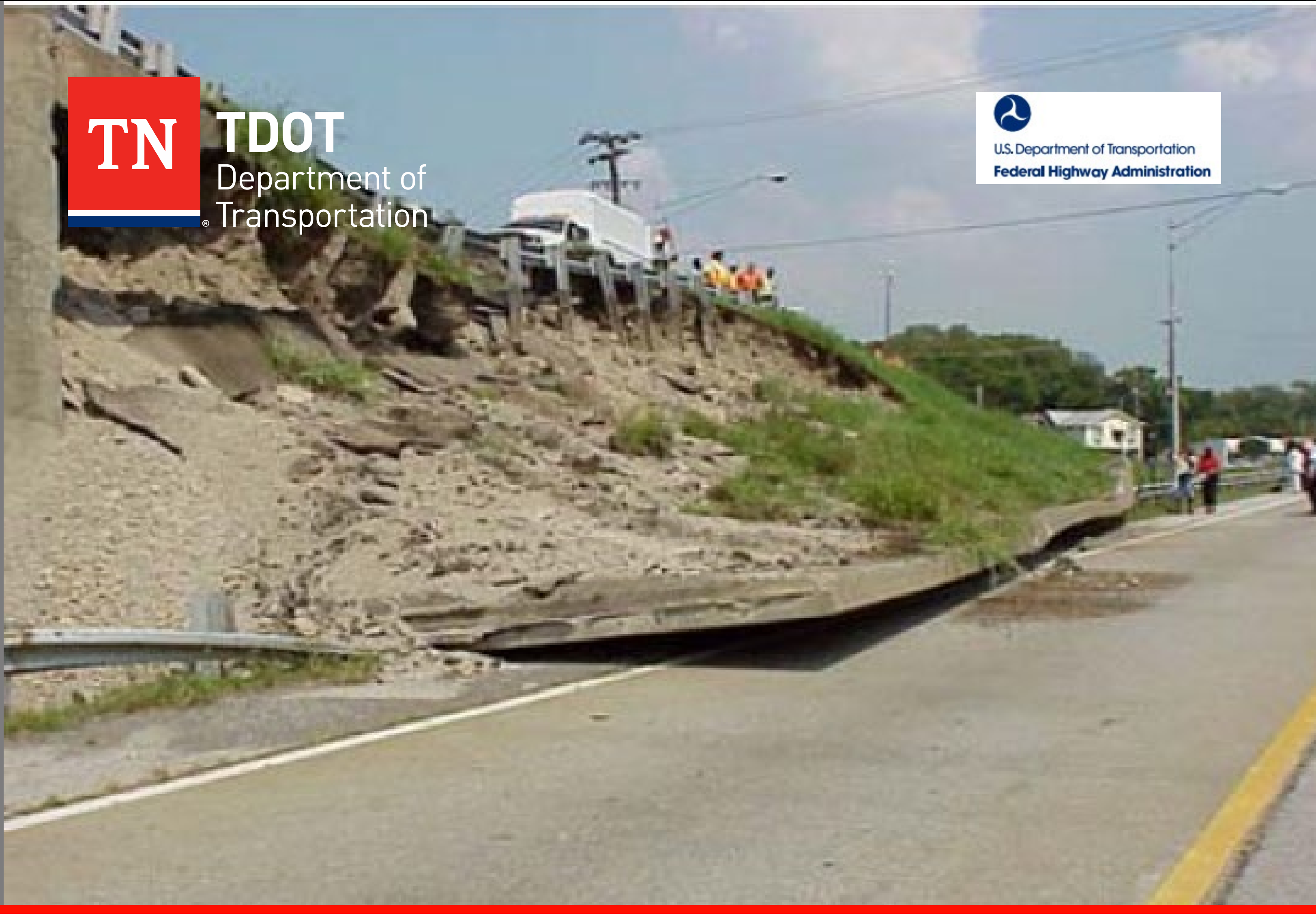

Rating and Inventory of TDOT Retaining Walls

Research Final Report from University of Tennessee at Chattanooga | Weidong Wu, Endong Wang, Mbakisya Onyango, & Dalei Wu | November 19, 2021

Sponsored by Tennessee Department of Transportation Long Range Planning Research Office & Federal Highway Administration

DISCLAIMER

This research was funded through the State Planning and Research (SPR) Program by the Tennessee Department of Transportation and the Federal Highway Administration under ***RES #:2019-08, Research Project Title: Rating and Inventory of TDOT Retaining Walls.***

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
RES 2019-08		

4. Title and Subtitle	5. Report Date
Rating and Inventory of TDOT Retaining Walls	November 2021
	6. Performing Organization Code
7. Author(s) Weidong Wu, Endong Wang, Mbakisya Onyango, & Dalei Wu	8. Performing Organization Report No.
9. Performing Organization Name and Address The University of Tennessee at Chattanooga 615 McCallie Ave. Chattanooga, TN, 37403	10. Work Unit No. (TRAIS) 11. Contract or Grant No. RES2019-08
12. Sponsoring Agency Name and Address Tennessee Department of Transportation 505 Deaderick Street, Suite 900 Nashville, TN 37243	13. Type of Report and Period Covered Final Report May 2019 – October 2021 14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

To meet the requirements under the Moving Ahead for Progress in the 21st Century Act (MAP-21), Tennessee Department of Transportation (TDOT) decided to develop a management program covering condition rating, service life prediction and inventory of retaining walls in the State of Tennessee to protect the safety and welfare of the public. This project created a comprehensive rating and inventory system to inspect, assess and record the condition of all walls throughout the State. A systematic approach that integrates analytic hierarchy process (AHP) and Markov model for rating the current and predicting the future conditions of retaining walls was developed. An overall rating score, as well as the composite scores following the two-part rating approach, were achieved through hierarchical configuration and pairwise comparison of retaining wall elements using AHP that respects engineering principles by considering importance weights. The aggregated rating scores, together with transition probabilities, are then passed on to the Markov model for retaining wall future condition rating and service life prediction. A GIS-based prototype mapping system and searchable inventory database was established to visually display and save key parameters of wall location, dimension, condition, risk and estimated cost of actions, and additional information. Moreover, this report includes a pilot study of thirty-one geographically distributed wall locations and short summaries of site survey. The findings of this project will provide TDOT the capability to establish effective retaining wall maintenance and replacement priorities in support of MAP-21.

17. Key Words	18. Distribution Statement
RETAINING WALLS, CONDITION RATING, WALL INVENTORY, AHP, MARKOV CHAIN, SERVICE LIFE PREDICTION	No restriction. This document is available to the public from the sponsoring agency at the website http://www.tn.gov/

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	88	

Acknowledgement

The project team acknowledges the Tennessee Department of Transportation (TDOT) for supporting and funding of this project.

Abdulazeez Lawal, now a University of Tennessee at Chattanooga (UTC) civil engineering alumni and a PhD student in Iowa State University, contributed heavily as a lead research assistant to the project. Baowen Zhang, a PhD student in State University of New York, Syracuse, and Rand Jackson, now a UTC computer science alumnus, assisted with ArcGIS mapping and inventory database during the late stages of the project. Adam Belton, a UTC undergraduate research assistant, Jibril Babatunde, a UTC graduate research assistant, assisted with the site visits data collection.

The participation and the contributions of TDOT personnel were especially noteworthy and helpful.

Executive Summary

Brief Description of Research Objective

Retaining wall (RW) is one typical type of Earth Retaining Structures. Irrespective of the structural configuration and the earth load supported, catastrophic failures in retaining walls are relatively rare. In their report, Brutus et. al. reported few notable catastrophic retaining wall failures, including one in Davidson County Tennessee. Such failures underline the need for reliable inventory, rating, and performance prediction of retaining wall systems in order to reach an efficient, secure, environment-friendly, and cost-effective transportation system [1].

Currently, there are no formal standard frameworks/procedures available for inventorying and rating retaining walls. Existing retaining wall management programs often differ significantly in terms of characteristics coverage, condition rating techniques, data collection methods, and database components.

- For inventory, existing programs often cover varied lists of characteristics [1], while others only considered few characteristics.
- Most condition rating practices have observable issues [2, 3]. Further, the weighting process on measuring the importance of different elements is often subjective without a formal judging process [4].
- Most states solely relied on qualitative visual inspections through manual operations, which had limitations on cost, accessibility, and safety.
- While most inventory databases only considered static condition rating, other components including remaining life projection, dynamic deterioration modeling and risk assessment are also important for retaining wall management.

While considerable effort from the Tennessee Department of Transportation (TDOT) has been spent on the quality management of the State Route System of Tennessee, with almost 14,150 miles of roadways, they lacked a system for tallying and rating of retaining wall components which can be principal contributors of safety and accessibility of roadway systems. As a result, the condition, performance, reliability, and other information related to these structures is largely unknown. Consequentially, the required preventive maintenance plans along with the associated budget are difficult to schedule.

To achieve the goal of rating and inventory of retaining walls throughout the state, the following objectives have been accomplished:

- Established a GIS-based mapping system, showing locations and attributes for retaining walls.
- Provided an Analytic Hierarchy Process (AHP) two-part weighted condition rating system for RW considering key characteristics.
- Applied the AHP-weighted rating system to assess selected retaining walls.
- Developed Markov-Chain based structure deterioration model to estimate service life and dynamic condition of retaining wall systems.
- Conducted action cost analysis of retaining wall systems.

- Built a comprehensive searchable ArcGIS inventory of TDOT retaining walls including key parameters, e.g., location, dimensions, condition, risk, and estimated cost of actions (e.g., replace, repair).

Methodology Used

This research proposed an AHP-Markov chain integrated method for retaining wall condition rating and service life prediction. The method started with defining specific criteria for rating all the components of retaining walls. After evaluation criteria were defined, field data were collected in the form of images and videos with the assistance of a drone. Based on field data, the condition rating scores for different retaining wall elements were assigned by civil engineers. By AHP, pairwise comparisons of retaining wall elements and their sub-elements were performed and the relevant weights were derived. An overall condition rating score for the entire wall was finally obtained by weighted aggregation. The obtained condition is then used as the initial condition for Markov chain modeling. Both future condition and service life can be predicted by applying Markov chain. The research team also performed risk management and maintenance cost estimation following the risk-based cost estimation method.

Results and Deliverables

This study delivered the following to TDOT:

- An adaptable AHP-weighted rating system that characterizes the key characteristics related to safety, structure, and function of TDOT retaining walls.
- A detailed framework/procedure for estimating future conditions, remaining service life of TDOT retaining walls.
- A user-friendly searchable inventory database built on ArcGIS linking location, descriptive data, photographs, conditions, risks, and associated action costs.
- User-friendly Excel dashboards that implement AHP for weighting the retaining wall and predicting dynamic condition rating scores and service life.
- An educational workshop/presentation offered to the relevant stakeholders of TDOT to introduce the developed procedures, skills, tools, and techniques for enhanced application of these project outcomes.

Conclusions

As an important part of asset management for retaining walls, reliably estimating the condition and life expectancy will guide transportation agencies to better maintain retaining walls at lower cost. This report proposes a framework that integrates AHP with Markov chain to rate the current condition and estimate future conditions as well as service life of retaining walls. The application of AHP for weighting the relative importance of wall elements can use the knowledge from experts or experienced engineers with respect to engineering principles. Markov chain provides a more realistic solution to service life prediction since it considers the practical condition of retaining walls. Finally, a prototype ArcGIS feature layer allows TDOT to store important retaining wall information in the state to better support asset management and Moving Ahead for Progress in the 21st Century Act (MAP-21).

Policy Implementation

The research team has developed a retaining wall rating system, and practical computer tools to apply AHP and Markov model to rate condition scores and predict future condition and service life of walls. An ArcGIS feature layer for storing information of retaining wall was established, which aligns with the existing TDOT GIS data.

Benefits to TDOT

The following benefits will be brought to TDOT through the findings of this project:

1 Inventory data and condition rating can assist TDOT in better understanding the spatial distribution and current condition of retaining walls in the state of Tennessee.
2 Dynamic condition prediction, remaining service life estimate, and risk analysis can assist TDOT in preventing catastrophic failures of retaining wall/catchment systems. Action cost analysis can be beneficial for accurate budget and allocation of available funds.
3 The user-friendly AHP and Markov model dashboards and database enables TDOT to easily update the information on retaining walls.
4 Overall, with the deliverables of this project, TDOT can better manage retaining wall structures in terms of maintenance, repairing and replacement through well-informed decisions within tight budget. They can also help to shape both short-term and long-term strategic plans on retaining wall asset management.

Key Findings

The following is a short summary of the findings informed by this research.

- Analytic Hierarchy Process - Markov method can be used to evaluate the overall condition rating and predict service life of retaining wall.
- The condition rating scores for the retaining walls surveyed in this research as shown in Table A.4 can contribute to the future nationwide retaining wall condition database.
- It is beneficial to use UAV to assist retaining wall data collection.

Key Recommendations

The UTC research team recommends:

- TDOT engineers conduct an in-house evaluation of the data collection form proposed in this research, as well as the key items to be included in the ArcGIS inventory database.
- It is necessary to perform additional nondestructive in-situ condition assessment using thermal camera, ultrasound or ground-penetrating radar for a retaining wall that is identified as in severe condition.
- The relative score assigned to retaining wall components used for AHP weighting should be assessed by experienced engineers.
- Lastly, the University of Tennessee at Chattanooga (UTC) research team recommends refining the initial inventory developed in this research, performing routine inspection cycle for individual retaining walls.

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Glossary of Key Terms and Acronyms

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AHP	Analytic Hierarchy Process
ASCE	American Society of Civil Engineers
CRS	Condition Rating System
DOT	Department of Transportation
ERS	Earth Retaining Structure
FHWA	Federal Highway Administration
IRP	Inventory, Rating and Prediction
MAP-21	Moving Ahead for Progress in the 21st Century
MCDM	Multi-Criteria Decision Making
MR&R	Maintenance, Rehabilitation and Repair
MSE	Mechanically Stabilized Earth
NBI	National Bridge Inventory
NHI	National Highway Institute
NPS	National Park Services
RW	Retaining Wall
TDOT	Tennessee Department of Transportation
UAV	Unmanned Aerial Vehicle
WIP	Wall Inventory and Condition Assessment Program

Chapter 1 Introduction

1.1 Research Objectives

This research is aimed to help the Tennessee Department of Transportation (TDOT) establish a rating and inventory system for its retaining walls (RWs).

It is intended to provide a general guideline on how to apply Analytic Hierarchy Process (AHP) and Markov chain to a more realistic condition rating and service life of retaining walls. To achieve this goal, this research team started with developing an AHP-weighted rating system considering RW key characteristics, then the AHP based rating system is applied to assess selected RW in the state, in addition, an integrated AHP-Markov chain based structural deterioration model was developed to estimate service life and dynamic condition of retaining wall systems. Furthermore, a GIS-based mapping system is established to show locations and attributes. In the end, a comprehensive searchable inventory database that documents valuable information regarding wall locations, current and future condition ratings, estimated service life, as well as risk assessment and action cost, which will allow TDOT to satisfy the requirement of Moving Ahead for Progress in the 21st Century Act (MAP-21) and better manage and maintain retaining walls.

1.2 Scope of Work

First, this research included review of extant documents pertinent to the inventory of retaining walls, to examine the typical parameters, models and procedures employed in the documents. Afterwards, the most extensively used inventory characteristics (based on literature research) were identified. The research team then created a condition rating system based on the identified key characteristics and previous systems. After necessary inspection training, the research team performed field inspection and rating of walls. An integrated AHP-Markov chain based systematic model was developed for objective weighting of involved characteristics and prediction of the remaining service life of retaining walls based on a structure deterioration model. Finally, the research team constructed an inventory and rating database using file geodatabase with ArcGIS, which also allows dynamic mapping, herein, refers specifically to the periodical mapping - for example:

1) current information, and

2) the information after 10 years, 30 years, 50 years of condition deterioration and action costs.

