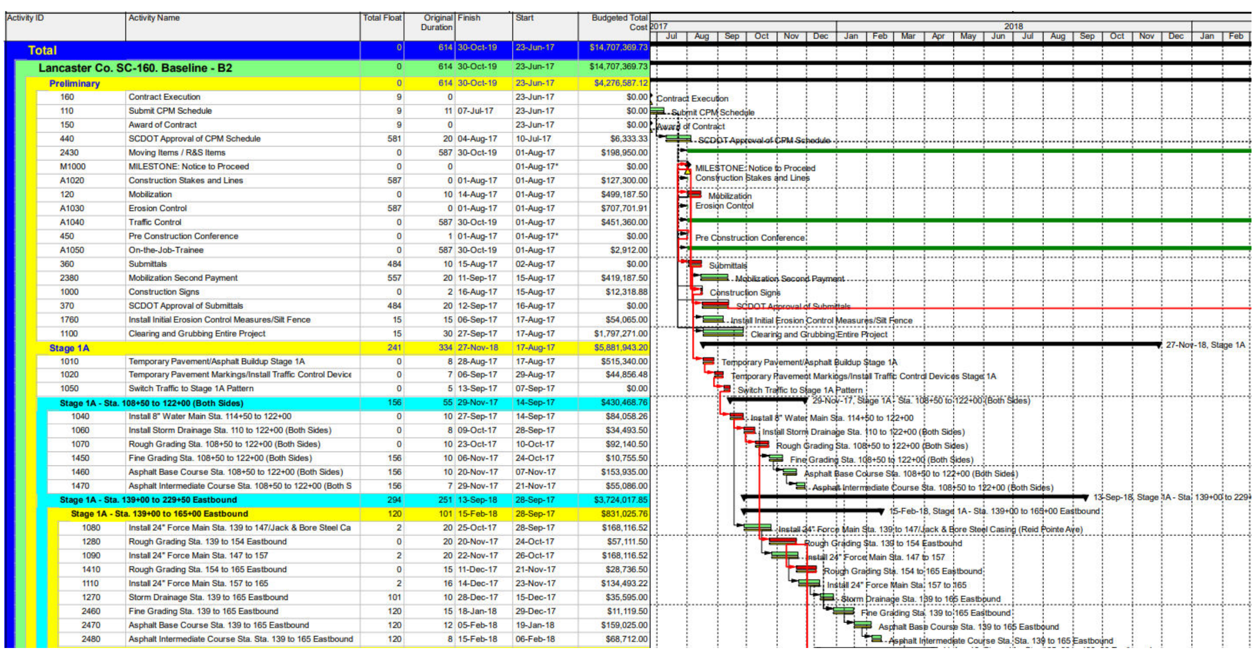

Figure 8. Example schedule from SCDOT – Roadway Widening 1

From **Figure 7**, the typical construction process for bridge projects was identified, as illustrated in **Figure 9**.

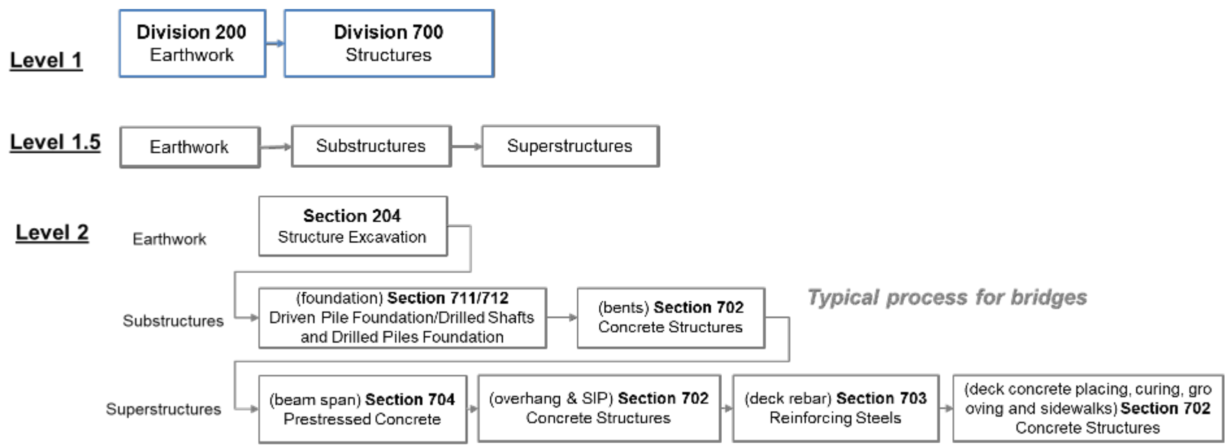

Figure 9. Typical process for bridge construction

Similarly, the typical construction processes for roadway projects were summarized as illustrated in **Figure 10** and **Figure 11**.

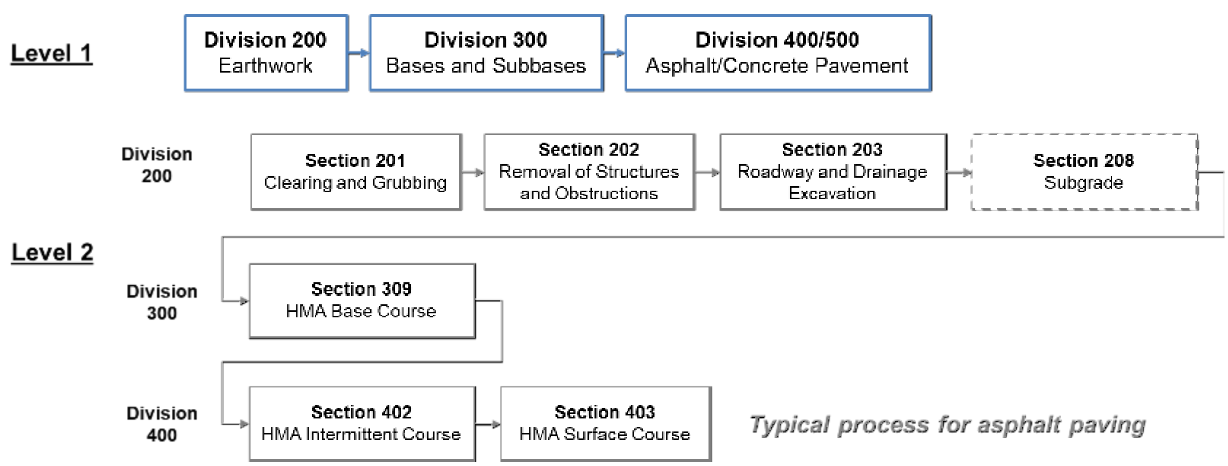

Figure 10. Typical process for asphalt paving (roadway)

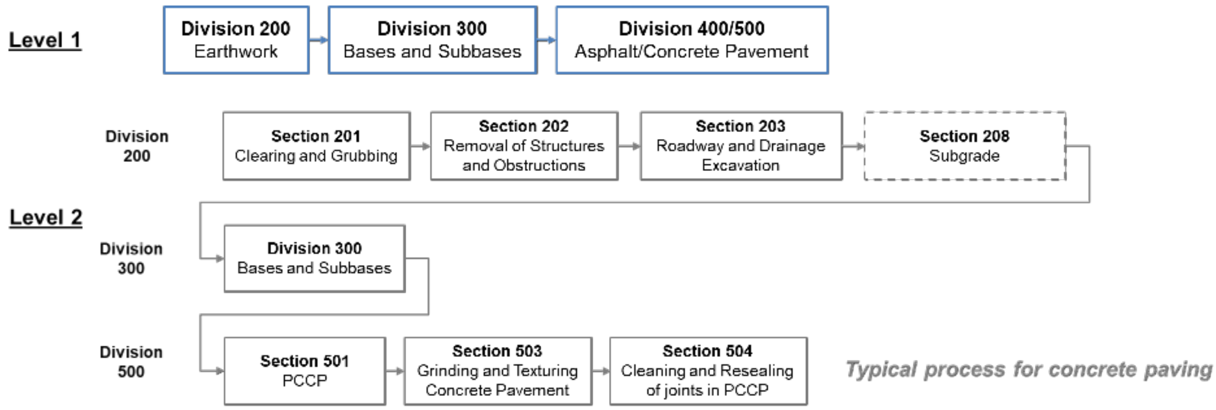

Figure 11. Typical process for concrete paving (roadway)

In the example schedules, each schedule activity is matched with pay items. This alignment allows to load risk information (e.g., risk level and inspection frequency) into the construction schedule and enables the inspectors to track the change of risks as well as the timing of inspection. For example, the schedule activities for Bridge Job 1 were aligned with pay items. Since each pay item was assigned with a risk level, the distribution of risk levels was then applied to the project schedule, as shown in **Figure 12**. Based on the risk calendar, managers can make decisions on the allocation of inspection resources and timing inspection to maximize the effectiveness.

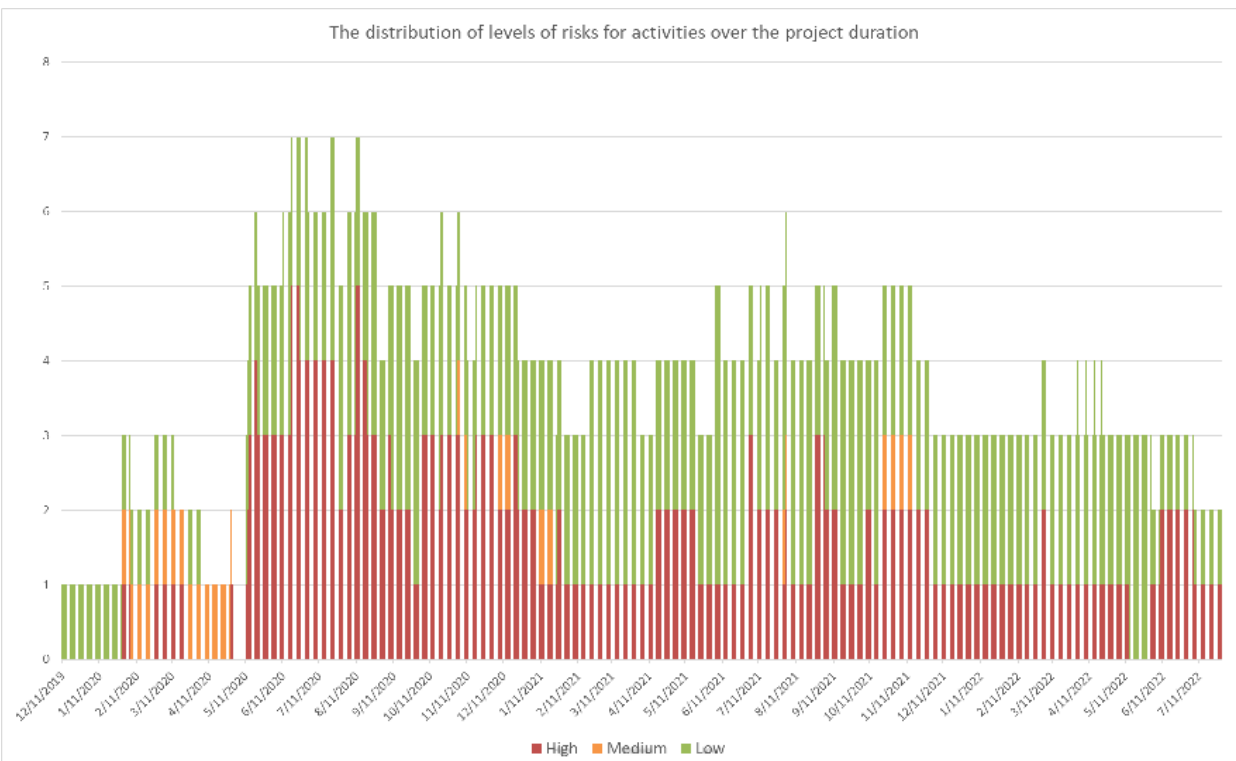

Figure 12. The distribution of levels of risks for activities over the project duration

4.3. Availability and cost of inspection resources

Task 3 aimed to identify inspection resources and their costs at SCDOT. The task was completed by following two steps:

1. A survey (*Appendix S_Survey on inspection resource.xlsx*) was conducted to understand the current practice of inspection resources at SCDOT.
2. The loaded hourly rates for in-house staff and CE&I contracts were provided by SCDOT.