1.3 Report Organization

The remainder of this project report is structured as follows. Chapter 2 provides a literature review of detailed information and background of previous research and findings related to retaining wall condition rating and inventory contributed by other state Departments of Transportation (DOTs) and highway agencies. Chapter 3 provides a background of methodologies of AHP two-part based rating system for wall condition assessment, Markov chain for condition and service life prediction, and data collection forms for site visits and technologies used for collecting basic wall information. Chapter 4 presents a recommended systematic AHP-Markov method and computer tools for retaining wall condition rating and service life prediction and the application of the selected walls. A prototype ArcGIS inventory database/feature layer that maps retaining walls currently identified and defines attributes/important characteristics of walls is included at the end of the chapter. Chapter 5 provides benefits to TDOT from the research, implementation of the findings, conclusions, and recommendations. The rest of the report presents references, and the appendices for the report.

Chapter 2 Literature Review

This chapter presents an expanded literature review to provide knowledge base for building an inventory, rating, and prediction (IRP) system for retaining walls in the state of Tennessee. More specifically, a review of the following was undertaken:

- Current retaining wall inventory and condition rating programs
- Construction of searchable inventory database

2.1 Current retaining wall condition rating and inventory programs

Section 1106 of Moving Ahead for Progress in the 21st Century Act (MAP-21) mandates that all individual state agencies must "develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system" [5]. With the overall infrastructure condition being rated as poor (e.g., Grade C- in 2021 by American Society of Civil Engineers) [6], a performance-based asset management plan should find wide application in America. Retaining walls are important assets of transportation infrastructure that are subject to potential failure due to structural degradation. For instance, in 2003, a 25-year-old retaining wall collapsed suddenly at the Jefferson Street On-Ramp to I-40 West in Davidson County Tennessee due to corrosion of reinforcements. Moreover, the management of walls is often difficult due to their dispersed locations, different structure types and serving purposes [7]. Consequently, as a significant component of transportation development, retaining walls became an integral part of asset management program stated in MAP-21.

As a beneficial geotechnical asset of transportation system, retaining walls typically serve to resist the lateral or other forces from soil, rock, and/or other mass to assist in the transporting functions of roads, bridges, etc. Retaining walls could potentially fail due to structural deterioration. Therefore, with retaining wall as a part of transportation asset management program [8] understanding, tracking, and monitoring the static and dynamic patterns of retain wall systems have become important for the safe operation of transportation systems.

The Federal Highway Administration Central Federal Lands Highway Division (FHWA-CFLHD) developed the "Retaining Wall Inventory and Condition Assessment Program (WIP): National Parks Service Procedure Manual" for Earth Retaining Structures (ERSs) located in national parks, which is currently the most extensive ERS inventory and inspection program in the United States [4]. The WIP program report provided a typical and comprehensive program on wall inventory and inspection. Developed by the FHWA-CFLHD, WIP mainly inventoried and rated the wall systems associated with park roadways. Basically, five main categories of data are collected including wall location data (e.g., latitude and longitude), wall description data (e.g., age, type, function, architectural facings, and measurement data), condition assessment (e.g., severity of distresses related to wall elements and overall performance), wall action assessment (e.g.no action, monitoring, minor maintenance, replacement), and work order development. The main aspects covered geographical location, wall geometry, construction features, condition (geotechnical and structural), failure consequence, cultural concerns, design criteria, cost for maintenance, repair, or replacement with each being described by corresponding parameters. Referring to the predetermined rating system using a numerical 1-10 scale (TABLE

2.A), the condition of each individual wall component is evaluated and ultimately, the overall wall rating is calculated as the weighted average of all the component ratings. DeMarco et al. [4] reported the details of WIP program of FHWA-CFLHD, including data collection process and procedures, wall selection and data collection guidelines, as well as future development. TABLE 2.B summarized the retaining wall collection specified in WIP.

TABLE 2.A THE NUMERICAL CONDITION RATING DEFINITIONS

Element Condition Rating	**Element Rating Definition**
9-10 Excellent	None-to-very-low extent of very low severity distress
7-8 Good	Low-to-moderate extent of low severity distress
5-6 Fair	High extent of low severity distress and/or low-to-medium extent of medium to high severity distress
3-4 Poor	Medium-to-high extent of medium-to-high severity distress
1-2 Critical	Medium-to-high extent of high severity distress

TABLE 2.B WALL DATA COLLECTION SPECIFIED IN WIP_DEMARCO ET AL. [4]

Wall data categories	**Descriptions**
Location	Latitude and longitude
Descriptions	Function, Type Year built Architectural facings and surface treatments Wall length, Maximum height Face area, Face angle Vertical and horizontal offsets from roadway Photos of wall
Condition assessment	Primary wall element numerically rated Secondary wall element numerically rated Overall performance of wall rated-Final wall rating
Action assessment	*Objective consideration is giving to:* Final wall rating Any identified requirements for further site investigations Design criteria at the time of construction Any cultural concerns Consequences of failure *Actions include:* No action Monitor the wall Conduct maintenance-level work Repair wall elements Replacement of wall elements / entire wall
Work order development	Unit costs for major work items

The primary wall elements defined in WIP include piles and shafts, lagging, anchor heads, wire/geosynthetic facing elements, bin or crib, concrete, shotcrete, mortar, manufactured block/brick, placed stone, stone masonry, wall foundation material, and other primary wall elements. The secondary wall elements in WIP consist of wall drains, architectural facing, traffic barrier/fence, road/sidewalk/shoulder, upslope, downslope, lateral slope, vegetation, culvert, curb/berm/ditch, and other secondary wall elements.

To identify the key elements of retaining walls to be rated, the implementation procedure of FHWA-CFLHD [4] will be followed by constructing a matrix showing the wall primary and secondary elements rated based on the wall structural type.

Professor Jensen of Construction Engineering at University of Nebraska-Lincoln developed a brief manual for rating tilting, structural cracking, facial deterioration, bowing, staining, fabric exposure at joints, erosion, joint spacing, v-ditch condition, coping deterioration, drainage system of mechanically stabilized earth walls [9]. Sponsored by National Cooperative Highway Research Program (NCHRP), based on the responses of 40 transportation agencies, Brutus et al.[1] identified the common components covered by the Inventory and Inspection (I&I) programs in the U.S., including map, database, condition assessment and performance assessment. The fundamental purposes and functions of these components were analyzed along with possible pathways to develop the components, i.e., how to filter wall systems for geographical mapping, what could be included in database, how to perform condition rating, and how the performance would be affected. They found that, limited to cost, some criteria (e.g., dimension size, ownership) should be applied to filtering walls for mapping. Eight (8) categories of data were recommended to be at least included, i.e., identification number, location, dimension, structure type, function, ownership, condition, and action records. A multi-item checklist for condition rating was suggested without deeply discussing the detailed condition rating procedure. This report also qualitatively identified some performance influencers, e.g., construction errors, corrosion, land development and excavation.

Gabr et al. [3] compared three condition rating systems including Butler et al. Rating System, FHWA-CFLHD Rating System and Nebraska Department of Roads Rating System for earth retaining structures. The study evaluated eleven (11) structures covering mechanically stabilized earth, soil nail, anchored, gravity, and cantilever retaining structures, and found that the traditional single-value numerical rating systems have challenges in revealing the deficiencies of elements critical to structural stability and function. Thereby, the researchers proposed an alternative two-part condition rating system generating information on both overall structure condition and specific problems associated with individual elements. It was recommended that state DOTs attempting to comply with MAP-21 could adopt the two-part system to better implement the earth retaining structure management program. The two-part rating procedure was also adopted by Butler et al. [2] for retaining wall assessment. Butler et al. modified the condition inspection data collection form provided by Brutus and Tauber (2009), the criteria numbers 1, 2, 3, 15, 16, and 21 in their form have the most significant impact on the retaining wall's safety condition. More specifically, the critical condition evaluation criteria adopted into their rating system are:

1. Wall or parts of it is visually out of plumb, tilting, or deflecting
2. Wall local bulges or distortion in the wall facing

3. Wall settlement of wall or visible wall elements
4. Soil settlement and/or tension cracks behind wall
5. Evidence of landslide or active earth movement
6. Drainage outlets (pipes/weepholes) are clogged or not operating properly

The rating system they chose is the 1-4 (best-worst) rating scale used for bridges abutment walls and retaining walls. Their wall rating procedure is summarized in Figure 2.1 below:

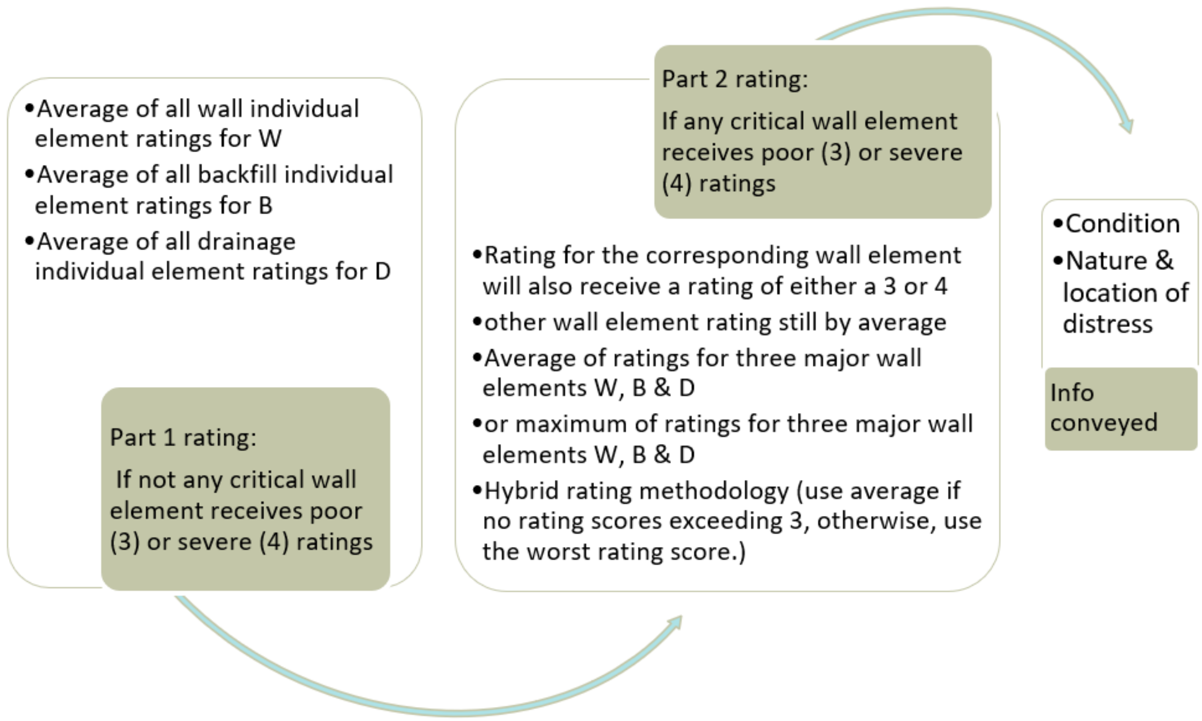


Figure 2.1 The Two-part Earth Retaining Structure Condition Rating Procedure ([2])

The significance of Butler's two-part rating system lies in that it reports both the overall condition of a wall and the location of potential problems.

Arguing that, many asset management systems failed to consider geotechnical issues, Bernhardt et al. [10] proposed a framework based on the generic framework of Federal Highway Administration (FHWA) for managing geotechnical structures by asset management principles. In the study, it was found that ERSs have both structural and geotechnical attributes.

Rasdorf et al. [11] and Gabr et al. [3] summarize the retaining wall inventory and assessment system for 18 highway agencies as shown in TABLE 2.C.

It is observed that:

- 9 out of 20 agencies developed both inventory and inspection program.
- only 5 out of 20 agencies developed both inventory and inspection program in an advanced asset management system.
- 17 out of 20 agencies developed either inventory or inspection program.
- different rating scales are adopted.
- 5 agencies reported number of ERSs surveyed.

- 9 out of 20 agencies created different inventory databases.

Brutus, et. al. [1, 12] developed their own inventory and inspection program summarized in TABLE 2.D, which is outlined in Rasdorf et al. [11].

More than 20 agencies and state DOTs, including FHWA, Alaska DOT, California DOT, Colorado DOT, Kansas DOT, Kentucky DOT, Maryland DOT, Minnesota DOT, Missouri DOT, Nebraska DOT, New York State DOT, North Carolina DOT, Oregon DOT, Ohio DOT, Pennsylvania DOT, Utah DOT, and Wisconsin DOT, have made significant progress towards effectively managing retaining walls and have developed their own asset inventory and condition rating programs/databases for earth retaining structures (including retaining walls) ([1]). After analyzing 13 inventory and inspection (I&I) programs from the U.S. agencies, the below four categories of information were found to be generally pursued [1, 12]:

1) **Geographical Map** showing the locations of retaining wall systems.
2) **Database** characterizing wall structure components.
3) **Condition Report** documenting present status.
4) **Performance Analysis** checking the changing rates between different conditions.

TABLE 2.C AGENCIES WITH AN INVENTORY AND INSPECTION PROGRAM [1, 3, 13]

Agency*	Inventory or inspection program	Inventory and inspection program	Inventory and inspection in an asset management system	Database	Rating scale
AK DOT	✓	-	✓	GIS	Good,Fair,Poor
British Columbia Ministry of Transportation	✓	✓	✓	DataBC, ArcGIS	Excellent,Good, Fair,Poor,Very Poor
CA DOT	✓	-	-	-	-
Cincinnati	✓	✓	✓	Oracle, ArcGIS	0-4
CO DOT (7,000)	✓	-	-	SAMI	0-9
FHWA and NPS (3,500)	✓	✓	✓	Access	1-10
KS DOT	✓	✓	-	-	-
KY Transp. Cabinet	✓	-	-	-	-
MA DOT	✓	-	-	-	-
MI DOT	✓	-	-	-	-
MN DOT	✓	-	-	-	-
MO DOT	✓	-	-	-	-
NE DOT	-	-	-	-	0-9
N.Y. City DOT (2,000)	✓	✓	-	-	1-7
N.Y. State DOT (2,100)	✓	✓	-	ArcMap	1-7
OH DOT	-	-	-	-	Yes/No
OR DOT (500)	✓	✓	-	Access	Good/Fair/Poor
PA DOT	✓	✓	✓	iForms	2-8
UT DOT	-	-	-	MAP Window GIS, Access	Yes/No
VicRoads Technical Consulting for Victoria Australia	✓	✓	✓	-	1-4

* Number in parenthesis represents the number of RW surveyed.

TABLE 2.D SUMMARY OF BRUTUS AND TAUBER'S INVENTORY AND INSPECTION PROGRAM [1]

Categories of information	**Descriptions**
Preliminary GIS mapping of wall location	• Review highway agency's in-house files of topographic surveys • Review aerial photographs or remote sensing data • Light Detection and Ranging (LiDAR) surveys • The Automatic Road Analyzer (ARAN) surveys • As-built drawings • FEMA flood insurance maps, wetland, and drainage maps • Field visits
Field inventory and build a database	• Wall ID, Location, Function type, Ownership • Dimensions (maximum height, total length, distance from edge of roadway; height of wall at left and right ends, wall face angle or batter, estimated total area of wall face) • GPS readings at midpoint of the wall's length for GIS mapping • Structure type • Wall attachments • Nearby utilities • Consequences of failure (COF, low-moderate-high) • Wall condition observations • Priority rating (low-moderate-high-urgent) • Inspection records and actions taken previously
Create a check list for condition assessment	• Bulges or distortion in wall facing • Severe cracking, and deformation • Severe corrosion of the reinforcement • Sulphate attack on concrete • Some elements not fully bearing against load • Misaligned joints • Cracks or spalls in concrete, brick, or stone masonry • Missing blocks, bricks, or other facing elements, • Settlement behind wall • Blockage of weepholes or outlets of drainpipes • Water leakage from water-carrying services adversely affecting stability • Lack of drainage • Damage from vehicle impact • Overall condition and performance rated 1-5 (critical, poor, fair, good, and excellent) or FHWA NPS WIFG (poor to critical, fair, good to excellent)
Rating system	• Inspection data are brought back to office personnel for review and a decision for future action is made. • Office personnel use the consequences of failure to establish the time frame for repair and future inspection. • Three-level consequence of failure (COF) rating system is suggested by Brutus et al. [1]: severe, significant, and minor

2.2 Retaining Wall Inventory

The North Carolina DOT designed and built its retaining wall information collection and assessment system (WICAS) using a relational database model which collects, organizes, and stores data in the form of tables [11]. They selected the Microsoft Access database management software tool.

Colorado DOT [14] employs a system for asset management and inspection (SAMI) that provides a geo-spatial platform consisting of mobile and in-office components for their retaining and noise wall data inventory.Oregon DOT has developed an Access database with basic information about their retaining walls[15].NYSDOT maintains the statewide retaining wall inventory and inspection data through their AgileAssets Structure Manager System (SMS). Inventory, inspection, and data collection for retaining walls in NY State is detailed in [16].

Various other database systems have been adopted by state and city DOTs, they include: Visidata, Access, SAMI, Oracle iForms, ArcMap and Arc GIS, FoxPro, and DataBC.

As for the data to be included in the database, Brutus et al. [1] proposed a minimum of 9 to be the required data fields, which are

- Identification number
- Location, such as GPS coordinates, highway number and mile point
- Dimension data such as height, length, and approximate face area
- Structural type, such as gravity wall or sheet pile wall
- Function type, such as supporting a roadway embankment or protecting a roadway
- Ownership and maintenance responsibility
- Condition
- Record of inspections and actions taken
- Estimate of replacement cost by dimension and wall-type

New York State DOT organized its retaining wall asset inventory as:

- Wall Status
- Inactivation Reason
- Inventory Edit Status
- Primary Owner
- Region
- Residency
- Route Number
- Reference Marker
- Longitude
- Latitude
- Wall Type
- Wall Backfill Reinforcement Type
- Wall Length

and additional items as described in [16].

More information regarding attributes for retaining wall defined in databases can be found from the state DOTs' project reports.

Chapter 3 Methodology/Data Analysis

3.1 AHP-Weighted Two-part Rating System

The traditional average single-number condition rating has two notable deficiencies [2]. First, the averaged single-number rating could distort the overall condition to supply a false signal on safety by masking the safety-critical problems (e.g., drainage clogging, reinforcement corrosion). Second, the locations of deficiencies could be unnoticed. The research team adopted an objective-weighting based two-part condition rating procedure. This method combines the strengths of typical multifactor weighting method of analytical hierarchy process (AHP) [17] to measure the relative importance of wall elements and Butler's two-part rating method which produces both overall condition and element ratings [2].

1) Concepts of Condition Rating System for retaining walls

Multiple definitions have been available for retaining wall condition rating system. According to DeMarco et al. [4], "An elemental condition assessment and rating system is used to evaluate overall wall condition, identify remedial actions that may be required immediately or soon, and provide condition measures to track performance changes with subsequent inspections. Primary and secondary wall elements are evaluated, as well as the performance of the overall system of wall elements. Primary elements include structural components; secondary elements include subsidiary features of the wall system and surrounding setting that contribute to wall performance." North Carolina DOT took advantage of a comprehensive web-based integrated asset management system (AMS) for retaining walls inventory and assessment. From Butler et al. [2], in addition to collecting and maintaining present and past data records, AMS also contains "condition ratings and performance analyses, and planned and actual work orders, the business processes and associated rules for each asset" using a centralized Oracle database. Butler et al. [2] proposed an improved retaining wall information collection and assessment system (WICAS) which "supports retaining wall data archiving and retrieval for electronic documentation, management, qualitative analysis, and displays in the form of photographs."

As one type of asset management system, Condition Rating System should follow the general principles of asset management. In accordance with Gabr et al. [3], the overall goal of asset management is to recognize and collect the information that is "the most useful, reliable, cost-effective" for informed decisions. The U.S. has identified four priority areas for development to effectively preserve, monitor and manage various assets and facility systems:

- efficient information gathering technologies
- reliable condition rating frameworks
- convenient asset inspection protocols
- asset valuation methods

FHWA [18] report introduces the definitions and motivations of asset management. Key components of Pavement Management Systems and Bridge Management Systems are identified as: data collection and storage, information analysis and strategy development, as well as feedbacks on the systems.

In this project, the condition rating system is designed to fulfill the demand for retaining wall condition assessment method in the state of Tennessee:

- identify the intents, purposes and/or associated utility of retaining wall condition assessment
- define the scope, and contents of condition rating activities
- propose a practical but well-founded condition rating procedure and protocol along with the collection and storage of both numerical rating data and photo image visual data
- interpret the condition rating results

2) Rationale and Principles

Figure 3.2 shows the overview of the inventory, rating, and performance prediction (IRP) system to be developed and implemented for this TDOT research project. The whole system basically covers seven individual modules: raw data, condition rating, wall criticality analysis, dynamic condition prediction, risk analysis, service life, corrective, or preventive action cost. It can be seen from Figure 3.1; condition rating module plays a crucial function in the overall system since this module can provide necessary information for both dynamic condition rating and risk assessment. From literature, multiple federal transportation agencies and/or state DOTs (e.g. FHWA, Alaska DOT, North Carolina DOT, Oregon DOT) have established condition rating systems to examine and rate retaining walls or ERSs [2]. Therefore, there are two optional strategies to deal with condition rating in this project. The first option would be to directly apply one existing condition rating tool to the evaluation of retaining walls in the state of Tennessee if the rating system meets the project requirements and is able to produce objective and reliable rating outcomes. When no such applicable rating systems are available, the second choice is to develop a new condition rating system.

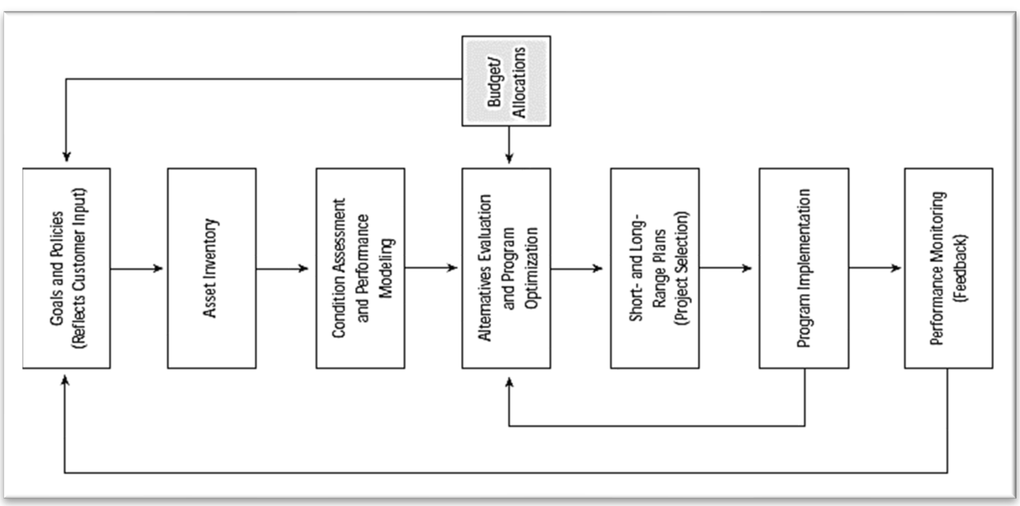


Figure 3.1 General Components of Asset Management Systems [18]

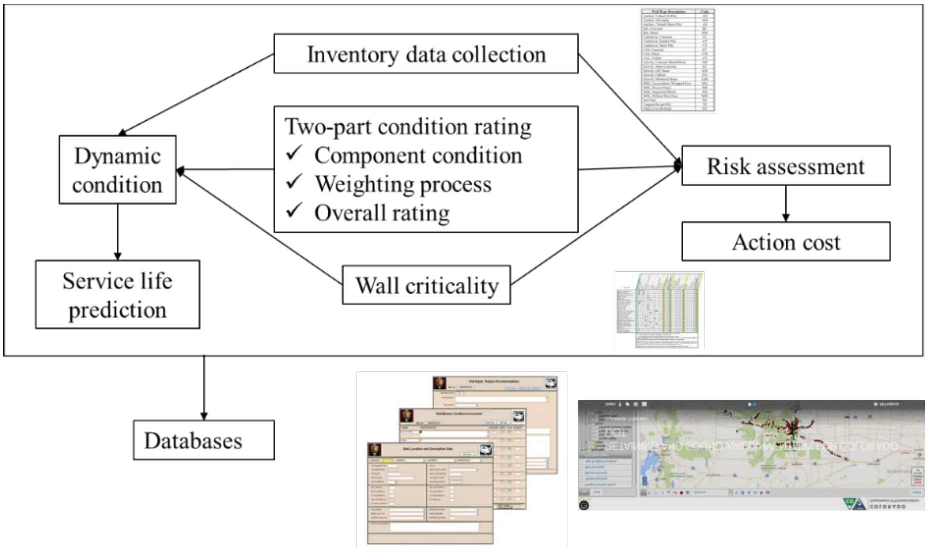


Figure 3.2 IRP System Overview [4]

3) Methodology

According to DeMarco et al. [4], to successfully rate the condition of retaining walls, the following three requirements should be satisfied: "(1) qualified and trained inspecting engineers, (2) a systematic, well-defined, element-based assessment methodology, and (3) a commitment to providing complete, consistent and concise element condition narratives and ratings." These principles will be followed to select the existing systems or develop a new system.

a. Examination of the existing condition rating systems.

The research team carefully examined and compared multiple representative rating systems. Overall, the following common issues of existing systems were identified:

i. Many systems were developed in an ad hoc context without formal justification, definition, or sound explanations.
ii. No unified lists of inventory characteristics were formed. The attributes, coverage, depth, classification criteria differ significantly from one to another without sound explanation. Some programs covered detailed data on geographical, environmental, structural, architectural, and geotechnical aspects [1], while others only considered few characteristics.
iii. Many condition rating methods and practices have observable issues. For example, an aggregated single rating score may mask critical stability, function, and safety issues by ignoring critical distress [2, 3]. This will make the systems less useful. Deeper but convenient methods are needed. Further, the weighting process on measuring the importance of different rating elements is often subjective without a formal judging process. An "arbitrary" weighting scheme has been often adopted. For example, in DeMarco et al.[4], equal weights were applied to all the wall components. Although simple, these important weighting schemes could be somewhat arbitrary which cannot really differentiate the importance of the involved elements.

iv. Most states solely relied on qualitative visual inspections through manual operations which had limitations on cost, accessibility, and safety. An advanced Unmanned Aerial Vehicle (UAV) based technology could be more useful.

ii. Most rating systems only considered static condition rating, where the system will have limited utility in providing information for other important issues of retaining wall systems, such as service life projection, dynamic deterioration, and risk analysis.

b. New Condition Rating System

i. Condition rating system framework

Condition rating system framework proposed in this research is shown in Figure 3.3. There are five major Condition Rating System (CRS) components: determine wall type, identify rating elements, determine numerical scale, define rating criteria, and finally determine element condition rating.

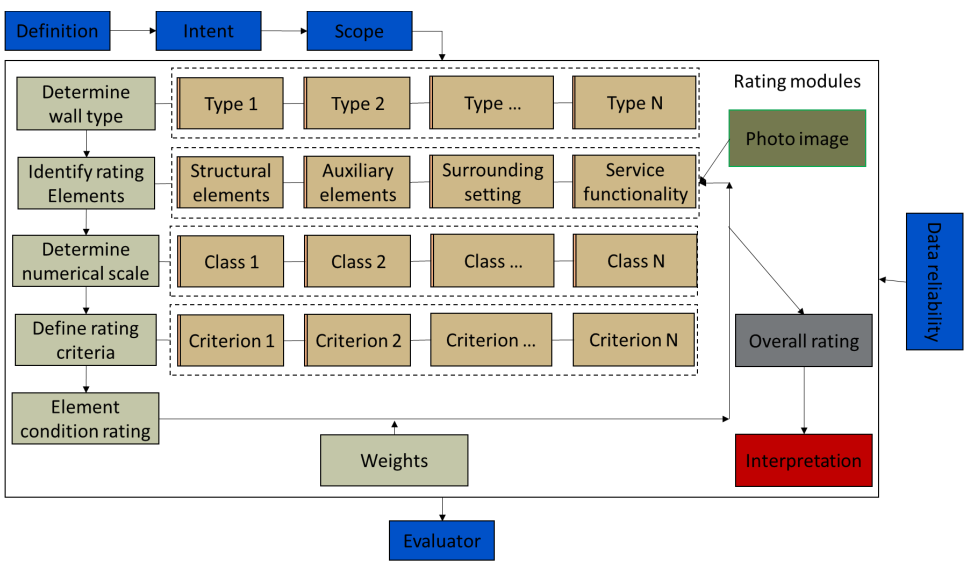


Figure 3.3 Condition Rating System Framework

ii. CRS components

1. Intent

The purpose of introducing this new condition rating system is to overcome the common issues of existing systems, develop a systematic, well-defined, element-based assessment methodology. The new CRS will provide complete, consistent, and concise element condition narratives and ratings, adopt a rational justification of retaining wall element weights, define procedures to compute two-part condition rating scores, and provide both static and dynamic condition rating such as service life projection, dynamic deterioration, and risk analysis.

2. Scope

The objective of this task is to design a unified new condition rating system for rating the condition of retaining walls in the state of Tennessee.

The application scope of the new condition rating system includes:

- Identify various retaining wall types
- Identify wall elements to be rated

- Design numerical rating scales to rate elements
- Define rating criteria and narratives
- Rate wall elements
- Determine weights of wall elements
- Specify procedures to compute overall two-part wall condition ratings
- Define how the final rating results should be interpreted

3. CRS component 1: Wall types
   There are a variety of retaining walls that can be selected depending on the technical feasibility and comparative economy. Wall type determines minimum required wall elements to be rated and rating criteria will not be identical for various wall types. The wall types proposed following TDOT Earth Retaining Structures Manual and FHWA-CFLHD's WIP are listed in Figures 3.4 and 3.5.

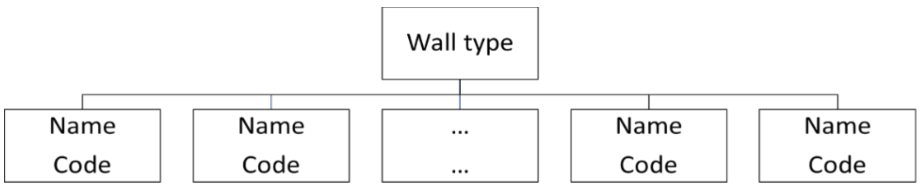


Figure 3.4 Wall Types

4. CRS component 2: Element identification
   Wall elements may be classified as a) structural elements, b) auxiliary elements, c) surrounding setting and d) service functionality/performance (Figures 3.6). Different types of elements are identified in Figures 3.8 to 3.11.