The survey results are shown in **Table 8**.

Table 8. Survey results on the current practice of inspection resources at SCDOT

Understanding and Assumptions	SCDOT Confirmation/Comments
CE&I takes two formats: on-call and site-specific?	Yes
Meaning of survey field (HR) and survey office (HR)?	SCDOT eliminated the survey field as only one survey position should be taken into account.
Site-specific type also charges based on an hourly rate or a lump sum?	We would like to only consider CE&I as a whole, not breakdown (on-call and site-specific). It could get really complicated trying to breakdown between the two, and we do not think that would add much value. With that being said, CE&I charges are paid based on an hourly rate.
On-call and site-specific charge the same hourly rate, i.e., the same person charges the same rate for both on-call and site-specific service?	For this research, please only use the provided loaded hourly rates in the "Average Loaded Rate" excel sheet.
Based on your experience, do you see significant time difference in inspecting the same type and quantity of construction activity between in-house, on-call, and site-specific?	In theory, all inspectors should spend the same amount of time on the same type and quantity of construction activities. Yes, there are some inspectors that are more thorough than others (CE&I and in-house alike), while there are a few slackers as well. In general, all inspectors do an excellent job inspecting our construction work activities.
For CE&I, is there a typical range of the ratio between inspection cost and construction/overall project cost?	We set inspection costs at 8% when programming projects. Typically when using CE&I, this overruns to around 10%-12% of the construction cost.

The loaded hourly rates for in-house staff and CE&I contracts were provided by SCDOT, and the hourly rates are listed in **Table** 9 and **Table** 10. Note that SCDOT has a job classification and a specific job class has a specific average salary.

Table 9. Loaded Average Hourly Rate for In-house and CE&I Staff

Position	CE&I	In-House
	Average	
Project Manager	$ 139.75	$ 47.91

Asst. PM	$ 122.24	$ 40.22
Proj Admin	$ 55.60	$ 28.95
Chief Inspector	$ 95.88	$ 47.85
Senior Inspector	$ 75.66	$ 38.28
Mid Level Inspector	$ 65.01	$ 31.74
Jr Inspector	$ 51.83	$ 25.82
Survey Office (HR)	$ 119.95	$ 46.69

Table 10. Salary Composition of CE&I Contracts

CEI postion	SCDOT position	SCDOT Band	SCDOT AVG Yearly Salaries	Overhead	Loaded Salary
Project Manager	ENG II	6A/6B	$57,855.00	172%	$99,649.45
Asst. PM	ENG I	5A/5B	$48,575.00	172%	$83,665.58
Project Admin	Admin Asst.	4A/4B	$34,963.00	172%	$60,220.27
Chief Inspector	Eng Tech IV	6A	$57,782.00	172%	$99,523.72
Senior Inspector	Eng Tech III	5	$46,228.00	172%	$79,623.11
Mid Level Inspector	Eng Tech II	4	$38,333.00	172%	$66,024.76
Jr Inspector	Eng Tech I	3	$31,185.00	172%	$53,713.04
Survey Office (HR)	ENG II	6A	$56,389.00	172%	$97,124.41

From the survey on inspection resources, the observations and findings are as follows:

1. SCDOT currently uses in-house staff and CE&I contracts to meet its inspection practice. CE&I is taken into account as a whole, not broken down into on-call and site-specific.
2. CE&I contracts have higher average hourly rates on all the positions compared with in-house staff.

Deliverable: *Appendix S – Survey on inspection resource.xlsx*

4.4. Risk identification and assessment for construction activity

Task 4 aimed to identify and assess the level of risk associated with SCDOT's current construction activities.

4.4.1 Risk breakdown structure (RBS)

RBS was developed to present the hierarchy of potential risks based on the expert interviews and the theoretical background provided by previous studies [2,22–25]. The initial list of risks was developed based on the literature review, and it was then reviewed by the 12 professionals (e.g., inspectors and managers) at SCDOT. As a result, a list of mutually exclusive and collectively inclusive risks was developed.

The risks were divided into six categories (5M1E)—Man, Machine, Method, Material, Money, and External/Environmental—which were developed to categorize risks in construction projects and identify the root causes of problems [26,27]. Each category of 5M1E is defined as follows: Man represents the operational and functional labor engaged in production; Machine indicates the facilities, systems, tools, and equipment employed for the construction process; Method is referred to as construction means and methods; Material represents raw materials, components, and consumables required for construction facilities; Money illustrates the financial conditions for production; and External/Environmental defines the weather, uncontrollable and unpredictable events. **Figure 13** illustrates RBS developed for transportation infrastructure projects, including a total of 45 risk factors (Man: 11 risks, Machine: 6 risks, Method: 11 risks, Material: 7 risks, Money: 2 risks, and External/Environmental: 8 risks). For more details, please refer to *Appendix T.*

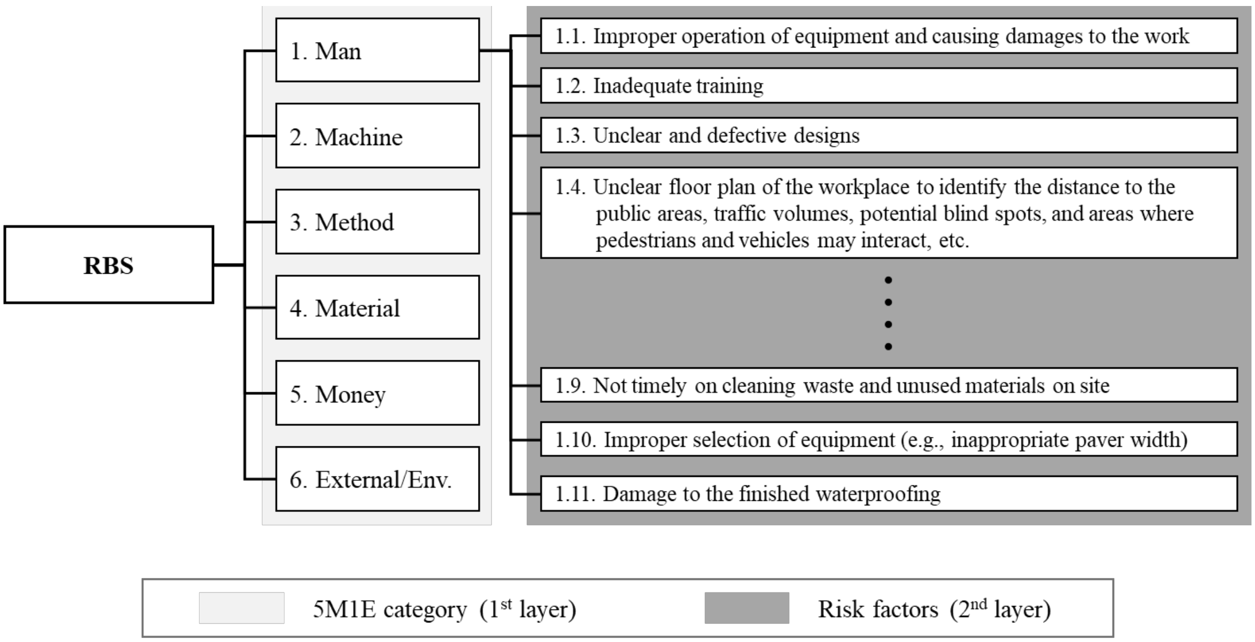

Figure 13. RBS for transportation infrastructure projects

Deliverable: *Appendix T – List of risk factors.xlsx*

4.4.2 Risk breakdown matrix (RBM)

Previously developed WBS and RBS were fused to establish RBM, which provides a foundation for identifying risks associated with construction activities in transportation infrastructure projects (**Figure 14**). The RBM consists of 142 construction activity groups under the corresponding construction area and 45 risks categorized under the 5M1E structure. The developed RBM is dynamic and flexible depending on the level of the WBS. For example, the RBM can be used to identify specific risk factors for construction areas (e.g., earthwork, bases & subbases, and structures), varying construction activity groups (e.g., shoring wall, base course, and pipe), or construction activities.

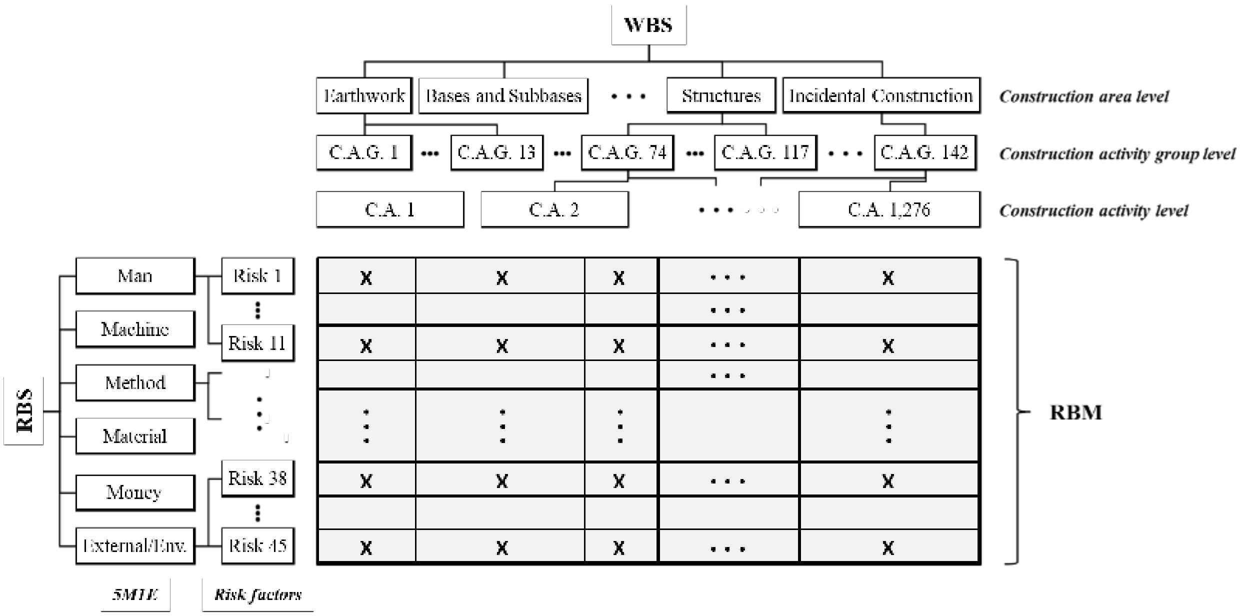

Figure 14. RBM for transportation infrastructure projects

4.4.3 Risk identification

Using the developed RBM, two rounds of surveys were conducted to identify risk factors for each construction activity. In the first survey, out of 45 risk factors, the top 11 risk factors were identified at the construction area level. In the second survey, the identified top 11 risk factors were sorted at the construction activity group level based on their ranking. The surveys were distributed to professionals (e.g., chief inspectors, senior inspectors, construction engineers, and managers) at SCDOT.

Top risks associated with construction area

The first survey aimed to identify significant risk factors for each of the seven construction areas (e.g., earthwork and structures) in **Table 4**. Respondents were asked to select the top 5 risk factors from 45 risk factors (categorized under 5M1E structure in **Figure 13**) for each construction area, as illustrated in **Figure 15**. The number of responses for each risk factor was used to identify and rank critical risks factors. Of the total 562 responses received, 162 responses were excluded due to incomplete information. The remaining 400 responses were analyzed to identify the top 11 risk factors at the construction area (standard specification division) level.

	Risk Factor	Earthwork	Bases and Subbases	Asphalt Pavement	Concrete Pavement	Maintenance and Control of Traffic	Structures	Incidental Construction
Man	Improper equipment operation	✓	○	○	○	○	○	○
	Inadequate training	○	✓	✓	○	○	○	○
	…	○	○	✓	✓	○	○	○
Machine	Machine noise, vibration, loading, and dust effect	✓	○	○	✓	○	○	○
	Interaction of work and customer vehicles	○	✓	✓	○	○	○	○
	…	✓	○	○	✓	○	○	○
Method	Irrational construction activity schedules	○	✓	○	○	○	○	○
	…	○	○	○	○	○	○	○
Material	Improper materials (e.g., soil, concrete, steel, etc.)	○	✓	✓	○	○	○	○
	…	✓	○	○	○	○	○	○
Money	Funding availability and cash flow	○	○	○	✓	○	○	○
	…	○	○	○	✓	○	○	○
External/ Environmental	Weather conditions	✓	✓	○	○	○	○	○
	…	○	○	✓	○	○	○	○

Figure 15. Survey designed to identify top risks for construction areas

After the first round of surveys on risk identification, the top 11 risk factors identified for each construction area were summarized in **Table 11**. Survey results of the three areas (bases & subbases, asphalt pavement, and concrete pavement) were combined as "Bases/Pavements" in the table since their results were identical. The table shows that the most common risk factors are inadequate training, improper equipment operation, and weather conditions. These risk factors appeared at least four times within the top 5 ranking across all construction areas. Also, inadequate training was the most dominant risk factor as it was ranked first in all the construction areas.