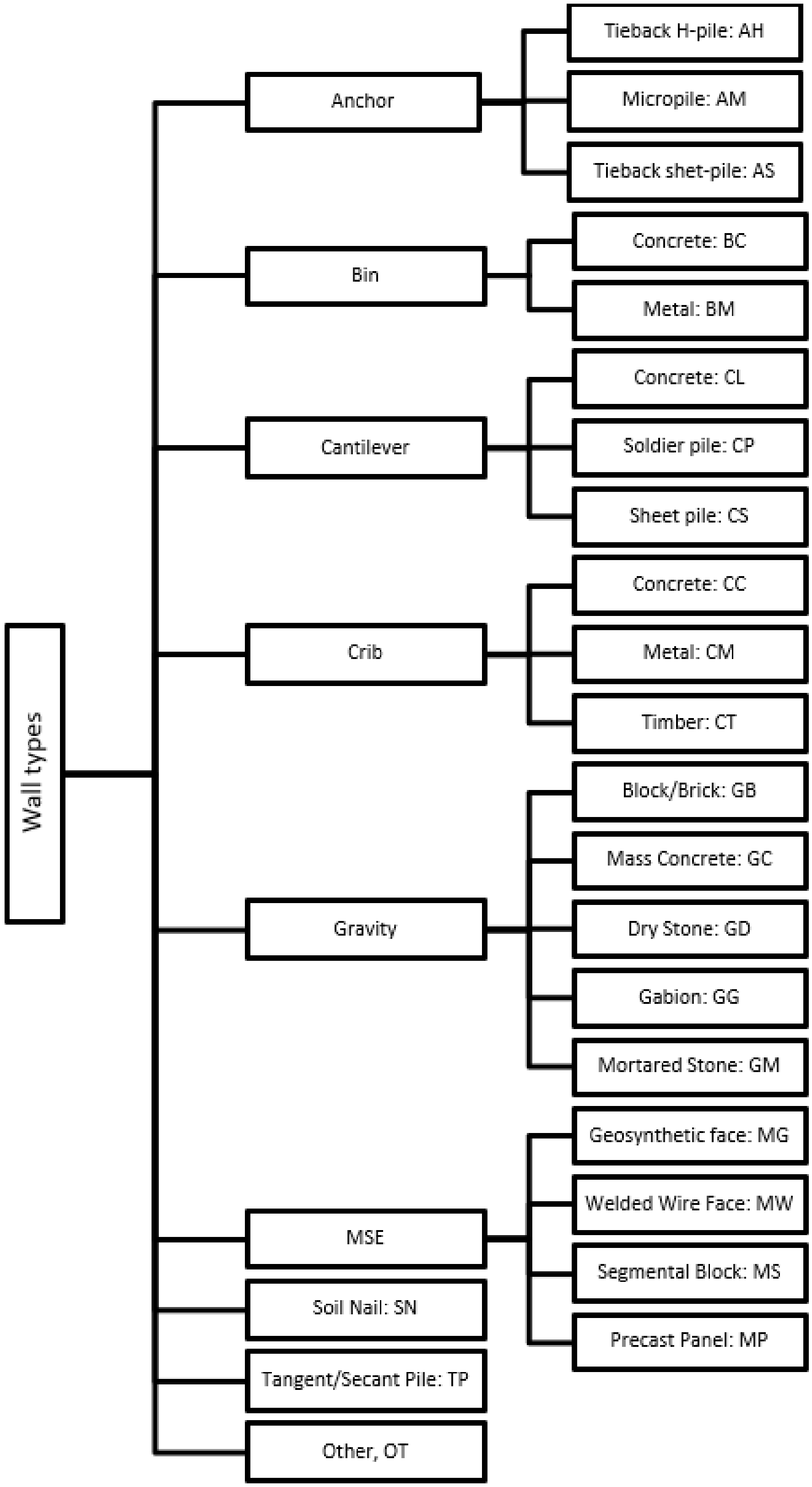


Figure 3.5 Detailed Wall Types

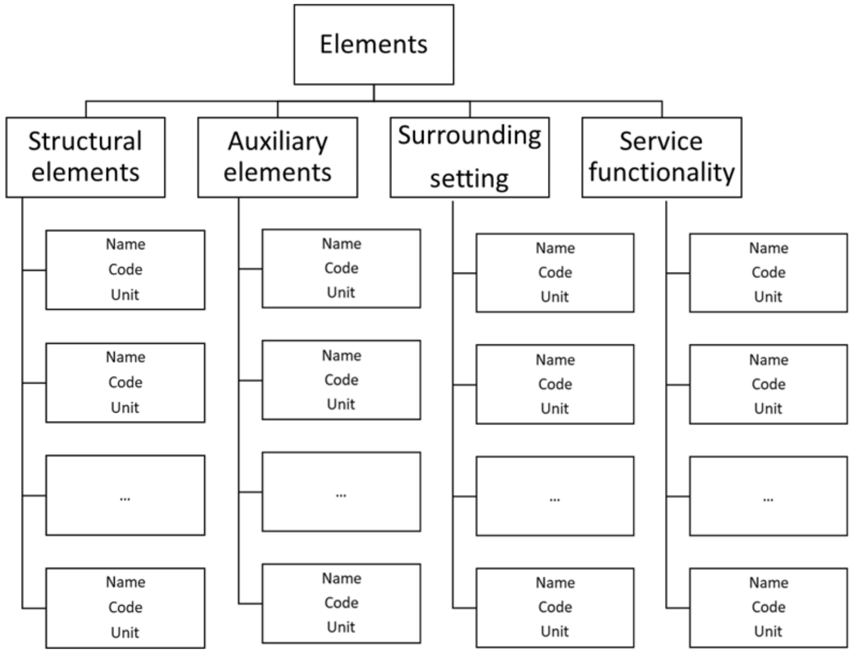


Figure 3.6 Identification of Elements

Depending on the type of wall**,** minimum retaining wall elements to rate were recommended by DeMarco, Keough et al.[4].

WALL TYPE	PRIMARY ELEMENTS	Piles and Shafts	Lagging	Anchor Heads	Wire/Geosyn. Facing Elements	Bin or Crib	Concrete	Shotcrete	Mortar	Manufactured Block/Brick	Placed Stone	Stone Masonry	Wall Foundation Material	Other Primary Element	SECONDARY ELEMENTS	Wall Drains	Architectural Facing	Traffic Barrier/Fence	Road/Sidewalk/Shoulder	Upslope	Downslope	Lateral Slope	Vegetation	Culvert	Curb/Berm/Ditch	Other Secondary Element	WALL PERFORMANCE	Performance
[AH] Anchor, Tieback H-Pile		●	●	●									●			●			○	○	○	●						●
[AM] Anchor Micropile		●		●									●			●			○	○	○	●						●
[AS] Anchor, Tieback Sheet Pile		●		●									●			●			○	○	○	●						●
[BC] Bin, Concrete						●							●			●			○	○	○	●						●
[BM] Bin, Metal						●							●			●			○	○	○	●						●
[CL] Cantilever, Concrete							●						●			●			○	○	○	●						●
[CP] Cantilever, Soldier Pile		●	●										●			●			○	○	○	●						●
[CS] Cantilever, Sheet Pile		●											●			●			○	○	○	●						●
[CC] Crib, Concrete						●							●			●			○	○	○	●						●
[CM] Crib, Metal						●							●			●			○	○	○	●						●
[CT] Crib, Timber						●							●			●			○	○	○	●						●
[GB] Gravity, Concrete Block/Brick									●	●			●			●			○	○	○	●						●
[GC] Gravity, Mass Concrete							●						●			●			○	○	○	●						●
[GD] Gravity, Dry Stone											○	○	●			●			○	○	○	●						●
[GG] Gravity, Gabion					●								●			●			○	○	○	●						●
[GM] Gravity, Mortared Stone									●		○	○	●			●			○	○	○	●						●
[MG] MSE, Geosyn. Wrapped Face					●								●			●			○	○	○	●						●
[MP] MSE, Precast Panel							●						●			●			○	○	○	●						●
[MS] MSE, Segmental Block										●			●			●			○	○	○	●						●
[MW] MSE, Welded Wire Face					●								●			●			○	○	○	●						●
[SN] Soil Nail								●					●			●			○	○	○	●						●
[TP] Tangent/Secant Pile		●											●			●			○	○	○	●						●
[OT] Other, User Defined													●			●			○	○	○	●						●

● Wall elements that should always be rated for the given wall type (others may also apply).
○ 1 of 2 primary wall elements required depending on material observed.
2 of 3 secondary wall elements required depending on wall location relative to roadway.

Figure 3.7 Minimum Retaining Wall Elements to Rate [4]

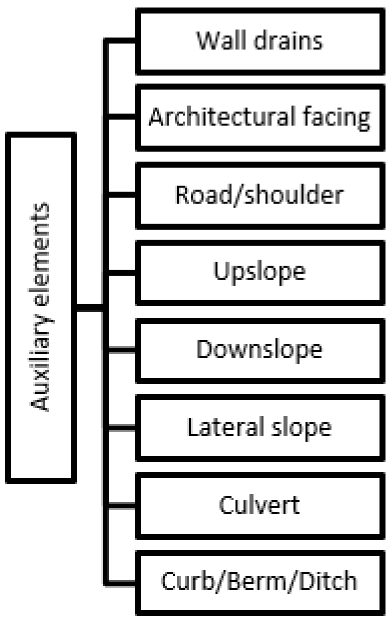


Figure 3.8 Wall Auxiliary Elements

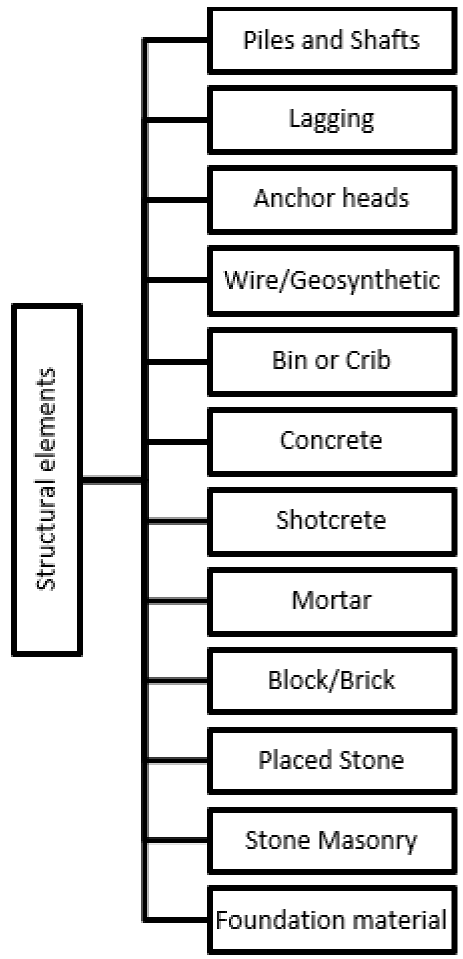


Figure 3.9 Retaining Wall Structural Elements

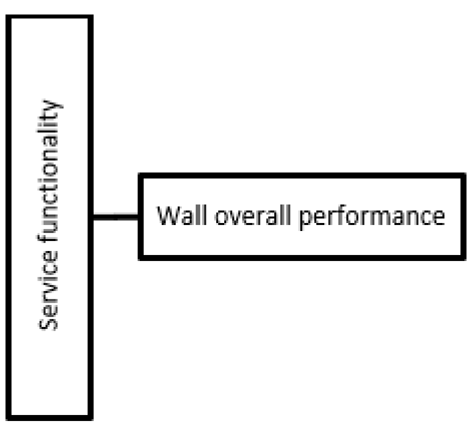


Figure 3.10 Retaining Wall Surrounding Setting

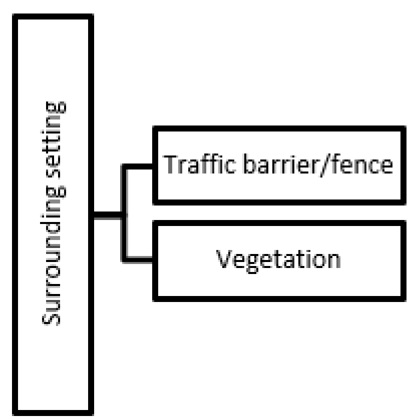


Figure 3.11 Retaining Wall Service Functionality

5. CRS component 3: Numerical rating scale
To evaluate the condition of each element, a rating scheme consisting of a list of condition criteria is established. The condition rating scheme defined by Butler et al.[2, 3] is shown in TABLE 3.A. An individual condition rating value indicates the functional capability of an element.

TABLE 3.A CONDITION RATING SCHEME [2, 3]

Numerical score	Physical condition	Abbreviated criteria	Detailed criteria
4	Good	Low severity extent of distress	No significant severe distress to major structural elements; highly functioning wall elements; only to show first signs of distress or weathering; no immediate/near-term attention is needed
3	Fair	Low to medium extent of distress	Lack of treatment may lead to impaired function or elevated risk of wall failure; distresses needed to be mitigated in near-term to avoid repair in longer term
2	Poor	Medium to high extent of distress	Distress threatens wall function; Element condition does not pose an immediate threat; a marginally functioning, severely distressed wall element in jeopardy of failing without near-term repair or replacement.
1	Severe	High severity distress	Wall element no longer serving its intended function; overall stability of the wall threatened; wall in danger of failing; roadway may need to be closed until wall replaced or stabilized

The condition rating

Numerical rating scales (Figure 3.12) are developed to assess and rate retaining wall elements.

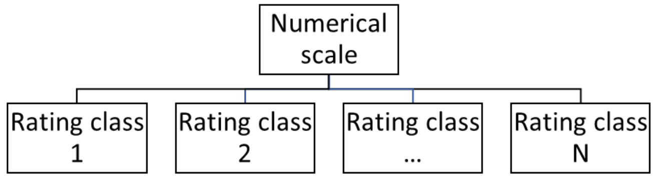


Figure 3.12 Numerical Rating Scale

Multiple existing condition rating scales have been used by different agencies as given in TABLE 3.B.

TABLE 3.B EXISTING CONDITION RATING SCALES

Agency	Rating scale	Definitions
FHWA and NPS	1-10	9-10 Excellent 7-8 Good 5-6 Fair 3-4 Poor 1-2 Critical
New York City/State DOT	1-7	-
Pennsylvania DOT	2-8	-
Nebraska Department of Roads	0-9	-
Oregon DOT	Good/fair/poor	-

The 1-4 numerical rating scale as given in TABLE 3.C is adopted in this research for its simplicity and to be consistent with the 1–4 rating system outlined in AASHTO's Manual for Bridge Element Inspection and with that is proposed by Demarco et al. [4].

TABLE 3.C WALL ELEMENT NUMERICAL CONDITION RATING DEFINITIONS ADOPTED IN THIS PROJECT

Element condition rating	**Rating definitions**
4 Good	• Very low or no distress • Very minor defects within normal range, • highly functioning wall elements
3 Fair	• low-to-medium extent of medium to high severity distress. • Functioning wall elements with specific distresses that need to be mitigated in the near-term to avoid significant repairs or element replacement in the longer term
2 Poor	• Medium-to-high extent of medium-to-high severity distress. Distress threatens element function. The element condition does not pose an immediate threat to wall stability and closure is not necessary. • Marginally functioning, severely distressed wall elements in jeopardy of failing without element repair or replacement in the near-term.
1 Severe	• high severity distress. Element is no longer serving intended function. Element performance is threatening overall stability of the wall at the time of inspection. • A wall that is no longer functioning as intended, and is in danger of failing catastrophically at any time

6. CRS component 4: Rating criteria
   With the numerical rating scales defined, rating criteria (Figure 3.13) or narratives for wall elements of each wall type can then be specified. The rating criteria provide detailed guidelines about how rating scores should be assigned to each individual wall elements considered. Generally, minimum retaining wall elements (Figure 3.7) must be selected before defining wall elements rating criteria or narratives.

   Selected rating criteria for walls commonly used in the state of Tennessee can be found in Appendix Figures B.1 – B.9.

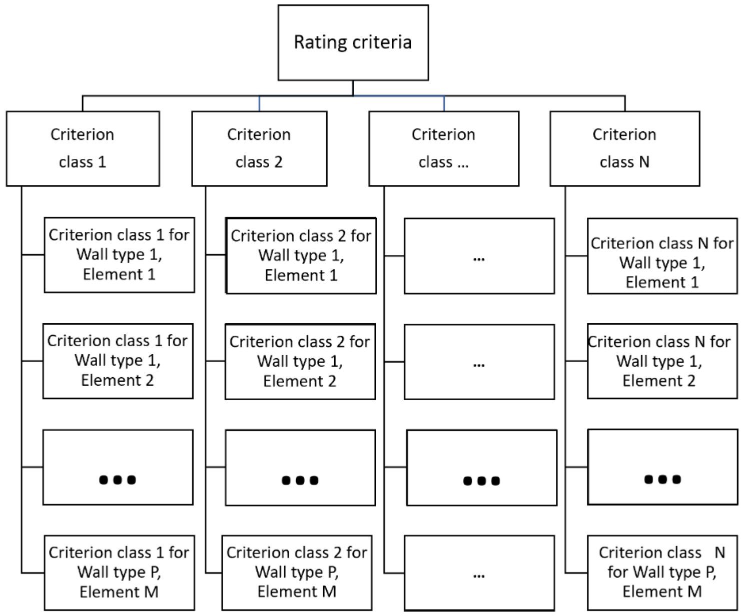


Figure 3.13 Structure of RW Rating Criterion Narrative

7. CRS component 5: Element condition rating
   For the condition rating of retaining walls, four significant aspects including structure, auxiliary, surrounding settings and service functionality are considered. Under each of the four 1st level aspect elements are different 2nd level elements (Figure 3.14). In total, as in Figure 3.14, nine 2nd level elements are assessed for every retaining wall. There may be the next level (i.e., 3rd level elements under some of the 2nd level wall elements. Each individual 3rd level component/element is rated by an objective numerical score following the rating criteria defined previously. Engineers may select important retaining wall elements instead of using what are listed in Figure 3.14 following the minimum retaining wall elements to rate defined in Figure 3.7 by [4] for each specific type of wall.

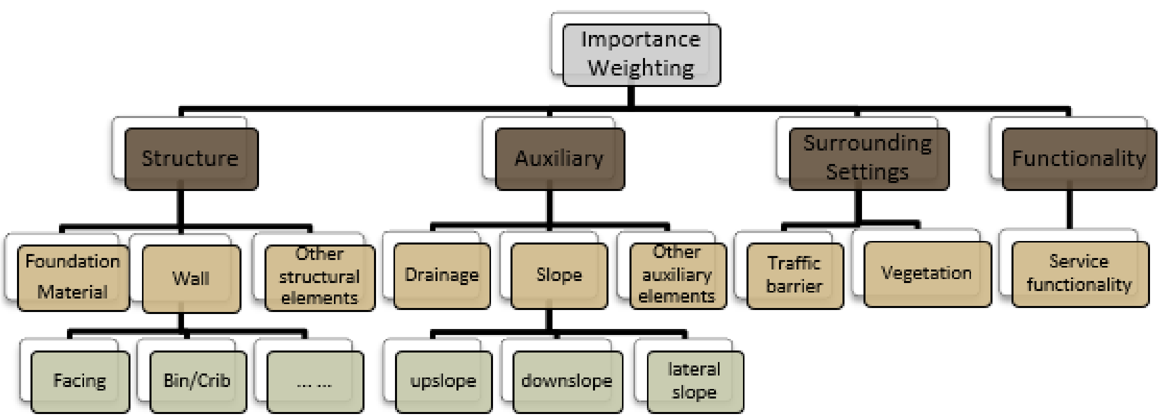


Figure 3.14 Hierarchy of Retaining Wall Elements/Components Elements in brown: major/1st level elements; Beige: 2nd level elements; Matte green: 3rd level elements (not all shown in the flowchart)

3.2 AHP for Wall Element Weights

After each individual component/element is rated by an objective numerical score, the importance weights are assigned to all the elements in terms of function, structure, and safety through AHP method, the overall condition will be indicated by an aggregated score on individual conditions and importance weights.

To differentiate the importance of these ten elements, the weighting factor associated with each element needs to be given. This eventually becomes a multicriteria decision-making problem. To handle this problem, the frequently used semi-quantitative multicriteria decision-making tool AHP is used to assign the importance weights to all the elements under four criteria. According to Saaty [17], AHP can resolve such complex multicriteria problems as importance weighting by structurally transforming them into straightforward pairwise comparisons [19].

Retaining wall condition rating based on AHP is performed in five consecutive steps:
First, it formats the element importance weighting problem into a hierarchy which contains the goal, four condition aspects and associated sub-elements under each aspect (Figure 3.14). Second, a series of pairwise comparison matrices $(a\_ij)_{m\times n}$ (a_ij represents the importance comparison value of alternative *i* relative to *j* among *m* alternatives) is created to show the relative importance between four aspects and among the elements relative to each aspect. The 1-9 scale as shown in TABLE 3.D is used for paired comparisons with 1 indicating equal importance and 9 meaning one aspect is extremely important relative to the other. TABLE 3.E shows the pairwise comparison results of four aspects based on one engineer's inputs.

Third, by normalizations on the pairwise comparison matrices using Equation 3.1, priority vectors are calculated to show the weights of four aspects and the elements under each aspect by Equation 3.2.

$$\overline{a_{ij}} = a_{ij} / \sum_{l=1}^{m} a_{lj} \qquad (3.1)$$

$$w_i = \sum_{l=1}^{m} \overline{a_{il}} / m \qquad (3.2)$$

where $\overline{a_{ij}}$ is normalized a_{ij} and w_i is the weight of alternative i.

TABLE 3.D THE 1-9 PREFERENCE SCALE FOR AHP

Preference level a_{ij}§	**Interpretation**	
1	*i* and *j* * are equally important	Wall elements *i* and *j* are equally important to the safety; both elements have the same impact on stability, functionality, and overall safety of the wall

3	*i* is slightly more important than *j*	Wall elements *i* is slightly more important than *j* to the safety of the wall; element *i* has slightly greater impact on stability, functionality, and overall safety of the wall than element *j*
5	*i* is more important than *j*	Wall elements *i* is more important than j to the safety of the wall; element *i* has greater impact on stability, functionality, and overall safety of the wall than element *j*
7	*i* is strongly more important than *j*	Wall elements *i* is strongly more important than *j* to the safety of the wall; failure of *i* will need immediate attention compare to that of *j*; element *i* has much greater impact on stability, functionality and overall safety of the wall than element *j*
9	*i* is absolutely more important than *j*	Wall elements *i* is absolutely more important than *j* to the safety of the wall; failure of *i* will lead to failure of entire wall while failure of *j* will not cause serious safety concern of entire wall; element *i* has the greatest impact on stability, functionality and overall safety of the wall compare to element *j*

* *i*, *j* are two evaluation criteria

§ a_{ij} is preference level or relative score between two evaluation criteria $a_{ij}a_{ji} = 1$

TABLE 3.E PAIRWISE COMPARISON OF THE 1ST - LEVEL ELEMENTS AND THEIR WEIGHT VECTOR

Wall Components	Pairwise Comparison Matrix				Normalized Matrix A_{norm}				Weight Vector *w*
Structure	1.00	5.00	9.00	3.00	0.608	0.547	0.409	0.662	0.556
Auxiliary	0.20	1.00	7.00	0.33	0.122	0.109	0.318	0.074	0.156
Surrounding setting	0.11	0.14	1.00	0.20	0.068	0.016	0.045	0.044	0.043
Functionality	0.33	3.00	5.00	1.00	0.203	0.328	0.227	0.221	0.245

* The preference scales represent one engineer's opinion only

Vector *w* = $[0.556 \quad 0.156 \quad 0.043 \quad 0.245]^T$ shows the relative importance weights of structure, auxiliary, surrounding settings, functionality. Similarly, weight vectors are obtained for all the elements under each aspect.

Fourth, after obtaining the weights of four aspects and the elements under each aspect, the priority weight of each sub element among all the sub elements can be obtained. To get an overall weight for each element, the weight of an individual sub element under each aspect is multiplied by the weight of its associated aspect. The weight vectors for lower level elements structure, auxiliary, surrounding setting and overall performance are $s^{(1)} = [0.334 \quad 0.111 \quad 0.111]^T$, $s^{(2)} = [0.074 \quad 0.074 \quad 0.008]^T$, and $s^{(3)} = [0.007 \quad 0.037]^T$, respectively.

Notice that the sum of elements in each of the three vectors s is equal to the first three elements in weight vector w, respectively.

From the pairwise comparison of main criteria illustrated in TABLE 3.E, a total of nine lower- or sub- level elements are assessed individually, compared, and rated during the field survey. For each lower-level element, the inspector determines how close to pristine condition the retaining wall element is and assigns a score, on a relative scale of 1-4 – with 4 being the best possible condition. The relative weights of the elements as obtained through the analytic hierarchy process is multiplied by the assigned score to obtain the weighted scores for all the nine considered elements. The overall condition rating of the wall results from an arithmetic sum of all the weighted element scores for each considered retaining wall.

Fifth, to obtain the overall rating of a retaining wall, the relative weights are multiplied by the corresponding assigned rating scores. The composite rating scores [2] derived from the multi-part rating approach are also computed.

3.3 Data Analysis/Markov Chain Predictions

Markov chain has been successfully applied in prediction of the deterioration of bridges, rock slopes and buildings [20, 21]. Markov chain predicts the service life of retaining walls by simulating the deterioration of wall structures with a stochastic approach based on the obtained overall wall rating.

Researchers and engineers have successfully applied the Markov Chain to make predictions of service life of infrastructure. Jiang and Sinha [22] applied Markov chain to predict bridge service life by defining states in terms of bridge condition ratings and obtaining the probabilities of bridge condition transiting from one state to another. Chimba et al. [23] used Markov chain to evaluate service life of pavement markings. Wellalage et al. [24] utilized Markov chain-based deterioration models for predicting future conditions of railway bridge elements.

1) Retaining wall structural deterioration modeling

Deterioration-modeling based techniques have been widely adopted to project the future condition trend and the remaining service life of various transportation assets, e.g. pavements [10, 25].

The analysis of future conditions is a vital component for asset management [18]. Deterioration-modeling based techniques have been widely adopted to project the future condition trend and the remaining service life of various transportation assets, e.g. pavements [25]. Based on previous literature, we will use the stochastic Markov Chain method (Figure 3.15) to simulate the deterioration process of wall systems essentially using equation 3.3:

$$p\,(X_{i+1} = j_{i+1} \mid X_i = j_i, X_{i-1} = j_{i-1}, \ldots, X_1 = j_1, X_0 = j_0) = p\,(X_{i+1} = j_{i+1} \mid X_i = j_i) \quad (3.3)$$

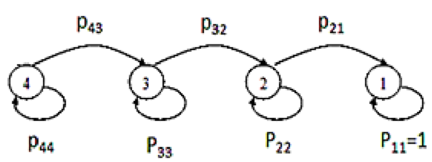


Figure 3.15 Markov Process ***The numbers 1-4 represent conditions; p represents the condition transition probability***

2) Remaining service life projection

At each designated time point, for each wall, the probability in each condition (conditions 1-4) can be calculated based on the current initial condition and transition probabilities (condition change rates). After defining the targeted condition, we can obtain the corresponding time point for this target. The remaining service life from current time point can then be estimated as the time difference between now and the time point corresponding to the targeted condition (Figure 3.16).

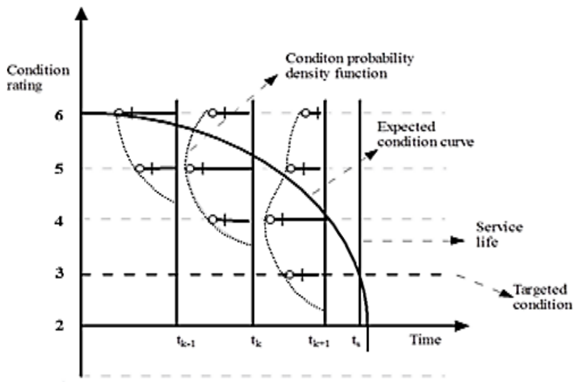


Figure 3.16 Overall Deterioration Profile

The application Markov chain modeling for service life prediction is implemented in four steps.

First, the initial condition of retaining walls is defined based on condition rating with AHP weighting method.

Second, Markovian transition probabilities need to be determined. Due to data unavailability, accurate estimation of a transition probability matrix is impossible. Transition probability matrices in NCHRP report 713 [26] for highway assets and in Morcous et al. [20] for concrete bridge decks for the four environments (benign, low, moderate, and severe environment) allowed us to make a reasonable assumption of transition probability matrix (Equation 3.4) to be used for retaining wall before enough historical data is accessible.

$$p_{jk} = \begin{array}{c} \begin{matrix} 4 & 3 & 2 & 1 \end{matrix} \\ \begin{bmatrix} 0.93 & 0.07 & 0 & 0 \\ 0 & 0.92 & 0.08 & 0 \\ 0 & 0 & 0.9 & 0.1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} 4 \\ 3 \\ 2 \\ 1 \end{matrix} \end{array} \qquad (3.4)$$

where p_{jk} = transition probability matrix from state *j* to *k*

We assume the transition probability matrix for each retaining wall group (*i.e*., ages from 0-6, 7-12, …) remains the same currently. However, it is more appropriate to use specific transition probability matrix for each retaining wall group as noted in Jiang and Sinha [22] when enough data are available.

Third, future condition is predicted based on initial condition and transition probability matrix. For a new retaining wall that is entirely in state 4, the future condition can be predicted by repeatedly multiplying the rated condition by the transition probability as in Equation 3.5.

$$y_k = \sum_j x_j p_{jk} \qquad (3.5)$$

where

y_k = the probability/fraction of state k in the next year

j = condition state in this year $j = 4,3,2,1$ for this project

p_{jk} = transition probability from state j to state k

Fourth, when the fraction in the failed state finally reaches 50% which means half of the wall elements have reached condition rating 1 (maintenance required), the typical life expectancy of the wall is determined.

3.4 Data Collection

3.4.1 In house data collection

The research team initially tried to collect any available in-house data starting from a questionnaire. Due to the lack of records, very few responses have been received. We must rely on field data collection. The questionnaire prepared for this project is given in the following.

3.4.2 Field data collection

1) Unmanned Aerial Vehicle

Pure manual data collection is often constrained by access and safety issues. The adoption of Unmanned Aerial Vehicles (UAV) technology could mitigate these limitations in retaining wall inspection. The research team combined the strengths of manual collection method which may be more accurate and UAV technology for field data collection. The major activities include a kick-off meeting (program overview, safety strategies, scheduling and team policies), field work preparation (forms, equipment, tools, etc.), wall reconnaissance (rough location of walls), systematic field work (detailed visiting, inspecting, data logging and compiling processes and activities), closeout meeting and equipment returning. Particularly, the field data include wall location data, descriptive data, condition rating (overall and element), risk analysis, action assessment and cost estimating.

UAVs have been gaining popularity over past few years with a wide variety of applications in infrastructure monitoring and data collection. A DJI Phantom pro drone with an integrated 20-MegaPixel visual camera (Figure 3.17) was used in this project to assist in collecting retaining wall data in the field. Use of UAV in data collection can overcome the challenge of surveying some retaining walls with large dimensions and/or low accessibility. This in-field survey captures data in the format of pictures and videos using UAV. A total of thirty (30) retaining walls were surveyed within Tennessee. These retaining walls vary in type, age, dimension, and location. The four screening factors used in selecting walls were: along the lines of route, relation to state transportation assets, ease of accessibility and perceived importance.