Table 11. Top 11 risk factors associated with construction area

Risk rank	Earthwork	Bases/Pavements	Traffic control	Structures	Incidental Construction
1	Inadequate training	Inadequate training	Inadequate training	Inadequate training	Inadequate training
2	Improper equipment operation	Improper equipment operation	Inadequate traffic control	Failure to follow design/specification	Failure to follow design/specification
3	Weather conditions	Weather conditions	Improper removal of signs and traffic control devices	Improper equipment operation	Irrational construction schedules
4	Irrational construction schedules	Improper equipment calibration/condition	Interactions of work and customer vehicles	Irrational construction schedules	Improper equipment operation
5	Not timely stabilization of disturbed areas	Failure to follow design/specification	Work not consistent with plan	Weather conditions	Weather conditions
6	Failure to follow design/specification	Improper timing and temperature at mixing, placement, curing, and finishing	Failure to follow design/specification	Inadequate fall protection	Work not consistent with plan
7	Damage to utilities	Irrational construction schedules	Irrational construction schedules	Unclear and defective designs	Unclear and defective designs
8	Work not consistent with plan	Inadequate traffic control	Weather conditions	Work not consistent with plan	Not enough materials
9	Improper equipment calibration/condition	Work not consistent with plan	Unclear floor plan of the workplace	Improper materials	Funding availability
10	Improper materials	Variable material quality	Improper choice of equipment entrance, routes, and parking	Improper timing and temperature at mixing, placement, curing, and finishing	Improper materials

11	Inadequate traffic control	Inadequate moisture in materials	Improper equipment operation	Improper handling and storage of materials	Not timely on cleaning waste and unused materials

Top risks associated with construction activity group

In the previous section, the top 11 critical risk factors were ranked at the construction area level. Note that inadequate training was set as the highest risk factor for all the construction activity groups since it was identified as the most significant risk in all the construction areas. Each respondent was asked to select the top 3 risk factors from the remaining 10 risk factors for each construction activity group. Out of the 155 responses received, 90 responses were excluded due to incomplete information. **Figure 16** illustrates the survey designed to identify top risks associated with 13 construction activity groups in the earthwork area.

Construction Activity Group	Top 10 risk factors identified at the construction area level				
	Improper equipment operation	Weather conditions	Irrational construction schedules	• • •	Inadequate traffic control
Site preparation, clearing & grubbing	✓	✓	○	○	✓
Removal and disposal of existing structures and obstructions	○	✓	✓	○	✓
Roadway and drainage excavation and grading	✓	○	✓	○	✓
Geotextile & geogrid for reinforcement and stabilization	✓	○	○	✓	✓
. . .	○	○	○	○	○
Overhaul	○	○	○	○	○
Fine grading	○	○	○	○	○
Flowable fill	○	○	○	○	○

Figure 16. Sample survey designed to identify top risks for earthwork construction activity groups

After the second round of survey on risk identification, the top 11 risk factors identified for each construction activity group were summarized in *Appendix U*. **Table 12** illustrates significant risks identified in each of the thirteen construction activity groups in the earthwork area. 11 risks were sorted based on the ranking orders (e.g., rank 0 indicates the most critical risk). The importance (ranking) of the risks varied depending on the types of construction activity groups. For example, the "weather conditions" risk was ranked 2 in the "Site preparation clearing & grubbing" activity group, while it was ranked 7 in the "Removal and disposal of existing structures and obstructions" activity group.

Table 12. Ranking of top 11 risks in each construction activity group

Construction Activity Group	Rank 0	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8	Rank 9	Rank 10
Site preparation, clearing & grubbing	Inadequate training	Not timely stabilization of disturbed areas	Weather conditions	Improper equipment operation	Damage to utilities	Inadequate traffic control	Work not consistent with plan	Failure to follow design/spec	Irrational constructio n schedules	Improper equipment calibration/ condition	Improper materials
Removal and disposal of existing structures and obstructions	Inadequate training	Damage to utilities	Improper equipment operation	Work not consistent with plan	Failure to follow design/spec	Inadequate traffic control	Irrational constructio n schedules	Weather conditions	Improper equipment calibration/ condition	Not timely stabilization of disturbed areas	Improper materials
Roadway and drainage excavation and grading	Inadequate training	Weather conditions	Not timely stabilization of disturbed areas	Work not consistent with plan	Damage to utilities	Improper equipment operation	Failure to follow design/spec	Irrational constructio n schedules	Improper materials	Improper equipment calibration/ condition	Inadequate traffic control

Geotextile & geogrid for reinforcement and stabilization	Inadequate training	Failure to follow design/spec	Work not consistent with plan	Improper materials	Weather conditions	Improper equipment operation	Not timely stabilization of disturbed areas	Irrational construction schedules	Improper equipment calibration/ condition	Damage to utilities	Inadequate traffic control
Settlement monitoring device and instrumentation for data collection and management	Inadequate training	Failure to follow design/spec	Improper equipment calibration/ condition	Improper equipment operation	Work not consistent with plan	Irrational construction schedule	Weather conditions	Not timely stabilization of disturbed areas	Inadequate traffic control	Damage to utilities	Improper materials
Structure excavation	Inadequate training	Failure to follow design/spec	Damage to utilities	Work not consistent with plan	Weather conditions	Improper equipment operation	Irrational construction schedule	Improper equipment calibration/ condition	Not timely stabilization of disturbed areas	Inadequate traffic control	Improper materials
Shoring wall	Inadequate training	Failure to follow design/spec	Improper equipment operation	Work not consistent with plan	Damage to utilities	Weather conditions	Irrational construction schedule	Improper equipment calibration/ condition	Improper materials	Not timely stabilization of disturbed areas	Inadequate traffic control
Ground modification for embankment	Inadequate training	Failure to follow design/spec	Work not consistent with plan	Weather conditions	Improper equipment operation	Improper materials	Irrational construction schedule	Not timely stabilization of disturbed areas	Improper equipment calibration/ condition	Damage to utilities	Inadequate traffic control
Stone & Granular bridge lift material	Inadequate training	Failure to follow design/spec	Work not consistent with plan	Improper materials	Weather conditions	Improper equipment operation	Not timely stabilization of disturbed areas	Improper equipment calibration/ condition	Irrational construction schedule	Inadequate traffic control	Damage to utilities
Embankment	Inadequate training	Weather conditions	Failure to follow design/spec	Not timely stabilization of disturbed areas	Work not consistent with plan	Improper equipment operation	Improper materials	Improper equipment calibration/ condition	Irrational construction schedule	Damage to utilities	Inadequate traffic control
Overhaul	Inadequate training	Failure to follow design/spec	Work not consistent with plan	Improper equipment operation	Irrational construction schedule	Weather conditions	Not timely stabilization of disturbed areas	Improper equipment calibration/ condition	Inadequate traffic control	Improper materials	Damage to utilities
Fine grading	Inadequate training	Weather conditions	Improper equipment operation	Failure to follow design/spec	Improper equipment calibration/ condition	Not timely stabilization of disturbed areas	Work not consistent with plan	Irrational construction schedule	Damage to utilities	Inadequate traffic control	Improper materials
Flowable fill	Inadequate training	Failure to follow design/spec	Work not consistent with plan	Improper materials	Weather conditions	Improper equipment operation	Improper equipment calibration/ condition	Irrational construction schedule	Inadequate traffic control	Not timely stabilization of disturbed areas	Damage to utilities

Deliverable: *Appendix U – Risk identification survey results.xlsx*

4.4.4 Risk assessment

Risks of an individual construction activity group were quantitatively assessed by developing a single composite risk index (score) that was computed based on the two risk attributes: likelihood and severity. The likelihood of the risk factor represents the possibility of construction failure, and the severity of the risk factor indicates the consequence severity in terms of cost, time, safety, and quality.

Likelihood and severity risk indexes

A separate survey was conducted to assess the impact of risks on construction activity groups in two aspects: (1) the likelihood of construction failure and (2) the severity of the failure. The respondents were asked to select the likelihood of a risk event occurring at each construction activity group and its associated severity in four dimensions (cost, time, safety, and quality). Three options (low, medium, and high) were provided for the evaluation process, as illustrated in **Figure 17**. The survey was distributed to professionals at SCDOT. Out of the 379 responses received, 185 incomplete responses were excluded from the analysis.

Construction Activity Group	Likelihood			Severity											
				Cost			Time			Safety			Quality		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Prime coat	✓	○	○	○	✓	○	○	○	✓	○	○	✓	○	✓	○
Asphalt binder (liquid, asphalt-rubber)	○	○	✓	○	○	✓	✓	○	○	○	✓	○	○	○	✓
Asphalt emulsion (undiluted, CRS-1H-Modified)	○	✓	○	✓	○	○	○	✓	○	○	✓	○	✓	○	○
Full depth asphalt pavement patching	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Milling existing asphalt pavement and shoulders	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Seal cracks and joints in asphalt pavement	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
⋮	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Figure 17. Illustration of risk assessment survey

Survey results were summarized in numerical forms by computing average scores based on the distribution of low, medium, and high responses. In **Table** 13, numbers in brackets represent the distribution (ratio) of low/medium/high responses, and the upper value denotes the weighted average after assigning 1/2/3 to low/medium/high, respectively. For example, for the likelihood of construction failure for the "prime coat" construction activity group, 61% of the responses are low, 33% are medium, and 6% are high. The weighted average was calculated to be 1.45 by first multiplying the response percentages with their corresponding numerical values (i.e., 1 for low, 2 for medium, and 3 for high) and then summing them up. The same process was applied to each severity dimension, i.e., cost, time, safety, and quality. Their weighted averages were averaged again to obtain the severity score in the "Mean" column.

Table 13. Computation of two risk indexes (likelihood and severity)

Construction Activity Group	Likelihood	Severity				
		Cost	Time	Safety	Quality	Mean
Prime coat	1.45 (0.61/0.33/0.06)	1.46 (0.57/0.40/0.03)	1.44 (0.61/0.34/0.05)	1.50 (0.60/0.30/0.10)	1.76 (0.35/0.54/0.11)	1.54
Asphalt binder (liquid, asphalt-rubber)	1.51 (0.56/0.36/0.08)	1.85 (0.33/0.49/0.18)	1.52 (0.51/0.46/0.03)	1.61 (0.49/0.40/0.11)	1.84 (0.31/0.54/0.15)	1.71
Asphalt emulsion (undiluted, CRS-1H-Modified)	1.53 (0.54/0.40/0.06)	1.69 (0.41/0.48/0.11)	1.48 (0.56/0.41/0.03)	1.60 (0.50/0.39/0.11)	1.82 (0.33/0.52/0.15)	1.65
Full depth asphalt pavement patching	1.81 (0.35/0.50/0.15)	1.95 (0.24/0.56/0.20)	1.83 (0.30/0.57/0.13)	1.80 (0.36/0.48/0.16)	2.03 (0.17/0.62/0.21)	1.90
Milling existing asphalt pavement and shoulders	1.65 (0.46/0.43/0.11)	1.72 (0.39/0.50/0.11)	1.69 (0.42/0.46/0.12)	1.75 (0.40/0.44/0.16)	1.87 (0.30/0.52/0.18)	1.76
Seal cracks and joints in asphalt pavement	1.45 (0.63/0.29/0.08)	1.50 (0.55/0.40/0.05)	1.57 (0.49/0.46/0.05)	1.61 (0.51/0.47/0.12)	1.66 (0.42/0.50/0.08)	1.59

where numbers in brackets denote the distribution ratio of responses (low/medium/high).

Risk index categorization

The results in **Table 13** indicate the likelihood and severity through weighted averages calculated by assigning numerical values (e.g., 1 for low) to survey responses. However, the direct use of these numerical scores is not effective attributed to the challenge in interpreting the numbers. For instance, two numerical values of 1.45 and 1.95 are between low and medium; 1.45 indicates a relatively balanced point between low and medium, while 1.95 indicates a strong medium. Furthermore, the same weighted average could come from different distributions. For example, a 0.50/0/0.50 distribution and a 0/1/0 distribution both lead to a weighted average of 2, but it is unlikely that they both represent the same medium. Therefore, it was essential to identify the ranges (e.g., 0-1.5, 1.5-1.8, and 1.8-2.5) that correspond to low, medium, and high.

The initial thought was to use the ranges of 0-1, 1-2, and 2-3, which correspond to low, medium, and high, to align with the assigned numerical values (i.e., 1 for low, 2 for medium, and 3 for high). However, doing so resulted in unbalanced risk distribution because construction activity groups in different construction areas have different risk score distributions and descriptive statistics (e.g., average, minimum, and deviation). This project adopted the K-means clustering—one of the well-established clustering approaches that allows for partitioning data points into k clusters based on distance functions—to recategorize the average risk scores presented in **Table 13** into low, medium, and high clusters based on the statistical distribution within each construction area. Similarly, three performance indexes of short-term performance, mid-term performance, and long-term performance were also categorized into low, medium, and high by K-means clustering. The total number of clusters was set to 3, i.e., k = 3:

The procedure of K-means clustering for likelihood risk score (x^l) was conducted based on the following five steps :

1. initialize the number of clusters as 3;
2. randomly generate the initial set of means $m_1^{l1}, m_2^{l1}, m_3^{l1}$ *from 1 to 3, l* represents the likelihood;
3. assign each data point x_i^l to the cluster with the nearest mean $m_1^{lt}, m_2^{lt}, m_3^{lt}$, where t represents the $n\ th$ iteration, as illustrated in Eq. (1);
4. recalculate the centers of clusters $m_1^{l(t+1)}, m_2^{l(t+1)}, m_3^{l(t+1)}$ based on the assigned data points x_i^l, as illustrated in Eq. (2); and
5. repeat steps 3) and 4) until the assignments no longer change.

$$S_i^{l(t)} = \{||x_i^l - m_p^{lt}||^2 \leq ||x_i^l - m_q^{lt}||^2 \ \forall q, 1 \leq q \leq 3 \} \tag{1}$$

$$m_i^{l(t+1)} = \frac{1}{|S_i^{l(t)}|} \sum_{x_i^l \in S_i^{l(t)}} x_i^l \tag{2}$$

The procedure of K-means clustering for severity (x^s) followed the same procedure. As a result, likelihood and severity risk indexes were clustered into low, medium, or high categories, as illustrated in **Table 14**.

Table 14. Categorization of likelihood and severity risk indexes

Construction Activity Group	Likelihood		Severity	
	Risk score	Cluster	Risk score	Cluster
Prime coat	1.45	Low (1)	1.54	Low (1)
Asphalt binder (liquid, asphalt-rubber)	1.51	Low (1)	1.71	Low (1)
Asphalt emulsion (undiluted, CRS-1H-Modified)	1.53	Low (1)	1.65	Low (1)
Full depth asphalt pavement patching	1.81	High (3)	1.90	Medium (2)
Milling existing asphalt pavement and shoulders	1.65	Medium (2)	1.76	Medium (2)
Seal cracks and joints in asphalt pavement	1.45	Low (1)	1.59	Low (1)

Figure 18 illustrates the overall risk index scoring and categorization procedure.

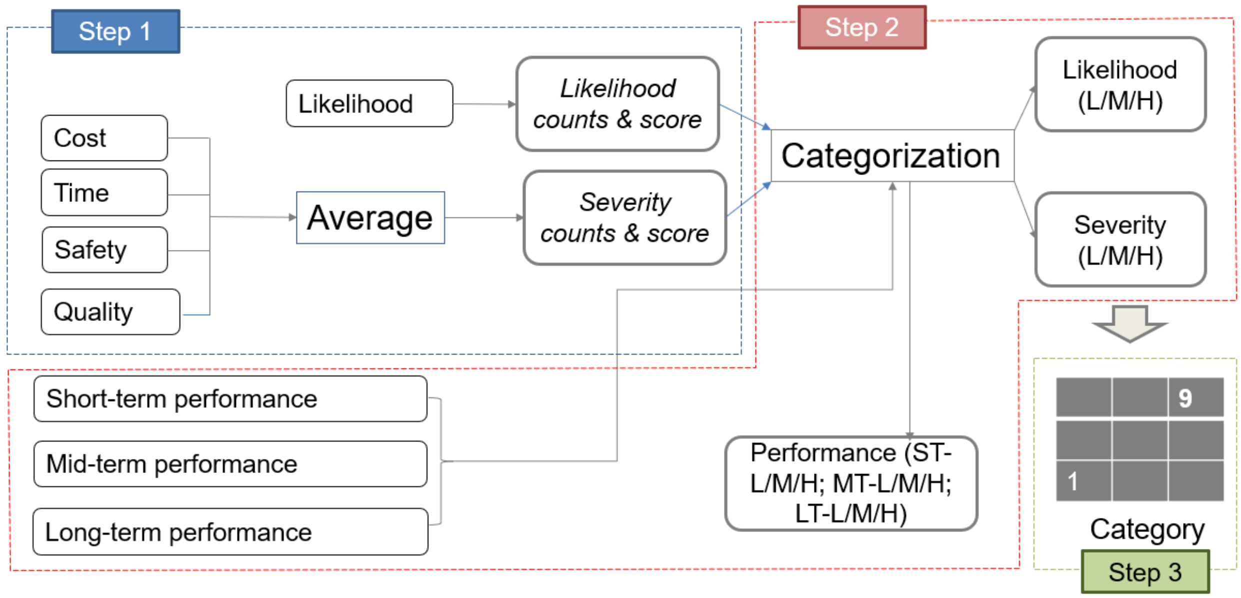

Figure 18. Risk scoring and categorization procedure

Composite risk score

Two clustering results obtained from likelihood and severity risk scores were then fused to develop a single composite risk score—which provides the overall risk level of individual construction activity group—based on 3x3 RAM in **Figure 19**. RAM allows for creating a composite index by aggregating multiple dimensions.

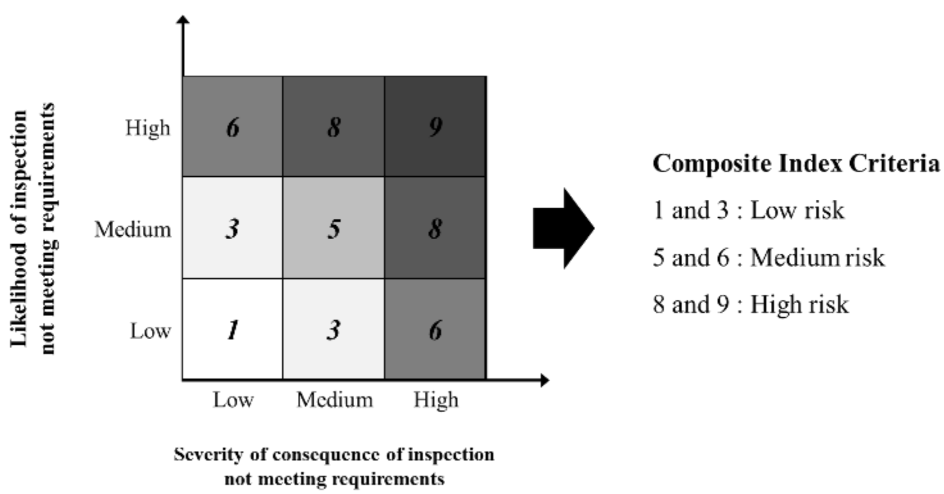

Figure 19. Risk assessment matrix (RAM)

For example, for the construction activity “Full depth asphalt pavement patching” in **Table 14**, the overall risk level (composite risk score) was determined as high (8) because the corresponding likelihood score was high (3) and the severity score was medium (2). **Table 15** illustrates the computation of the composite risk score and overall risk level, using six construction activity groups in **Table 14** as an example. Note that the overall risk level was derived from the composite risk score based on the criteria (e.g., composite risk scores of 1 and 3 correspond to low overall risk) illustrated in **Table 15**.

Table 15. Computation of composite risk score and overall risk level

Construction Activity Group	Likelihood	Severity	Composite Risk Score	Overall Risk Level
Prime coat	Low (1)	Low (1)	1	Low
Asphalt binder (liquid, asphalt-rubber)	Low (1)	Low (1)	1	Low
Asphalt emulsion (undiluted, CRS-1H-Modified)	Low (1)	Low (1)	1	Low
Full depth asphalt pavement patching	High (3)	Medium (2)	8	High
Milling existing asphalt pavement and shoulders	Medium (2)	Medium (2)	5	Medium
Seal cracks and joints in asphalt pavement	Low (1)	Low (1)	1	Low

As such, the overall risk level for each of the 142 construction activity groups identified in this research was computed and summarized in *Appendix V*. As illustrated in **Table 16**, the "Structures" area contains the highest number of medium and high-risk construction activity groups. On the other hand, the "Incidental Construction" area mainly consists of low-risk construction activity groups.

Table 16. Summary of overall risk level for the entire construction activities

Construction Area	Number of Construction Activity Groups	Overall Risk Level		
		Low	Medium	High
Earthwork	13	6	2	5
Bases and Subbases	10	1	6	3
Asphalt Pavement	17	10	4	3
Concrete Pavement	15	2	10	3
Maintenance and Control of Traffic	18	5	6	7
Structures	44	1	21	22
Incidental Construction	25	20	5	0

Deliverable: *Appendix V – Risk assessment survey summary.xlsx*

4.5. Recommendation of inspection priority, inspection frequency, and documentation based on risk

Task 5 aimed to determine the inspection priority, inspection frequency, and documentation requirements based on the risk.

The inspection priority was determined through risk ranking. In Task 4, each construction activity group was associated with a calibrated risk score based on their impacts in terms of likelihood, severity (cost, time, safety, and quality), and performance (short/mid/long term). The inspection priority was defined as follows: High priority (high-risk level), Medium priority (medium-risk level), and Low priority (low-risk level). All the construction activity groups were ranked, and their corresponding inspection priorities were assigned based on their risk levels. Following this, the best inspection frequency was assigned considering the level of risk, the inspection priority, nature of construction activity, and current inspection practice. The inspection frequency was defined as follows: Full-time inspection, Intermittent inspection, and End of product Inspection. **Table 17** provides specific descriptions for inspection frequency. Similarly, the documentation requirement was also determined by taking into account the risk level. **Table 18** provides specific descriptions for documentation.

Table 17. Specific descriptions for inspection frequency

Inspection Frequency	Description
Full-time inspection	Inspection performed continuously while the item is actively under construction
Intermittent inspection	Inspection performed daily on an as-needed basis, but emphasize on initial setups, critical stages, and finishing up, and focus on critical attributes
End of product inspection	Inspection performed when the item is completed

Table 18. Specific descriptions for documentation

Documentation	Description
Daily / Per Segment	Construction quality documentation frequency is on a daily basis during active work
Per Pay item	Required at major intervals in the construction process (e.g., initial setups, critical intermediate stages, and finishing up prior to being covered by subsequent work) of the active pay item
Once per pay item	Required once for each pay item

As a result, the inspection priority, inspection frequency, and documentation for each of the 142 construction activity groups were summarized in **Table 19**, **Table 20**, and **Table 21**.