Figure 3.17 Data Collection Using Drone

In line with the designed rating criteria for different types of retaining walls, a numerical rating scale was developed to evaluate the condition of all the wall elements identified as significant contributors to overall safety. A rating score from 1 to 4 as defined in the previous section is assigned to each retaining wall sub-element depending on the data collected and the detailed criteria defined.

Based on previous literature review and demands of TDOT, the research team identified the flowing data categories to be included in the IRP database: ID numbers, location, dimension, structure type, function, ownership, condition, action records, remaining service life and dynamic conditions predicted by using Markov chain, risk assessment and action cost will also be included in the searchable inventory database.

Data needed was first collected in the office through the highway agency (TDOT in this case) from their as-built drawings. Otherwise, field collection of data will be needed. Modern technologies such as UAVs, digital cameras, infrared camera, LiDAR, and cell phone can be used to assist field data collection without additional effort. The Minnesota DOT has conducted a series of projects [27-29] to use a UAV to inspect bridges in the state of Minnesota. Modern computer-vision based technologies [30] in conjunction with UAVs can also have potentials for infrastructure assessment including retaining wall. The reduced cost of LiDAR makes it possible to make use of the technology in retaining wall assessment and monitoring [31, 32].

As requested from TDOT, geodatabase will be built using ArcGIS. An ArcGIS geodatabase is a collection of geographic datasets of various types held in a common file system folder, a Microsoft Access database, or a multiuser relational DBMS (such as Oracle, Microsoft SQL Server, PostgreSQL, Informix, or IBM DB2).

2) Retrieve retaining walls information by Google Maps

The research team used currently available technologies such as Google Maps and street-view to pin locations (e.g. latitude and longitude) of selected TN retaining walls to assist identifying and screening retaining walls. Other information such as dimensions (e.g. length, and height) may also be possible to be roughly estimated.

A sample Google Map indicating the approximate locations of TN retaining walls is shown in Figure 3.18.

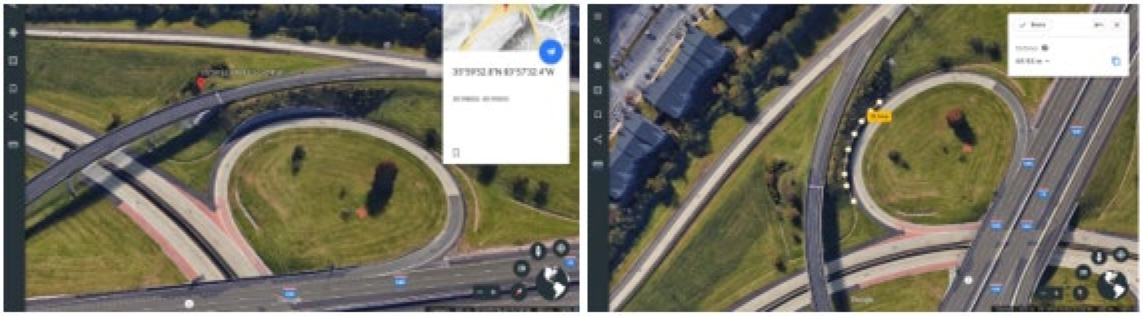


Figure 3.18 An Example of Using Google Earth to Locate and Measure Length of a Retaining Wall on I-75 Northbound Exit Ramp (exit 122A) at SR 61 (N Charles G Seviers Blvd.)

3) Screening Retaining Walls

It is not possible or necessary to survey and inspect all retaining walls in the state of Tennessee. The research team defined criteria that is acceptable to be included within the wall rating and inventory database (TABLE 3.F). The team made decisions on walls to be included in the TDOT inventory and rating database mainly based on the following criteria:

TABLE 3.F RETAINING WALL SCREENING CRITERIA

Criteria	**Description**
Route	Walls should be located on paved interstate HWY, TN highway
Accessibility	Relatively easy to access, will not pose hazards to survey team
RW dimensions	Height of wall must be greater than or equal to 6 ft
RW face angle	Internal wall face angle equal or greater than 45 degree
Relation to TN transportation asset	Is the wall used to protect TN transportation infrastructure?
Importance	Will failure of the wall significantly affect the TN roads and cause loss of life and properties?

4) Retaining wall inspection and field survey form

Following Demarco et al.[4], a field data collection form (appendix Table D.1) was prepared to record data during a field visit. Evidence in the form of descriptive data, photos and videos will be collected to support rating of wall elements. Images and videos are analyzed through image processing technology to identify the critical structure, safety, and function deficiencies. Engineers will rate the conditions of wall elements following criteria defined in the previous sections during and after the field survey.

Chapter 4 Results and Discussion

The research team developed a systematic framework/procedure for retaining wall condition rating, estimating future conditions, remaining service life of TDOT retaining walls. A more rational two-part AHP based weighted rating system for retaining wall elements assessment was created. To facilitate implementation of this new approach for TDOT engineers, the team developed a user-friendly interactive Excel dashboard that can be easily applied for retaining wall condition rating. To align with the standard of TDOT GIS data, a user-friendly searchable inventory database built on ArcGIS linking location, descriptive data, photographs and images, conditions, risks, and associated action costs of each structure was developed in this project. Finally, the research team may also offer an educational workshop to the related stakeholders of TDOT to introduce the developed procedures, skills, tools, and techniques for enhanced application of these project outcomes.

4.1 A Systematic AHP & Markov Model Based Retaining Wall Assessment Procedure

Figure 4.1 depicts the proposed AHP-Markov integrated method for retaining wall condition rating and service life prediction. The method starts with designing a condition rating system and defining specific criteria for rating all the components of a variety of retaining walls. After evaluation criteria are defined, field data are collected in the form of images and videos with the assistance of a drone. Based on field data, the condition rating scores for different retaining wall elements are assigned by civil engineers following the rating criteria defined in the previous step. The major wall elements are broadly divided into structural elements, auxiliary elements, surrounding settings, and service functionality in this project. The 3rd level elements rating scores are derived from field survey data (i.e. descriptive narratives about wall elements condition, images, and videos). The ratings of the 2nd level elements depend on the ratings of wall critical elements. If any critical element received poor (2) or severe (1), the corresponding 2nd level element will be rated as 2 or 1. Otherwise, average of all 3rd level elements' ratings will be applied to the rating score of the 2nd level element. By AHP, pairwise comparisons of these four major or 1st level retaining wall elements and their sub-elements or the nine 2nd level elements are performed, and the relevant weights are derived. An overall condition rating score for the entire wall is finally obtained by weighted aggregation or a composite score obtained by 1) average, 2) the worst, and 3) hybrid. The obtained overall condition rating score is then used as the initial condition for Markov chain modeling. Both future condition and service life can be predicted by applying Markov chain. The four risk levels (negligible, moderate, critical & catastrophic) are assessed based on the amount of traffic to be affected and lost-of-life risk level if the retaining wall failed. Finally, maintenance actions (No action/monitor/maintenance/repair wall elements/replace wall elements/replace wall) will be taken depending on the risk level, the corresponding cost is calculated.

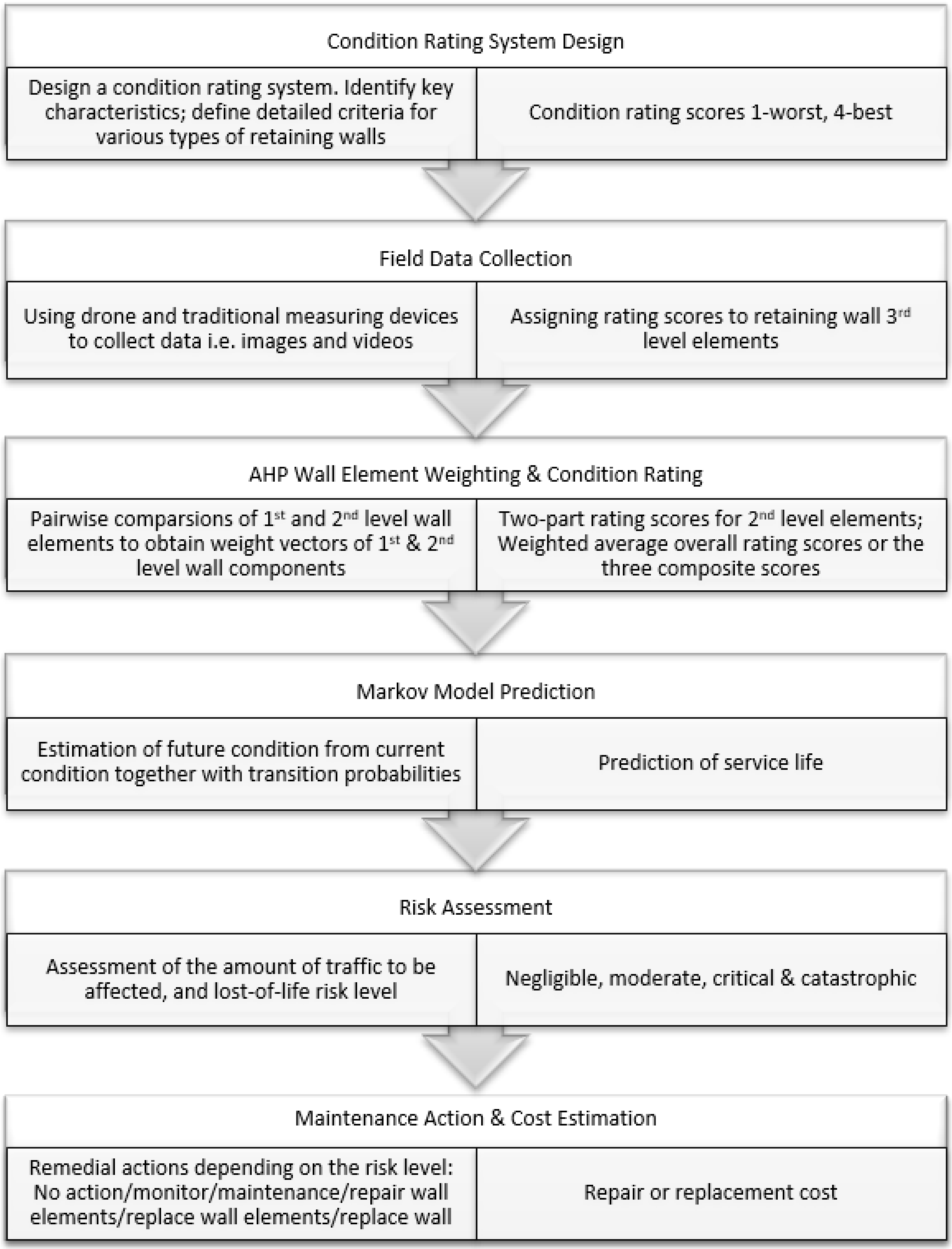


Figure 4.1 A systematic AHP & Markov Model Based Retaining Wall Assessment Procedure

4.2 Two-part AHP Based Weighted Rating System

The research team developed an AHP based weighted rating system (Figure 4.2) using Excel to allow TDOT engineers to rate wall elements easily and conveniently. The Excel based version was later created by referring to the free web based AHP software developed by Goepel[33].