Table 19. Summary of inspection priority for the entire construction activity groups

Construction Area	Number of Construction Activity Groups	Inspection Priority		
		Low	Medium	High
Earthwork	13	6	2	5
Bases and Subbases	10	1	6	3
Asphalt Pavement	17	10	4	3
Concrete Pavement	15	2	10	3
Maintenance and Control of Traffic	18	5	6	7
Structures	44	1	21	22
Incidental Construction	25	20	5	0

Table 20. Summary of inspection frequency for the entire construction activity groups

Construction Area	Number of Construction Activity Groups	Inspection Frequency		
		Full Time	Intermittent	End of Product

Earthwork	13	4	5	4
Bases and Subbases	10	5	4	1
Asphalt Pavement	17	6	4	7
Concrete Pavement	15	4	9	2
Maintenance and Control of Traffic	18	0	11	7
Structures	44	21	20	3
Incidental Construction	25	0	6	19

Table 21. Summary of documentation for the entire construction activity groups

Construction Area	Number of Construction Activity Groups	Documentation		
		Daily / Per Segment	Per Pay item	Once per pay item
Earthwork	13	5	2	6
Bases and Subbases	10	3	6	1
Asphalt Pavement	17	3	4	10
Concrete Pavement	15	3	10	2
Maintenance and Control of Traffic	18	7	6	5
Structures	44	22	21	1
Incidental Construction	25	0	5	20

Deliverable: *Appendix W – Risk assessment survey summary and Inspection priority.xlsx*

4.6. Construction inspection documentation – database

Task 6 aims to identify the valuable data critical for construction inspection and streamline the process to effectively document construction inspection data. The construction inspection data are vital to downstream maintenance and operation tasks and lifecycle infrastructure management. In this task, a database is designed to facilitate the construction inspection documentation, and a three-step approach is taken as follows:

1. Retrieve the construction quality requirements from construction documents using deep learning approaches.
2. Design a database system to store construction quality requirements linked to construction activities and pay items.
3. Develop a digital inspection system for the automatic generation of dynamic inspection forms.

4.6.1 Retrieval of quality requirements from construction documents

The first step is to extract textual sentences from SCDOT standard specification and construction manual. For the standard specification, the source file in PDF format was converted to WORD format using publicly available software–Foxit PDF-to-Word Doc Converter, and all the tables were removed from the WORD file through XML parsing. Unnecessary textual components (e.g., header, footer, picture, and line number) were removed using Word Macros, the composing paragraphs were extracted from the cleaned WORD file, and the paragraphs were separated into sentences. A similar process was taken for the construction manual. The source file in PDF format was converted to text format (.txt), unnecessary contents (e.g., page number) were removed using the customized Python code developed by the research team, and paragraphs constituting the cleaned texts were recognized based on regular expressions (e.g., '[.]\n' and '[.]') and further separated into sentences. The resulting sentences from the standard specification and construction manual were stored in CSV format.

In the second step, the extracted sentences were manually examined and labeled by the research team. Requirement sentences—sentences that specify construction quality requirements for inspectors to check—were labeled with "1"; information sentences—sentences that provides information to help inspectors perform the inspection (e.g., definition and explanation of construction activities)—were labeled with "0"; and "not a quality requirement" sentences—sentences that are irrelevant to construction inspection (e.g., ownership, contractor's responsibilities, and section introduction)—were labeled with "2". For example, sentences under the three subsections (Description, Measurement, and Payment) were considered as irrelevant. All the sentences labeled by the research team were reviewed and confirmed by the professionals at SCDOT.

In the third step, a classifier was developed based on convolutional neural networks (CNN) and global vectors for word representation (GloVe) to classify the sentences into either requirement (labeled with "1") or information (labeled with "0"). Sentences not associated with quality requirements (labeled with "2) were excluded at this stage. **Figure 20** illustrates the structure of the developed algorithm.

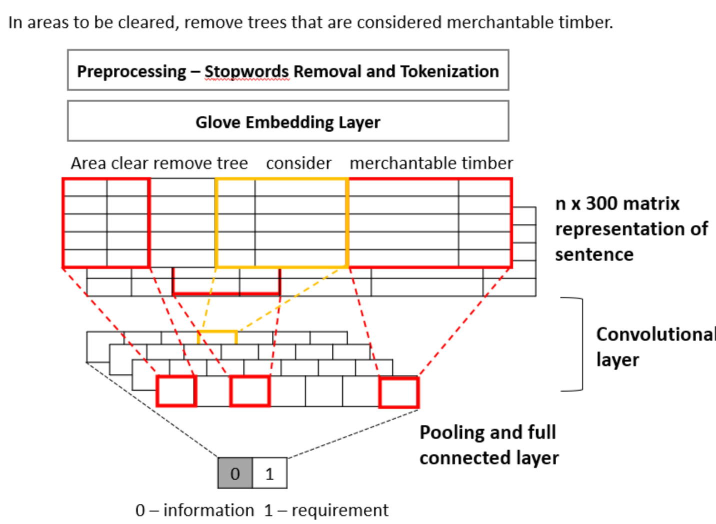

Figure 20. CNN + GloVe model for sentence classification

After preprocessing input sentences (e.g., stopwords removal, words stemming, and tokenization), each word was represented by a 1×300 vector using GloVe. After the word embedding step, the sentence was represented by an $\mathrm{n} \times 300$ matrix, where n is the length of the sentence (padded where necessary). The matrix was then used as inputs to the CNN, and the features were extracted with convolutional layers. Finally, the binary classification was conducted with the pooling and fully connected layers.

The dataset (sentences extracted from the standard specification) was split between training and testing with an 80/20 split, and the following four experiments were conducted:

1. Train classifier using the sentences (80%) extracted from all Divisions (200-800) and test on the remaining sentences (20%).
2. After excluding sentences from one subsection (Description), train and test the classifier for each Division.
3. After excluding sentences from three subsections (Description, Measurement, and Payment), train and test the classifier for each Division.
4. For each division, train classifier on the sentences from two subsections (Measurement and Payment) and test on the sentences (excluding those from Description, Measurement, and Payment subsections).

An accuracy of 81% was achieved from the first experiment, and **Table 22** summarizes the accuracy achieved from the remaining three experiments. The classification performance varies depending on the experiment and division.

Table 22. Classification accuracy results

Division	Experiment 2	Experiment 3	Experiment 4
200	89%	85%	90%
300	74%	75%	80%
400	86%	84%	79%
500	92%	92%	82%
600	84%	79%	84%
700	88%	82%	74%
800	83%	86%	77%

To investigate the classification performance in detail, a confusion matrix was created. **Figure 21** presents the example of a confusion matrix, which was obtained from Experiment 3 in **Table 22**.

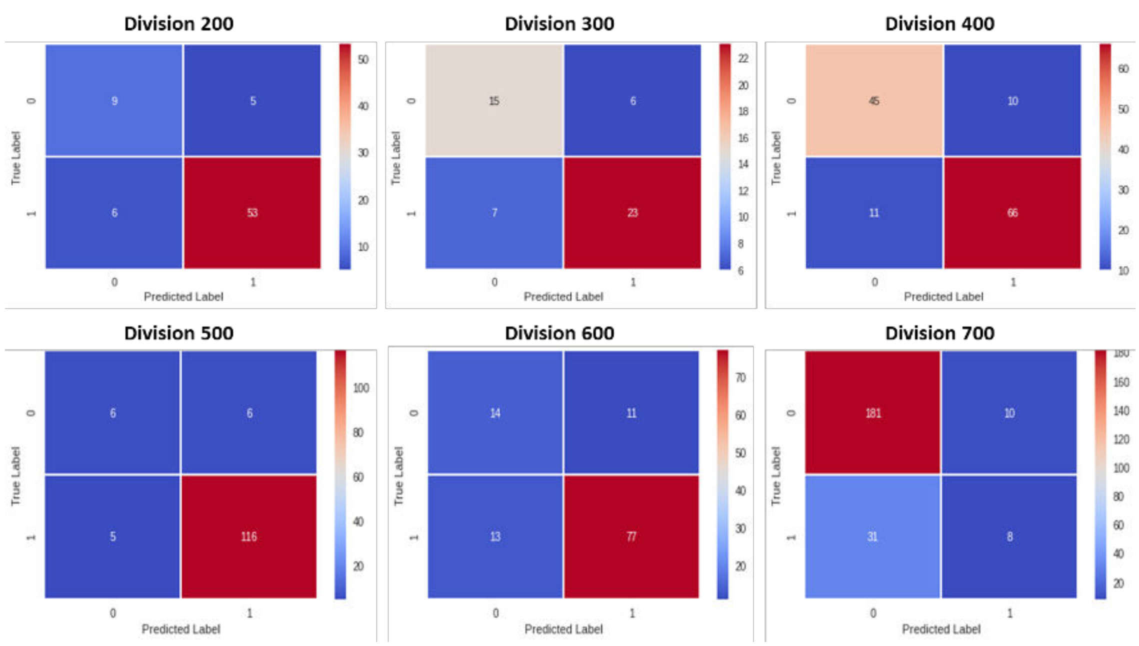

Figure 21. Confusion matrix from Experiment 3

Analyzing the confusion matrix led to the following observation; the number of false-positives and false-negatives are approximately the same, except division 700. It is likely that the differences in the division-specific performances were caused by the subjective nature of sentence labeling because different people have different perspectives when labeling sentences. Therefore, as a test case, sentences in division 200 were reexamined and relabeled by the research team to improve the consistency in sentence labeling. The classifier was retrained based on the same setting used in Experiment 3 in **Table 22**, and the accuracy improved from 85% to 90%, which suggests that more consistent sentence labeling can lead to better performance as well as the development of a more reliable sentence classifier. Based on this observation, the following training and testing strategies were designed to improve the overall classification performance: (1) for each division, train on the sentences (including those sentences from Measurement and Payment subsections) and test on the sentences (excluding those sentences from Description, Measurement, and Payment subsections), (2) train one classifier for each division, and (3) retrain and retest the classifiers after several rounds of error corrections. The final classification performance for the standard specification is illustrated in **Table 23**. The confusion matrices for all the divisions in the standard specification are presented in **Figure 22**.

Table 23. Classification accuracy for each division in standard specification

Division	Data size	R1	R2	R3	Notes
200	465	0.85	0.90	/	For these two divisions, working sessions were held to relabel the sentences, so R2 was directly used.
300	334	0.75	0.93	/	
400	720	0.88	0.91	/	Based on the R1 predictions, corrections were made, and they were used in R2.
500	705	0.92	/	/	No need for improvement.
600	665	0.86	0.86	0.89	Two rounds of corrections result in an accuracy improvement.
700	1200	0.88	0.88	0.86	No improvement was observed, although two rounds of corrections were made.
800	440	0.82	0.86	0.93	Two rounds of corrections result in an accuracy improvement.

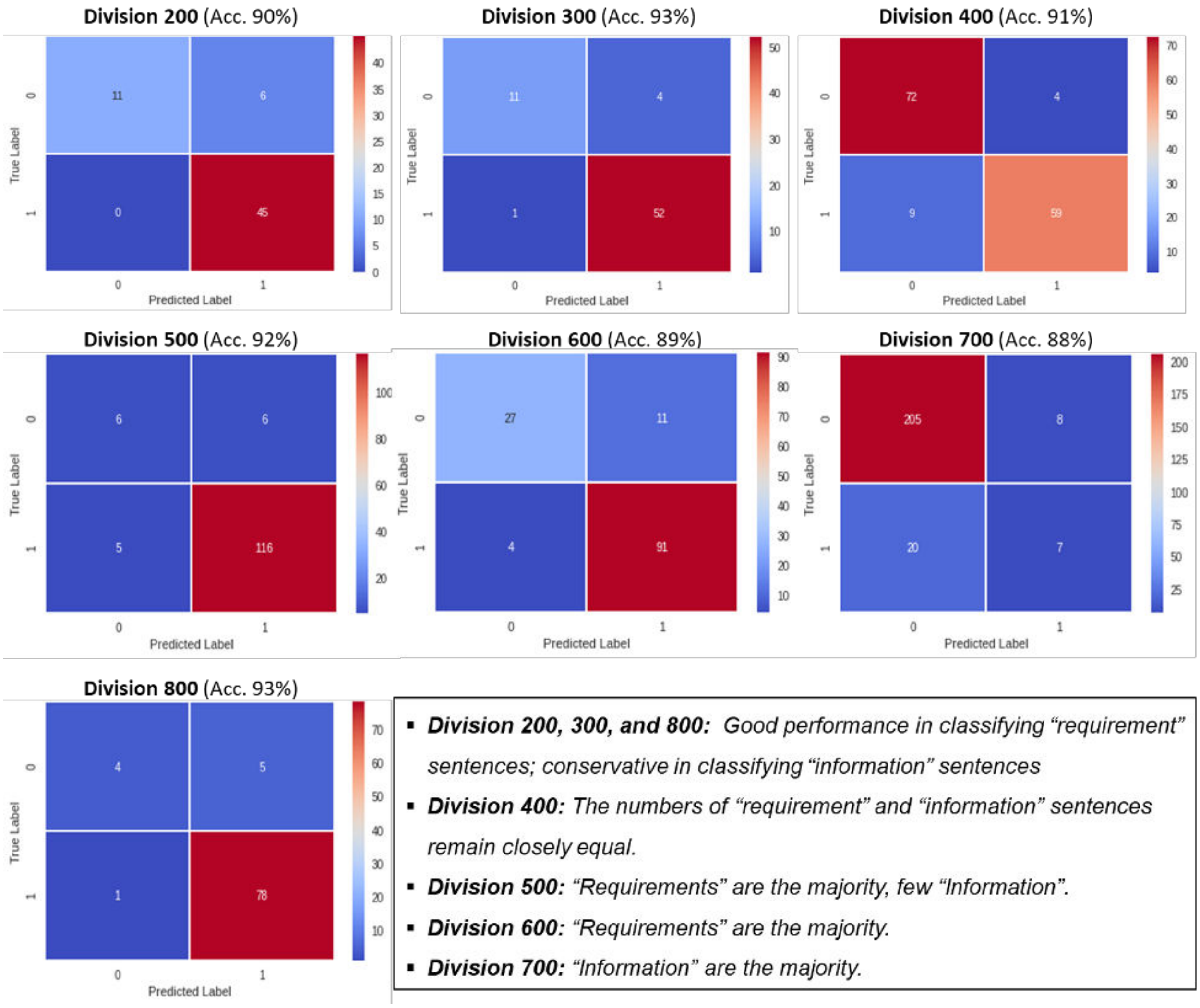

Figure 22. Confusion matrix for each division in standard specification

Deliverable: *Appendix X – Final sentence classification results (standard specification).zip*