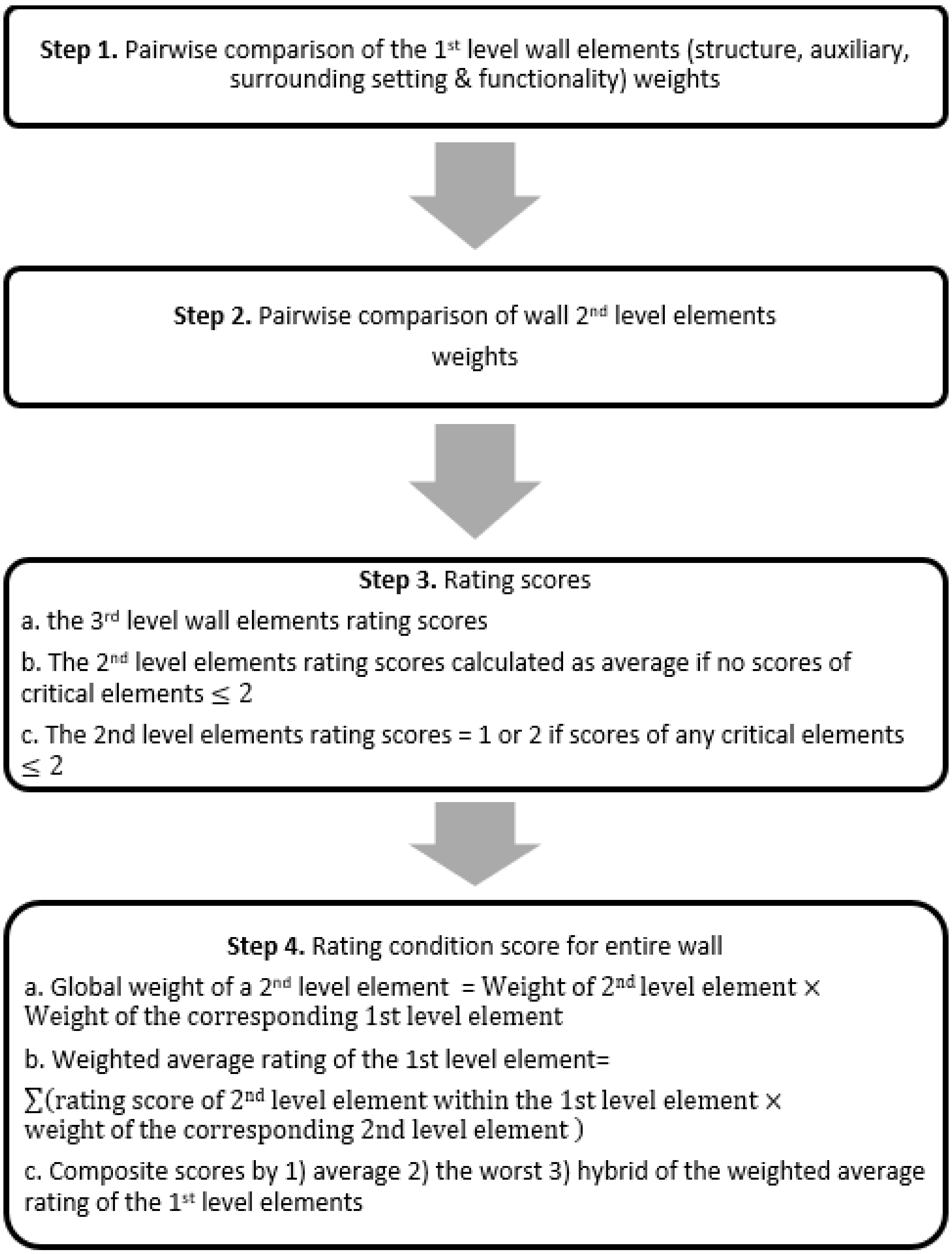


Figure 4.2 Flowchart of the Two-part AHP Based Weighted Rating

1) Development tool selection

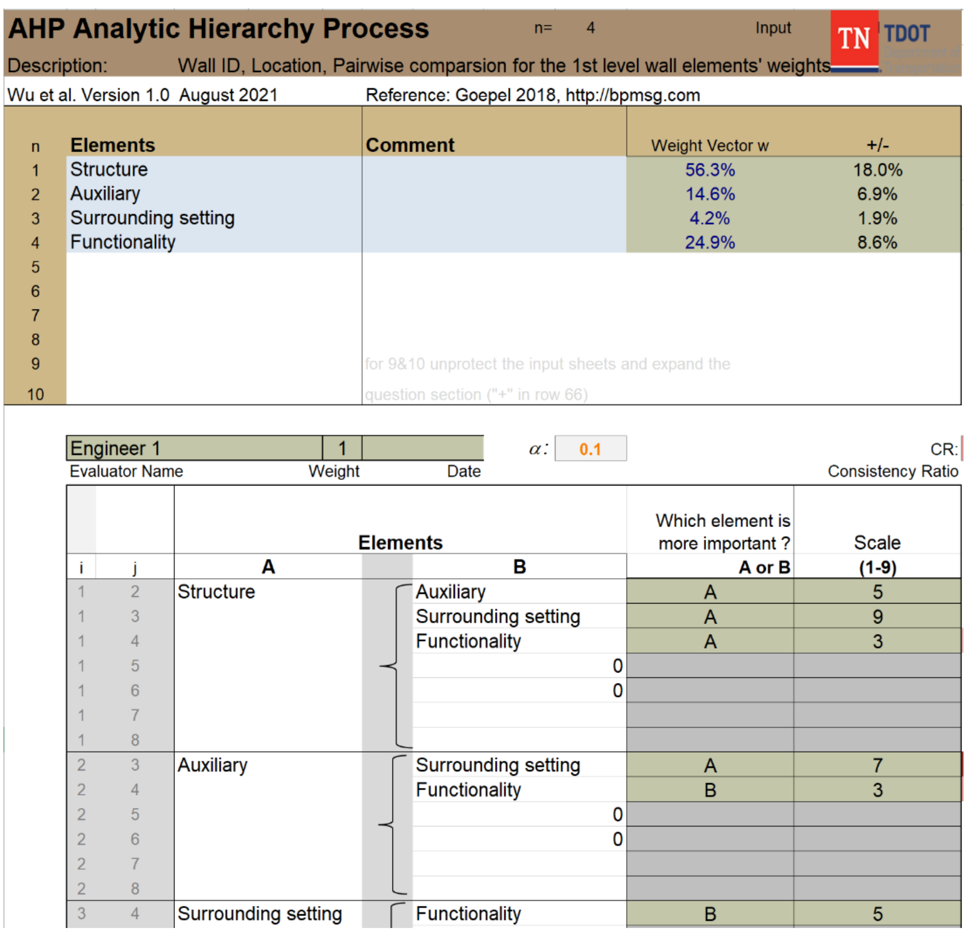
The AHP wall rating application was initially developed using statistics software R. To design and develop a more user-friendly application, the project research team switched to the Microsoft Excel since it is the most widely used and popular software tool. Other factors that lead to this decision are: 1) MS Excel is currently available to most engineers in TDOT and no extra cost is needed, 2) it is user friendly and familiar to most engineers, and 3) the applications created in this research can be further developed as a web-based dashboard.

2) User interface

There are only a few simple steps to follow to use the Excel two-part AHP based weighted rating software.

Step 1. Enter the relative scale between the 1st level wall elements (e.g. structure, auxiliary, surrounding setting and functionality) as shown in Figure 4.3.

For example, enter "A" if element A is more important than element B, a rating scale "5" will be selected if element A- "structure" is more important than element B-"auxiliary". The scale "5" selected following the relative scores defined in TABLE 3.C.



AHP Analytic Hierarchy Process n= 4 Input

Description: Wall ID, Location, Pairwise comparsion for the 1st level wall elements' weights

Wu et al. Version 1.0 August 2021 Reference: Goepel 2018, http://bpmsg.com

n	Elements	Comment	Weight Vector w	+/-
1	Structure		56.3%	18.0%
2	Auxiliary		14.6%	6.9%
3	Surrounding setting		4.2%	1.9%
4	Functionality		24.9%	8.6%
5				
6				
7				
8				
9		for 9&10 unprotect the input sheets and expand the		
10		question section ("+" in row 66)		

Engineer 1 | 1 | — Evaluator Name, Weight, Date; α: 0.1; CR: Consistency Ratio

i	j	A	B	Which element is more important ? A or B	Scale (1-9)
1	2	Structure	Auxiliary	A	5
1	3		Surrounding setting	A	9
1	4		Functionality	A	3
1	5		0		
1	6		0		
1	7				
1	8				
2	3	Auxiliary	Surrounding setting	A	7
2	4		Functionality	B	3
2	5		0		
2	6		0		
2	7				
2	8				
3	4	Surrounding setting	Functionality	B	5

Figure 4.3 Inputs for Pairwise Comparison of 1st - level Wall Elements

Figure 4.4 shows the Excel dashboard summary for the 1st -level wall elements' weights. Number of wall elements (i.e. major elements or sub-elements) n, number of engineers who will rate the same wall N, and the engineer whose results will be displayed *p* should be specified by users in this dashboard. *P* of 0 indicates the consolidated results of all engineers who assessed the wall will be shown on the screen. Default values 1 for scale (different rating scale methods, 1 indicates the 1-9 scale as defined by Saaty) and 0.1 for α (the inconsistency of pairwise comparisons) are recommended.

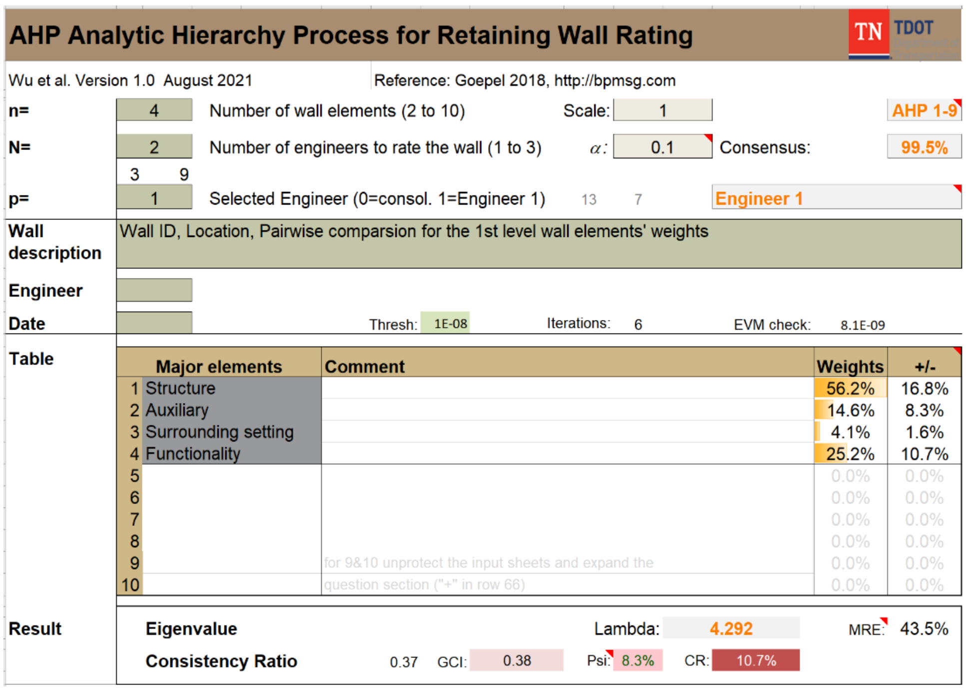


Figure 4.4 Retaining wall Excel Dashboard of Summary for the 1st - level Wall Elements' Weights

Step 2. Enter the relative score between the 2nd - level elements (e.g. foundation materials, wall materials, and other structural elements are three sub-elements of major wall element-structure) as shown in Figure 4.5. For example, enter "A" if element A is more important than element B, a rating scale "3" will be selected if element A- "foundation material" is slightly more important than element B-"wall materials". The scale "3" selected following the relative scores defined in TABLE 3.C.

AHP Analytic Hierarchy Process n= 3 Input

Objective: Pairwise comparsion for structural 2nd-level elements' weights

Wu et al. Version 1.0 August 2021 Reference: Goepel 2018, http://bpmsg.com

n	Elements	Comment	Weight Vector w	+/-
1	Foundation material		60.0%	0.0%
2	Wall		20.0%	0.0%
3	Other structural elements		20.0%	0.0%
4				
10				

Evaluator Name	Weight	Date	α:	CR: Consistency Ratio
Engineer 1	1		0.1	0%

i	j	Elements A	Elements B	Which element is more important ? A or B	Scale (1-9)
1	2	Foundation material	Wall	A	3
1	3		Other structural elements	A	3
1	4				
1	5				
1	6				
1	7				
1	8				
2	3	Wall	Other structural elements	A	1

Figure 4.5 Inputs for Pairwise Comparison of Structural 2nd- level Wall Elements

Figure 4.6 shows the Excel dashboard of summary for structural 2nd - level element weights.

AHP Analytic Hierarchy Process for Retaining Wall Condition Rating

Wu et al. Version 1.0 August 2021 Reference: Goepel 2018, http://bpmsg.com

n=	3	Enter number of wall elements (2 to 10)	Scale: 1	AHP 1-9
N=	1	Number of engineers to rate the wall (1 to 20)	α: 0.1	Consensus: n/a
	3 9			
p=	1	Selected Engineer (0=consol. 1=Engineer 1)	13 7	Engineer 1
Description	Pairwise comparsion for structural 2nd-level elements' weights			
Engineer				
Date		Thresh: 1E-08	Iterations: 9	EVM check: 2.2E-09

Table

	Elements	Comment	Weights	+/-
1	Foundation material		60.0%	0.0%
2	Wall		20.0%	0.0%
3	Other structural elements		20.0%	0.0%
4			0.0%	0.0%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9			0.0%	0.0%
10			0.0%	0.0%

Result

Eigenvalue		Lambda: 3.000		MRE: 0.0%
Consistency Ratio	0.37 GCI: 0.00	Psi: 0.0%	CR: 0.0%	0.0%

Figure 4.6 Retaining Wall Excel Dashboard of Summary for Structural 2nd-level Element Weights

Step 3. Compute composite scores and weighted overall rating scores

a. To determine the composite scores as in [2] and weighted overall rating score for retaining wall, the global weights of the 2nd level elements must be calculated first, which is given by $\text{Weight of 2nd level element x Weight of the corresponding 1st level element}$.

For example, the global weight of the 2nd level element foundation materials within the 1st level element structure = $\text{Weight of foundation material} \times \text{Weight of structure element} = 60\% \times 56.2\% = 33.7\%$.

b. The weighted average rating of the 1st level wall element will be then determined as $\sum(\text{rating score of 2nd level element within the 1st level element} \times \text{weight of the corresponding 2nd level element})$

For example, the weighted average rating of the 1st level element structure $= 4.0 \times 60\% + 2.0 \times 20\% + 2.0 \times 20\% = 3.2$.

c. After the weighted average condition ratings for the 1st - level wall elements are determined, the composite scores will be computed following three different methodologies (i.e., average of the major wall elements' ratings, the worst of the major wall elements' ratings, and the hybrid of the first two methods. That is, given a wall element has a rating not greater than 2, the worst rating will be used as the wall condition score, otherwise, the average score will be selected.

d. As for the weighted overall rating score, it is simply a weighted average of rating score of the 2nd level wall elements. As the example wall shown in Figure 4.7, the weighted overall condition rating score is given by:

$\sum(\text{rating score of 2nd level element} \times$ global weight of the corresponding 2nd level element) $= 4.0 \times 33.7\% + 2.0 \times 11.2\% + 2.0 \times 11.2\% + 3.0 \times 6.9\% + 3.0 \times 6.9\% + 3.0 \times 0.8\% + 2.0 \times 0.7\% + 4.0 \times 3.4\% + 4.0 \times 25.2\% = 3.39$.

The computed composite scores and weighted overall rating score using the Excel based software for the sample wall is shown in Figure 4.7.

Two-part AHP Based Weighted Rating for Retaining Wall TN TDOT

Wu et al. Version 1.0 August 2021

	1st - level element	2nd - level element	Weight of 2nd - level element	Global weight of 2nd - level elements	Rating score of 2nd - level element	Weighted average rating of the 1st - level element	Composite Scores: Rating by average	Composite Scores: Rating by worst	Composite Scores: Rating by hybrid	Weighted Average Rating Score
1	Structure	Foundation materials	60.0%	33.7%	4.0	3.2	3.47	3.00	3.47	3.39
2		Wall	20.0%	11.2%	2.0					
3		Other structural elements	20.0%	11.2%	2.0					
4	Auxiliary	Drainage	47.4%	6.9%	3.0	3.0				
5		Slope	47.4%	6.9%	3.0					
6		Other auxiliary elements	5.3%	0.8%	3.0					
7	Surrounding setting	Traffic barrier	16.7%	0.7%	2.0	3.7				
8		Vegetation	83.3%	3.4%	4.0					
9	Functionality	Functionality	100.0%	25.2%	4.0	4.0				

Figure 4.7 Retaining Wall Excel Dashboard of Two-part AHP Based Weighted Rating for Aggregated Condition Score

4.3 Markov based dynamic condition and service prediction

Dynamic condition prediction, remaining service life estimate, and risk analysis, can assist TDOT in preventing catastrophic failures, allocating budget, prioritizing, and planning inspection. The development of user-friendly computer tools makes practical implementation of the findings from this research straightforward.

1) Service life prediction

The future conditions of a new retaining wall forecasted by applying Markov chain following Equation 3.5 are shown in Figure 4.8. The fractions in the table represent probabilities of wall remaining in the corresponding condition states. When the fraction in the failed state finally reaches about 50%, which means half of the wall elements have reached condition rating 1 (maintenance required), the typical life expectancy of the wall is determined. In figure 4.8, the highlighted percentage indicates 49.3% (i.e., approximately 50%) of the wall will reach condition state 1 at year 32.

Markov Model For Prediction of Retaining Wall Service Life TN TDOT

Wu et al. Version 1.0 August 2021 Ref: NCHRP, 2012

Markov transition probability matrix *P*

State Today	**State probability in one year** 4	3	2	1
4	0.93	0.07	0	0
3	0	0.92	0.08	0
2	0	0	0.9	0.1
1	0	0	0	1

Future condition forcasts

Year	**Percentage by condition state (%)** 4	3	2	1
0	100.0	0.0	0.0	0.0
1	93.0	7.0	0.0	0.0
2	86.5	13.0	0.6	0.0
3	80.4	18.0	1.5	0.1
4	74.8	22.2	2.8	0.2
5	69.6	25.6	4.3	0.5
30	11.3	22.0	21.7	45.0
31	10.5	21.0	21.3	47.2
32	9.8	20.1	20.8	49.3
33	9.1	19.2	20.3	51.4
34	8.5	18.3	19.8	53.4
35	7.9	17.4	19.3	55.4

Figure 4.8 Retaining Wall Excel Dashboard for Service Life Prediction

2) Dynamic condition rating/remaining service life prediction

The research team proposed estimating the future condition ratings at years 10, 30, and 50 or anytime in need. Figure 4.9 shows the Excel dashboard that may be used for predicting the dynamic condition ratings of retaining wall at any time. With the transition probability matrix defined in the dashboard for predicting service life, TDOT engineers only need to define the initial state vector Q and the years when the condition ratings need to be estimated (i.e., those cells in green). This Excel spreadsheet may also be used to estimate the remaining service life if no maintenance or repair action is taken, which can be easily done by changing year *t* until the estimated condition score reaches approximately 1.0 (poor).