For the construction manual, four experiments were designed and conducted as follows:

1. Directly apply the division-specific classifiers trained on standard specification to construction manual
2. Apply transfer learning to fine-tune the pre-trained classifier (trained on standard specific) for construction manual
3. Retrain a new CNN-GloVe classifier on construction manual divisions, separately (separate approach)
4. Retrain a new CNN-GloVe classifier on construction manual divisions, jointly (joint approach)

The labeled sentences extracted from divisions 200 and 300 in the construction manual were used as examples to compare the performance of different experiments. **Table 24** illustrates the results.

Table 24. Results of different experiments

<table>
<tr><th>Division</th><th>Experiment 1</th><th>Experiment 2</th><th>Experiment 3</th><th>Experiment 4</th></tr>
<tr><td>200</td><td>45%</td><td>82%</td><td>85%</td><td rowspan="2">88%</td></tr>
<tr><td>300</td><td>39%</td><td>91%</td><td>88%</td></tr>
</table>

Based on the proven performance and discussion (between the research team and professionals at SCDOT), the Experiment 4 approach (joint approach) was adopted to classify sentences in the remaining divisions in the construction manual. At this stage, multi-rounds of error corrections were conducted to further improve the performance. The final classification performance for the construction manual based on the joint approach is illustrated in **Table 25**.

Table 25. Classification accuracy for each division in the construction manual

<table>
<tr><th>Division</th><th>200</th><th>300</th><th>400</th><th>500</th><th>600</th><th>700</th><th>800</th></tr>
<tr><td>Number of sentences</td><td>180</td><td>595</td><td>285</td><td>204</td><td>115</td><td>361</td><td>218</td></tr>
<tr><td>Accuracy (separate approach)</td><td colspan="7">85%</td></tr>
<tr><td colspan="8">Results after several rounds of error corrections</td></tr>
<tr><td>Accuracy (separate approach)</td><td colspan="7">90%</td></tr>
</table>

Deliverable: *Appendix Y – Final sentence classification results (construction manual).zip*

4.6.2 Development of database system

An intelligent database system that allows for automatic generation of dynamic inspection form (checklist) was developed to maximize the practical value of the risk-based approach to the SCDOT construction inspection process.

First, the established relationship between pay items and construction documents (standard specification and construction manual) was used to associate pay items with corresponding quality requirements. Based on the hierarchy of division-section-subsection-subsubsection that can be observed in both standard specification and construction manual, three linking scenarios were developed at the subsection and subsubsection levels.

1. Specific subsections: subsections that are only applicable to particular pay items by matching the section heading with the pay item description. In this case, the links can reach the subsubsection level.
2. General subsections: subsections that contain both "information" and "requirement" sentences, and they are linked to all pay items. In this case, the links can reach both the subsection and subsubsection levels.
3. Information subsections: subsections that contain "information" sentences only, such as Description, Measurement, and Payment subsections, and these subsections are also linked to all pay items.

Figure 23 illustrates three linking scenarios between pay items and section 201 (clearing and grubbing) in the standard specification.

PAY ITEM	IDESCRL	Specific Subsections	General Subsections	Information Subsections
2010100	SITE PREPARATION FOR DESIGN/BUILD PROJECT		201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6
2011000	CLEARING & GRUBBING WITHIN RIGHT OF WAY	201.4.2	201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6
2011001	CLEARING & GRUBBING WITHIN RIGHT OF WAY	201.4.2	201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6
2012000	CLEARING & GRUBBING WITHIN ROADWAY	201.4.3	201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6
2012001	CLEARING & GRUBBING WITHIN ROADWAY	201.4.3	201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6
2013000	CLEARING & GRUBBING MATERIAL PITS		201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6
2013050	CLEARING & GRUBBING DITCHES	201.4.5	201.2, 201.3, 201.4.1, 201.4.6	201.1, 201.5, 201.6

Figure 23. Three linking scenarios between pay items and standard specification

Second, the database model was designed, as illustrated in **Figure 24**. Since the construction inspection activity centers around the pay items, the database design began by creating a table, *tblPayItem*. Two tables (*tblPayItemToSpec* and *tblPayItemToCM*) were developed to link pay items to applicable subsections in the standard specification and construction manual, respectively. Both "requirement" and "information" sentences were stored in *tblSpecCheckItem* and *tblCMCheckItem*, as check items. In addition, *tblConstructionActivity* and *tblConstructionActivityGroup* served as a bridge to link risk information (e.g., risk level, score, rank, and inspection priority) to corresponding pay items. Furthermore, relevant construction materials from standard drawings (*tblStandardDrawing*) and supplementary technical specifications (*tblSupplTechSpec*) were connected to pay items via *tblPayToSD/Suppl*.

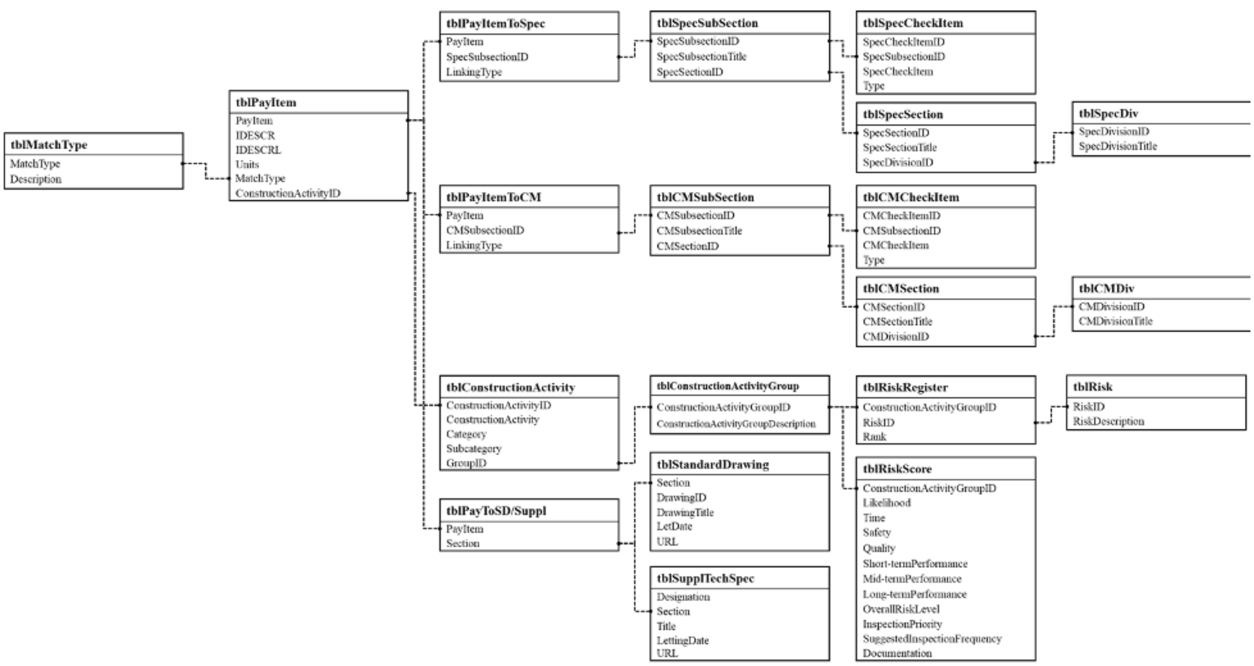

Figure 24. Database model

Lastly, the intelligent inspection system was developed based on the designed database model using MS Access 2016. **Figure 25** illustrates the database system developed in this research. For implementation, sections 201, 203, 205, 301, 305, 401, 501, 502, 602, 604, 607, 701, 708, 723, 801, 803, and 809 in standard specification were selected for linking (*Appendix Z*). For the construction manual, all divisions were used for linking (*Appendix AA*).

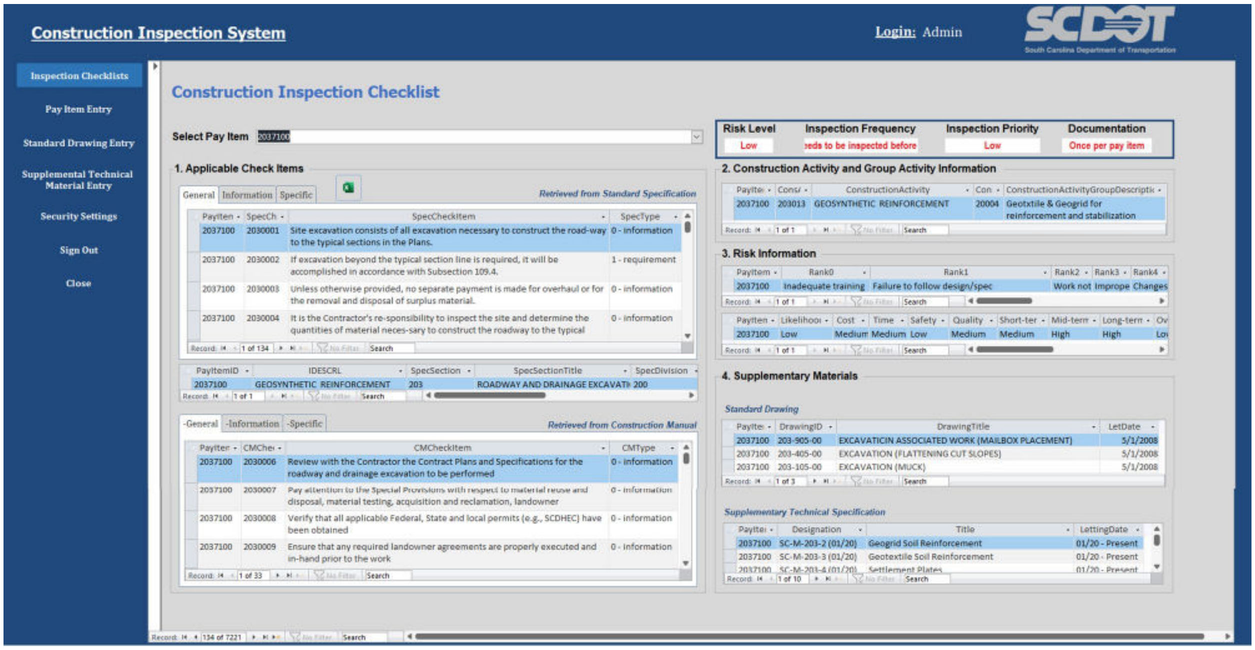

Figure 25. Developed database system

The system achieved the following four functionalities, as illustrated in **Figure 26**.

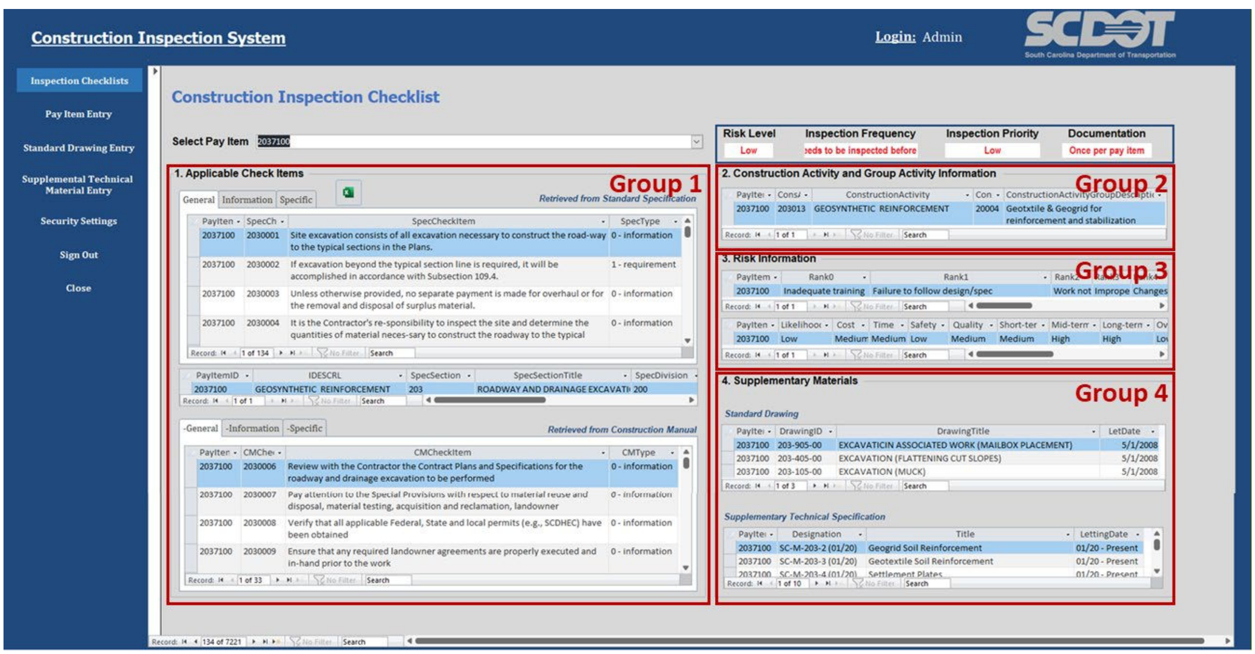

Figure 26. Four main functionalities achieved in the database system

First, check items ("requirement" and "information" sentences) are retrieved from the standard specification and construction manual and displayed based on the selected pay item. The check items are displayed based on the three linking scenarios (general, information, and specific).

Second, upon selection of a pay item, the construction activity and construction activity group information is displayed.

Third, based on the selected pay item, the corresponding risk rank (rank 0-10) and risk levels (likelihood, cost, time, safety, quality, short/mid/long-term performance, overall risk level, inspection priority, suggested inspection frequency, documentation) are retrieved. Note that four risk information of risk level, inspection frequency, inspection priority, and documentation was designed to be displayed next to the pay item drop-down list in order to directly deliver critical risk information to users (e.g., inspectors).

Lastly, the fourth functionality supports the retrieval of supplementary materials extracted from standard drawings and supplementary technical specifications. The provided URLs allow for users to access the most up-to-date information.

All the above results can be exported to an Excel template to generate a customized checklist. The research team developed tutorials to maximize the practicality for various users at SCDOT, and details are provided in 4.8.

1. Automatically generate applicable check items for the selected pay item
2. Retrieve corresponding construction activity and group information
3. Retrieve associated risk information
4. Retrieve relevant construction materials (e.g., standard drawing and supplementary technical specification)

Deliverables: *Appendix Z – Pay items to SpecSubsection_Selective.xlsx*
Appendix AA – Pay items-CMSubsections
Appendix BB – SCDOT Inspection Database.zip

4.7. Inspection summary

Task 7 aims to summarize a list of inspection requirements based on four documents (standard specification, construction manual, supplementary technical specification, and supplementary specification). Initially, several approaches (e.g., a summary of inspection requirements at the section level, pay item-based risk summary at the project level, and optimization of risk and cost at the project level) were proposed to SCDOT. Based on the discussion between the research team and SCDOT professionals, the following three-step approach was adopted.

First, the risk at the section level was calculated based on the risk scores of relevant pay items. The risk summary of each section contains information such as overall risk level and score, risk distribution over pay items, and most severe impacts. **Figure 27** illustrates the risk summary at the section level by taking section 203 (Roadway and Drainage Excavation) as an example. In this example, the overall risk for roadway and drainage excavation is medium; cost, time, and safety are the most severe consequence impacts; and short-, mid-, and long-term performance all severally impact the infrastructure performance.

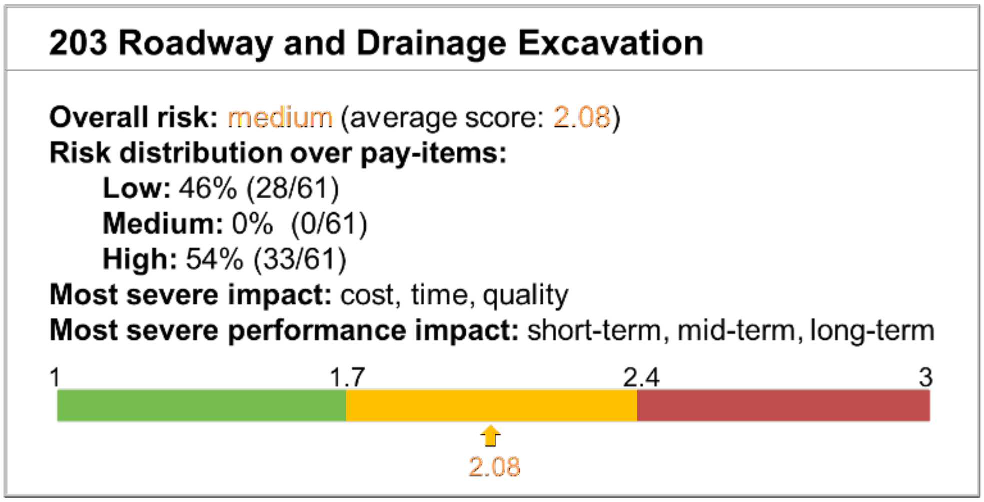

Figure 27. Risk summary at the section level

Second, a list of inspection objectives was developed at the grouped section level. Sentences in the standard specification were examined and interpreted to extract inspection objectives. **Table 26** illustrates two example inspection objectives for section 201. Throughout this process, it was found that relevant sections share similar inspection objectives. With the help of SCDOT experts, these relevant sections are grouped to share the same set of inspection objectives. For example, sections 203, 204, 205, 206, 207, 208, and 209 were grouped together and they share the same set of inspection objectives.

Table 26. Illustration of inspection objective development

Standard specification		Inspection objectives
Section	Sentences	
201 (clearing and grubbing)	Ensure that the equipment necessary for the proper construction of the work is on site, in acceptable working condition, and approved by the RCE as to both type and condition before the start of work under this section.	Ensure proper equipment is used.
	Preserve from injury or defacement all natural terrain, vegetation, and objects designated to remain.	Ensure the preservation of all natural terrain, vegetation, and objects designated to remain.

Third, a list of inspection activities was developed at the grouped section level based on the relevant parts in standard specification, construction manual, supplementary technical specification, and supplementary specification. It was found that the following five inspection activities could be applied to all sections; therefore, they were listed at the beginning of the inspection summary file.

1. Review contract plans and specifications. Verify ROW lines, BCA lines, construction lines, NPDES lines are staked.
2. Check that RCE-approved equipment is on site.
3. Review permits and agreement - contractor must comply with all applicable Federal, State, and local permits, especially those required by SCDHEC; any required landowner agreements must be properly executed and in-hand.
4. Review plans for disposal and salvage items, pay special attention to hazardous materials.
5. Check that materials and suppliers to be used meet requirements.

Then, the inspection activities identified from subsection “Inspection during construction” (in construction manual) and subsections associated with construction (in standard specification, supplementary technical specification, and supplementary specification) were used to summarize the inspection activities during construction.

The resulting inspection summary includes three major components: risk and risk-based inspection strategy, inspection objectives, and inspection activities, illustrated using the tabular format. Figure 28 presents an example (sections 203, 204, 205, 206, 207, 208, and 209 that share the same set of inspection objectives and inspection activities). The list of inspection activities before work begins applies to all pay items and is thus listed only once.

BEFORE work begins:

- Review contract plans and specifications. Verify ROW lines, BCA lines, construction lines, NPDES lines are staked.
- Check that RCE-approved equipment is on site.
- Review permits and agreement - contractor must comply with all applicable Federal, State and local permits, especially those required by SCDHEC; any required landowner agreements must be properly executed and in-hand.
- Review plans for disposal and salvage items, pay special attention to hazardous materials.
- Check that materials and suppliers to be used meet requirements.

Work Activity Groups	**Sections**	**Section Titles**	**Risk Level (H/M/L)**	**Inspection Objectives**	**Inspection Activities during Construction**
Excavation and Embankment *(High risk, continuous inspection)*	203 204 205 206 207 208 209	ROADWAY AND DRAINAGE EXCAVATION STRUCTURE EXCAVATION EMBANKMENT CONSTRUCTION EMBANKMENT IN-PLACE OVERHAUL SUBGRADE SHOULDERS AND SLOPES		Ensure proper environmental controls are in place. Ensure area to be excavated as per plans, limit disturbed areas to minimize erosion and siltation. Ensure depth of fill embankment layers as per specifications. Verify contractor's effort in obtaining desired density and moisture content as defined in the specifications. Ensure cut and fill slopes are constructed on the specified ratio. Ensure slopes intercept ditch line or shoulder line at correct location.	• Before staring the excavation, review with the contractor the contract plans and specifications, verify permits and agreements (e.g., SCDHEC), verify NPDES lines, BCA lines and right-of-way lines have been staked and the construction lines have been established. • Verify borrow pit material and embankment material have been sampled and tested by the contractor and reset items have been reset properly. • Verify the contractor is limiting the erodible area and has in place proper erosion and sediment control checks. • Remove all soft, unstable, or unsuitable material that does not compact readily. • Verify that 1) excavation achieves the proper grade and slope required by the Contract Plans; 2) the resulting excavated areas are backfilled with suitable material compacted as required; 3) the deviation of pre-split face is within the tolerance. • Embankment:

Figure 28. An illustrative example of inspection summary

Deliverable: *Appendix CC – Inspection summary.doc*

4.8. Toolbox for construction inspectors

Task 8 aims to develop tools to assist construction inspectors in effectively performing inspections. The primary tool is the digital inspection database system developed in 3.6.2. The user can select a pay item from the complete list of SCDOT pay items, and the system displays four groups of data (see **Figure 29**) to assist in the inspection.

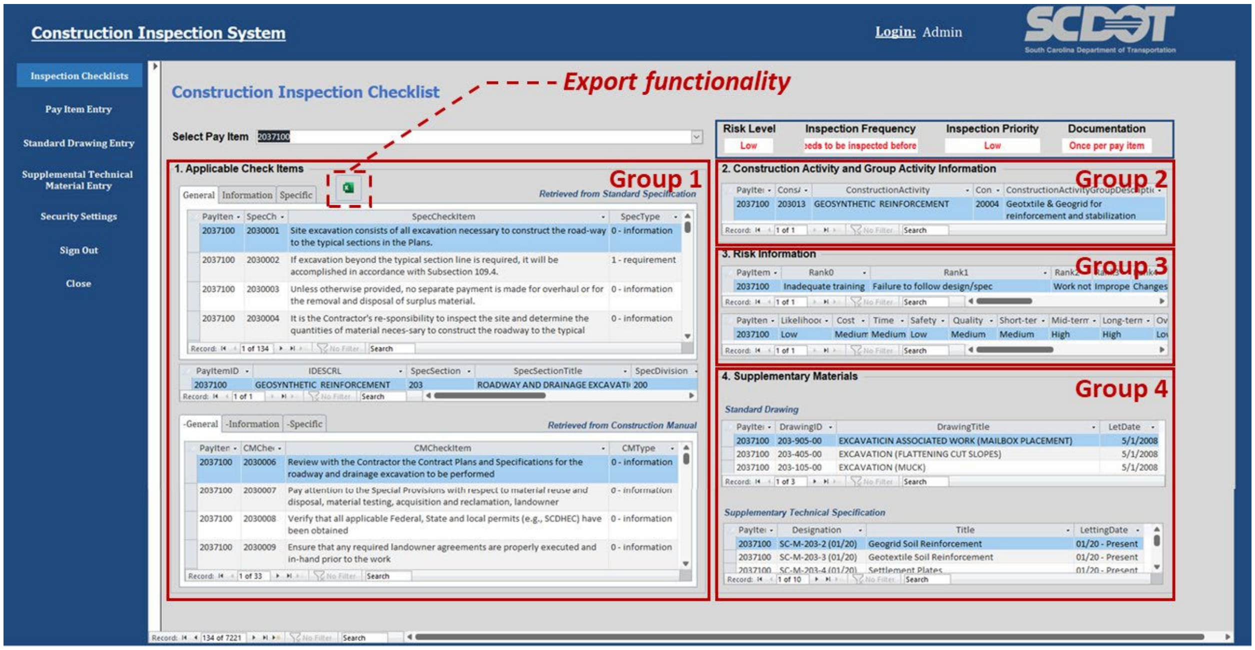

Figure 29. Four main functionalities achieved in the database system

Group 1 data – applicable check items ("requirement" and "information" sentences) specified in the standard specification and construction manual for any user-selected pay item. The check items are displayed based on the three linking scenarios (general, information, and specific).

Group 2 data – the position of the selected pay item in the construction activity group-construction activity-pay item hierarchy.

Group 3 data – risk, including the top 11 risks and their rankings; the risk assessment results of the pay item, i.e., the likelihood and the impact in aspects of cost, time, safety, quality, short-/mid-/long-term performance; the overall risk level; and the corresponding inspection priority, suggested inspection frequency, and recommended documentation frequency. Note that the overall risk level and the risk-based inspection strategy (i.e., the corresponding inspection frequency and priority, and the documentation frequency) is displayed next to the pay item drop-down list in order to underscore the critical risk information to users.

Group 4 data – the URLs for retrieving relevant standard drawings and supplementary technical specifications.

All the above data can be exported to an Excel or PDF template to generate a customized checklist. **Figure 30** illustrates the example checklist for the pay item 2038120 exported from the database in **Figure 29**. All the corresponding data in four groups (1, 2, 3, and 4) is exported, and requirement type check questions are highlighted with an orange background color. In addition, a drop-down option (pass or fail) is provided for these inspection requirements to help inspectors check the construction activities comply with associated construction documents (standard specification and construction manual). Video and Word tutorials were developed to help inspectors use the system.

SCDOT Inspection Checklist_2038120					
1. Header					
Contract ID		**Co/Rt**		**Date Inspected (MM/DD/YY)**	
Project ID		**Project Name**		**Inspector(First, Last)**	
Project Let Date		**Station Range**			
2. Pay Item, Section, And Division					
PayItem ID	2038120	**Section Number**	203	**Division Number**	200
PayItem Description	MONITORING DEVICE - SLO	**Section Title**	ROADWAY AND DRAINAGE	**Division Title**	EARTHWORK
Overall Risk Level	Low	**Inspection Priority**	Low	**Suggested Inspection Frequency**	Intermittent
Documentation	Once per pay item				
3. Risk Information					
3.1 Risk Register					
Rank0	Inadequate training	**Rank4**	Work not consistent with pl	**Rank8**	Inadequate traffic controls
Rank1	Failure to follow design/spe	**Rank5**	Irrational construction sche	**Rank9**	Damage to utilities
Rank2	Improper equipment calibra	**Rank6**	Changes in weather conditi	**Rank10**	Improper materials
Rank3	Improper equipment operati	**Rank7**	Not timely stabilization of disturbed areas		
3.2 Risk Score					
Likelihood	Low	**Safety**	Low	**Mid-term Performance**	Medium
Cost	Medium	**Quality**	Medium	**Long-term Performance**	Medium
Time	Medium	**Short-term Performance**	Medium		
4. Checklist (associated check items)					
4.1 Standard Specification					
Category	**ID**	**Question**	**Type**	**Pass/Fail**	**Comments**
General	2030001	Site excavation consists of all ex	0 - information		
General	2030002	If excavation beyond the typical	1 - requirement		
General	2030003	Unless otherwise provided, no se	0 - information	Pass	
General	2030004	It is the Contractor's re-sponsibil	0 - information	Fail	
General	2030005	Unclassified excavation consists	0 - information		
General	2030006	When the item Unclassified Exca	0 - information		
General	2030007	It is the Contractor's responsibili	0 - information		
General	2030008	Muck excavation consists of the	0 - information		
General	2030009	If the item Muck Excavation is n	0 - information		

Figure 30. Exported inspection checklist

The toolbox includes the digital inspection database (with an export tool), the template of the inspection form, the summary inspection guidance, a video tutorial, and a Word-format user manual.

Deliverables: *Appendix CC – Inspection summary.doc*
Appendix DD – Digital Inspection System Tutorial.zip

5. Conclusions

5.1. Key Findings

5.1.1. Construction activities and construction requirements at SCDOT

In Task 1, which aimed to identify construction activities and construction requirements at SCDOT, the main findings are as follows (*Appendix A-P*):

1. A total of 7,024 pay items were found to be associated with the construction activities at SCDOT.
2. The 7,024 pay items can be organized into the developed WBS in which the hierarchical structure consists of 1,276 construction activities, 142 construction activity groups, and 7 construction areas.
3. For each construction activity, construction requirements were identified from standard specification, construction manual, standard drawings, supplementary technical specifications, special provisions, and supplemental materials.

5.1.2. Current inspection practice at SCDOT

In Task 2, which aimed to identify current inspection practice at SCDOT, the main findings are as follows (*Appendix Q and R*):

1. The focus of the construction inspection at SCDOT is on 6 areas (asphalt, earthwork, concrete, traffic control, structures, and erosion control and survey).
2. The SCDOT inspection process consists of 4 steps—(1) notification, (2) requirements retrieval and planning, (3) inspection, and (4) documentation— and a significant amount of time is spent on requirements retrieval, inspection, and documentation.
3. There exist discrepancies between the field inspectors and SCDOT guidelines in the sequence of reviewing inspection documents.
4. Project plans/drawings, special provisions/contracts, and standard specifications are the most frequently used inspection documents.
5. “Continuous” frequency is the most widely used inspection frequency.
6. The top 3 most important factors considered to determine inspection frequency are nature of work, construction method, and risk.
7. As illustrated in sample roadway and bridge projects (in 4.2.2), pay items can be aligned with the construction process, which allows for effective risk management and optimized allocation of inspection resources.

5.1.3. Availability and cost of inspection Resources

In Task 3, which aimed to identify inspection resources and costs at SCDOT, the main findings are as follows (*Appendix S*):

1. In the current inspection practice, SCDOT mainly uses in-house staff and CE&I contracts.

2. CE&I contracts have relatively higher average hourly rates on all the positions compared with in-house staff.

5.1.4. Risk identification and assessment for construction activity

In Task 4, which aimed to identify risks and assess corresponding risk levels associated with construction activity groups, the main findings are as follows (*Appendix T-V*):

1. Based on the expert interviews and literature reviews, 45 risk factors were identified and organized into a 5M1E structure, and they were used to develop RBS.
2. The RBM, which was developed based on WBS and RBS in this research, can be used to identify risks for construction areas, construction activity groups, or even construction activities.
3. Top 11 risks were identified for 142 construction activity groups and 7 construction areas.
4. The risk level for each of the 142 construction activity groups and the overall risk level of the construction area were assessed; the "Structures" area contains the highest number of medium and high-risk construction activity groups, while the " Incidental Construction" area mainly includes low-risk construction activity groups.

5.1.5. Recommendation of inspection priority, inspection frequency, and documentation based on risk

In Task 5, which aimed to determine inspection priority, inspection frequency, and documentation for construction activity groups, the main achievements are as follows (*Appendix T-W*):

1. Three levels of inspection priority were designed: high, medium, and low.
2. Three levels of inspection frequency were proposed: full-time, intermittent, and end of production.
3. Three levels of documentation were developed: daily/per segment, per pay item, and once per pay item.

5.1.6. Construction inspection documentation – database

In Task 6, which aimed to identify critical inspection information from documents and streamline the inspection process, the main achievements are as follows (*Appendix X-BB*):

1. The sentence classifier developed in this research can correctly classify requirements in standard specifications with an average accuracy of 91% and those in the construction manual with an average accuracy of 90%.
2. The intelligent inspection system supports various practical functionalities, which are detailed in 5.1.8.

5.1.7. Inspection summary

In Task 7, which aimed to summarize a list of inspection requirements from construction documents, the main achievements are as follows (*Appendix CC*):

1. The inspection summary containing inspection objectives and inspection activities at the section level was developed.

5.1.8. Toolbox for construction inspectors

In Task 8, which aimed to develop tools to help inspectors efficiently perform construction inspections, the main achievements are as follows (*Appendix CC and DD*):

1. The intelligent inspection database system can (1) automatically generate applicable check items for the selected pay item from standard specification and construction manual, (2) retrieve corresponding construction activity and group, (3) display associated risk information, (4) retrieve supplementary materials (e.g., standard drawing), and (5) generate inspection forms as a checklist format.
2. Tutorials (video and Word documents) for the digital inspection system and inspection summary were developed.

5.2. Recommendations

The research team of this project provides the following recommendations:

1. As revealed in the survey, which attempted to investigate current inspection practice at SCDOT (in 4.2), the discrepancy between the field inspectors and SCDOT guidelines regarding the sequence of reviewing inspection documents was observed. This highlights the need for more education and training of field inspectors on the hierarchy of the governing inspection documents.
2. It is recommended that SCDOT adopts the NLP-Deep learning approach (CNN+GloVe) to retrieve requirements from construction documents (e.g., standard specifications), especially for the newer version of the documents.
3. The intelligent inspection system developed in this project is recommended for SCDOT to manage their inspection system and generate dynamic inspection forms.
4. Testing the inspection system in a field application is highly recommended prior to full-scale implementation.

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Appendices

Appendix A – Pay items categorization.xlsx

Appendix B – Pay items-construction activities match table.xlsx

Appendix C – Grouped Activities.xlsx

Appendix D – Pay Item-Std Section based on matched pay item.xlsx

Appendix E – Pay Item-CM based on matched section.xlsx

Appendix F – Pay Item-SD based on matched pay item.xlsx

Appendix G – Pay Item-SD based on matched section.xlsx

Appendix H – Pay Item-STS (latest) based on matched pay item.xlsx

Appendix I – Pay Item-STS (latest) based on matched section.xlsx

Appendix J – Pay Item-SP compiled based on matched pay item.xlsx

Appendix K – Pay Item-SP compiled based on matched section.xlsx

Appendix L – Pay Item-SP compiled based on matched division.xlsx

Appendix M – Pay Item-SP_Supp ind based on matched pay item.xlsx

Appendix N – Pay Item-SP_Supp ind based on matched section.xlsx

Appendix O – Pay Item-Supp compiled based on matched pay item.xlsx

Appendix P – Pay Item-Supp compiled based on matched section.xlsx

Appendix Q – Survey_inspection practices.docx

Appendix R – Survey Analysis_With Observations and Question.pptx

Appendix S – Survey on inspection resource.xlsx

Appendix T – List of risk factors.xlsx

Appendix U – Risk identification survey results.xlsx

Appendix V – Risk assessment survey summary.xlsx

Appendix W – Risk assessment survey summary and Inspection priority.xlsx

Appendix X – Final sentence classification results (standard specification).zip

Appendix Y – Final sentence classification results (construction manual).zip

Appendix Z – Pay items to SpecSubsection_Selective.xlsx

Appendix AA – Pay items-CMSubsections

Appendix BB – SCDOT Inspection Database.zip

Appendix CC – Inspection summary.doc

Appendix DD – Digital Inspection System Tutorial.zip