Markov Model For Prediction of Retaining Wall Dynamic Conditions				
Wu et al. Version 1.0 August 2021		Ref: NCHRP, 2012		
Condtion rating score vector				
R = [	4	3	2	1]
Initial state vector Q				
Q = [	0	1	0	0]
Year *t*				
t =	5			
t_{10} =	10			
t_{30} =	30			
t_{50} =	50			
State vector @ year *t*				
Q_t = [	0.00	0.66	0.27	0.07]
Q_{t10} = [	0.00	0.43	0.34	0.22]
Q_{t30} = [	0.00	0.08	0.16	0.76]
Q_{t50} = [	0.00	0.02	0.04	0.94]
Estimated condition score @*t*				
S_t =	**2.6**			
S_{t10} =	**2.2**			
S_{t30} =	**1.3**			
S_{t50} =	**1.1**			

Figure 4.9 Retaining Wall Excel Dashboard for Predicting Dynamic Conditions and Remaining Life

4.4 Searchable GIS Inventory Database

1) Mapping of retaining walls

The research team used the Geotech Project Microsoft Access database and managed to identify some of the existing retaining wall locations and their geographical coordinates (latitude and longitude) as shown in TABLE 4.A using Google Map/Google Earth. Unfortunately, the TDOT Geotech database did not specify the exact location of the retaining walls built, the research team had to locate the walls by limited information from the description of retaining walls in the database. The geographical coordinates for the walls given in the table only indicate the approximate locations. And the dimensions shown in the table are measured roughly using the tool in Google Map and they are not exact.

TABLE 4.A RETAINING WALLS RETRIEVED USING GOOGLE MAP

S/N	Location	Geographical coordinates	Length (ft)	Min. height (ft)	Max. height (ft)
1	Briley Pkwy, Nashville, TN	36°13'39.87"N,	1020	4.3	18
2	Church Street, Nashville, TN	36°09'27"N,	173	3.1	9.4
3	Briley Pkwy, Nashville, TN	36°13'45.63"N,	1811	5.2	19.9
4	Elm Hill Pike, Nashville, TN	36°09'06.00"N,	688	4	16
5	Ellington Pkwy, Nashville, TN	36°09'10.28"N,	534	5	15
6	Ellington Parkway, Nashville,	36°12'18.34"N,	701	6	21.69
7	Downtown Chattanooga,	35°02'46"N,	304	3	9
8	West 4th street, Chattanooga,	35°03'09.52"N,	1179	5	19
9	Signal Mountain Road,	35°04'06.85"N,	656.4	2.14	15.64
10	Signal Mountain Road,	35°04'14.56"N,	991.52	1.97	12.13
11	Old Broadway Road,	36°00'54.64"N,	2177.8	2	7.64
12	East Brainerd Road, 9302 TN-	35°00'16.98"N,	463	2.2	8
13	Mountain Creek Road, TN	35°05'02.42"N,	435.29	5.2	19
14	Mountain Creek Road, TN	35°04'59.36"N,	1114	4	18
15	N Grundy Quarles Hwy,	36.3724368N,	243	8	21
16	2nd Avenue Road, Nashville,	36.1470647N,	2217	5	17
17	I40, Nashville, TN	36.1584132N,	254.28	2.3	9.5
18	I840, Arrington, TN	35.8466511N,	367	5.3	12
19	Buship Hollow, Pleasant	36.3525019N,	928	4.7	18.2
20	Sycamore Road, Nashville, TN	36°04'39"N	1419.1	2.8	13.7
21	Courtyard By Marriott,	35.0733395N,	1029.8	3	9
22	1447, TN-6, Brentwood, TN	35.9815418N,	370	3	11
23	Kirby Whitten Pkwy, BarTLett,	35.2443446N,	556.65	2.7	9.42
24	55FX+26 Nashville, Tennessee	36°10'21.3"N	73.83	2.5	11
25	668F+CQ Nashville, Tennessee	36°12'57.7"N	608.3	3	9
26	Hillsboro Pike, Nashville,	36°07'02.5"N	350	4	7.5
27	I440, Nashville, TN	36°07'07.64"N,	1728	1	14.72
28	Four-Forty Pkwy, Nashville, TN	36°07'08.10"N,	1153	1	16.6
29	Four-Forty Pkwy, Nashville, TN	36°07'28.63"N,	750	4	9
30	Briley Pkwy, Nashville, TN	36°11'22.76"N,	412	4	19
31	Hermitage Avenue, Nashville,	36°09'16"N	365	4	16
32	Mulberry Street, Nashville, TN	36°08'58.92"N,	488	7	14
33	4th Avenue Street, Nashville,	36°09'02.61"N,	296	2	10
34	Elm Hill Pike, Nashville, TN	36°09'08.07"N,	313	4	7
35	Briley Pkwy, Nashville, TN	36°08'52.19"N,	1567	3	15
36	Briley Pkwy, Nashville, TN	36°08'55.55"N,	689	2.5	18
37	Ellington Pkwy, Nashville, TN	36°12'34.46"N,	976	6	11
38	Ellington Pkwy, Nashville, TN	36°12'21.40"N,	425	5	10
39	Ellington Pkwy, Nashville, TN	36°12'11.20"N,	610	8.2	16
40	GRMM+G5 Jellico, Tennessee	36°32'01.7"N	821	3	17.5
41	6RGX+P6 Rocky Top,	36°13'36.6"N	777	14.7	1
42	US-174, Chattanooga	35° 01'57.12"N	1100	18.1	6.2
43	US-174, Chattanooga	35° 03'32.52"N	280	9.2	2.1
44	Off Bonny Oaks Dr to US174,	35° 03'38.82"N	431	9.4	2.5
45	Off Bonny Oaks Dr to US174,	35° 03'35.49"N	317	6.1	1.1

46	US-74, Chattanooga	35° 01'38.70"N	120	13.4	4.1
47	US-74, Chattanooga	35° 01'41.77"N	200	13.4	4.1
48	US-74, Chattanooga	35° 01'28.76"N	376	12.9	3.4
49	900, Birgham highway,	34° 59'47.89"N	40	14.9	3.2
50	US 74, Chattanooga	35° 01'26.27"N	115	15.1	3.1
51	1136 TN- 8, Chattanooga	35° 04'40.52"N	85	8.9	2.6
52	US-27, Chattanooga	35° 04'48.50"N	550	8.6	8.6
53	US-27, Chattanooga	35° 04'48.46"N	560	14.5	7.2
54	9320 TN-320, Chattanooga	35° 00'16.36"N	700	9.1	2.9
55	TN-153, Chattanooga	35° 02'03.64"N	490	8.7	3.8
56	TN-153, Chattanooga	35° 02'12.66"N	403.5	14.6	4.2
57	TN-153, Chattanooga	35° 04'50.97"N	462	15.2	4.3
58	TN-153, Chattanooga	35° 04'51.20"N	360	12.8	4.3
59	TN-153, Chattanooga	35° 05'07.61"N	310.6	13.1	4.5
60	Old Ring Road, East Ridge,	35°00'32.18"N,	542	4.2	11
61	Riverside Drive, TN-58,	35°03'04.53"N,	242	4.3	9.2
62	Signal Mountain Road,	35°05'02.25"N,	365	5.8	14.1
63	Downtown Chattanooga, TN-27	35.0535354°,	228	4.1	12.9
64	Trinity Lane, Gatlinburg, TN	35°43'27.26"N,	201	2.2	8.1
65	Trinity Lane, Gatlinburg, TN	35°43'35.49"N,	163	2.1	7.8
66	Trinity Lane, Gatlinburg, TN	35°43'35.26"N,	274	3.1	9
67	Trinity Lane, Gatlinburg, TN	35°43'34.87"N,	682	5.2	17
68	Trinity Lane, Gatlinburg, TN	35°43'42.91"N,	404.3	4.2	21.2
69	Haywood Lane, Antioch, TN	36°04'11.16"N,	957	5.4	18.1
70	George L David Blvd, Nashville,	36°09'43.99"N,	430.21	3.5	11.7
71	Saunders Avenue, Madison,	36°14'14.90"N,	844	4	12
72	Saunders Avenue, Madison,	36°14'17.79"N,	1270	3	13
73	Madisson, Nashville, TN	36°14'32.92"N,	450.65	12.5	4.1
74	1591 TN-106 - Hillsboro Rd,	35°58'13.72"N	560	18	4
75	I-65, Brentwood, Tennessee	35°57'58.03"N	230	13	3
76	TN-100, Fairview, Tennessee	35°56'21.61"N	260	10	3
77	Thompson's Station,	35°49'04.55"N	195	9	3
78	TN-106, Franklin, Tennessee	35°55'46.86"N	615	20	6
79	James White Pkwy, Knoxville, TN	35°57'50"N	855	24	5
80	James White Pkwy, Knoxville, TN	35°57'51"N	893	15	3
81	James White Pkwy, Knoxville, TN	35°57'56"N	904	24	5
82	James White Pkwy, Knoxville, TN	35°57'48"N	420	20	3
83	James White Pkwy, Knoxville, TN	35°57'45"N	450	21	3
84	James White Pkwy, Knoxville, TN	35°58'11"N	184	9	2
85	James White Pkwy, Knoxville, TN	35°58'52"N	503	17	3
86	James White Pkwy, Knoxville, TN	35°58'58"N	248	8	2
87	Hwy 25, Knoxville, TN	36°00'16"N	948	17	4
88	Hwy 25, Knoxville, TN	36°00'23"N	1170	10	3
89	Hwy 25, Knoxville, TN	36°00'20"N	628	12	3
90	Hwy 25, Knoxville, TN	36°00'29"N	653	11	4
91	Hwy 25, Knoxville, TN	36°00'56"N	2122	14	4
92	I-75, Knoxville, TN	35°56'39"N	1061	14	3
93	W Town Way, Knoxville, TN	35°55'40"N	1162	12	3
94	I-40, Knoxville, TN	35°56'56"N	638	9	4

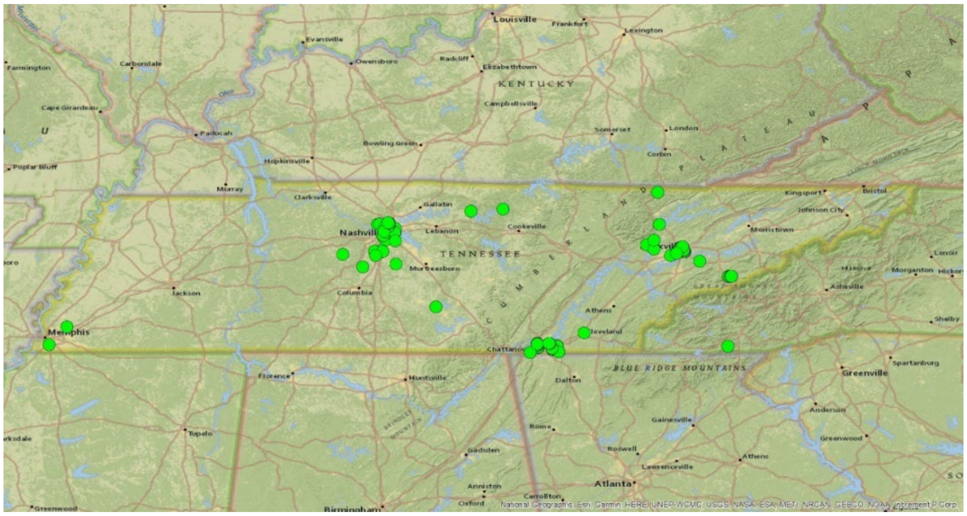


Figure 4.10 ArcGIS Mapping the Locations of Some of the Existing Retaining Walls in the State of Tennessee

2) GIS database

a. Database components:

Based on literature review, expert interview (e.g., Professor Jensen from University of Nebraska-Lincoln) and customized to the demands of TDOT, the research team identified the data categories that need to be included in the IRP database. Based on Brutus et al. [1], at least eight (8) types of data will be collected, i.e., identification number, location, dimension, structure type, function, ownership, condition, and action records. The team created about 50 data fields based on the consolidated list of 96 data fields in the existing wall systems. In addition, based on the needs of TDOT, the data field of “remaining service life” was added.

Risk assessment is rated based on the consequences of failure indicating the possible risk and damage increase when the walls collapse and their current conditions.

Moreover, dynamic conditions (after 10 years, 30 years, and 50 years) and action cost were included as well to provide more comprehensive information for planning, prioritizing, scheduling, and budgeting the repairing, rehabilitation, and maintenance of wall systems.

Following the TDOT concrete barrier wall ArcGIS database layer, The Geographic Coordinate System “GCS_North_American_1983” was used when creating the retaining wall database.

The research team decided to include the weather data (i.e. Precipitation, Minimum temp, Mean temp, Maximum temp, Mean dewpoint temp, Minimum Vapor-pressure deficit (VPD), Maximum VPD) in the database since there are potential impacts of climate change on retaining wall condition [34].

b. Types of data:

Data types (e.g., numerical data, descriptive data, or graphical image) will be determined by the nature of the investigated items and the demands of TDOT. They are listed in TABLE 4.B.

TABLE 4.B RETAINING WALL ATTRIBUTES DATA FIELDS IN ARC GIS INVENTORY DATABASE

Item	Data Type	Description
Survey log data		
Wall ID	Double	TBD, suggest starting with county such as 33XXXX for any RW in Hamilton County
County	Str	County ID i.e., 33 for Hamilton
Route name	Str	
Location (Latitude and Longitude)	Double	
Wall ownership	Str	
Approximate Year built	Double	
Last inspection date	Double	
Weather data (10-year average)		
Precipitation	Double	
Ppt (total precipitation)	Double	
Tmin	Double	
Tmax	Double	
Tmean(mean temperature)	Double	
Tdmean (mean dew point	Double	
VPDmin (Vapor Pressure Deficit)	Double	
VPDmax	Double	
Vapor Pressure Deficit (VPD)	Double	
Description data		
Function	Str	fill, cut, head, bridge, slope protect
Type	Str	
Measurement data		
Length	Double	
Face area	Double	
Min height	Double	
Maximum height	Double	
Face angle	Double	
Vertical offset	Double	
Structural elements		
Foundation	Str	Site visit comments
Foundation rating	Double	Condition rating score
Wall	Str	
Wall rating	Double	
Other structural elements	Str	
Other structural elements rating	Double	

Auxiliary elements		
Slope	Str	
Slope rating	Double	
Drainage	Str	
Drainage rating	Double	
Other auxiliary elements	Str	
Other auxiliary elements rating	Double	
Surrounding settings		
Traffic barrier	Str	
Traffic barrier rating	Double	
Vegetation	Str	
Vegetation rating	Double	
Service functionality		
Wall overall performance	Str	
Wall overall performance rating	Double	
Images	Str	Hyperlinks to photos collected in the field as evidence stored in geodatabase, may include multiple fields
Img1		
Img2		
Img…		
Overall rating scores		
Weighted average rating score		
Composite score - average		
Composite score - worst		
Composite score - hybrid		
Predicted condition ratings @ 10 years	Double	
Predicted condition ratings @ 30 years	Double	
Predicted condition ratings @ 50 years	Double	
Remaining service life	Double	
Wall Action/Assessment/Repair Recommendations		
Failure consequence	Str	Catastrophic, Critical, Marginal,
Recommended Action	Str	No action/monitor/maintenance/repair wall elements/replace wall
Repair Cost	Double	

c. File geodatabase

i. Tool and geographic coordinate system

To meet the IT standards and requirements from TDOT, file geodatabase is built via commonly used tool ArcMap version 10.8.1 with "GCS_North_American_1983" as the geographic coordinate system.

Following an existing TDOT concrete barrier wall ArcGIS database[35], a file geodatabase was created by the research team that maps locations of the retaining wall identified so far, and key characteristics of the retaining wall are added into the database as attribute properties (TABLE 4.B).The information of retaining wall currently stored in the layer was collected mainly using Google Map, the wall dimensions (length and height) were estimated by computer tool and they may not be exact.

ii. How the geodatabase was built

The process to create a queryable ArcGIS feature class layer for retaining wall is shown in Figure 4.10 and an attribute table (Figure 4.11) that contains several wall characteristics (ID, locations etc.), field survey data, condition ratings and predicted service life, as well as pictures from site visits.

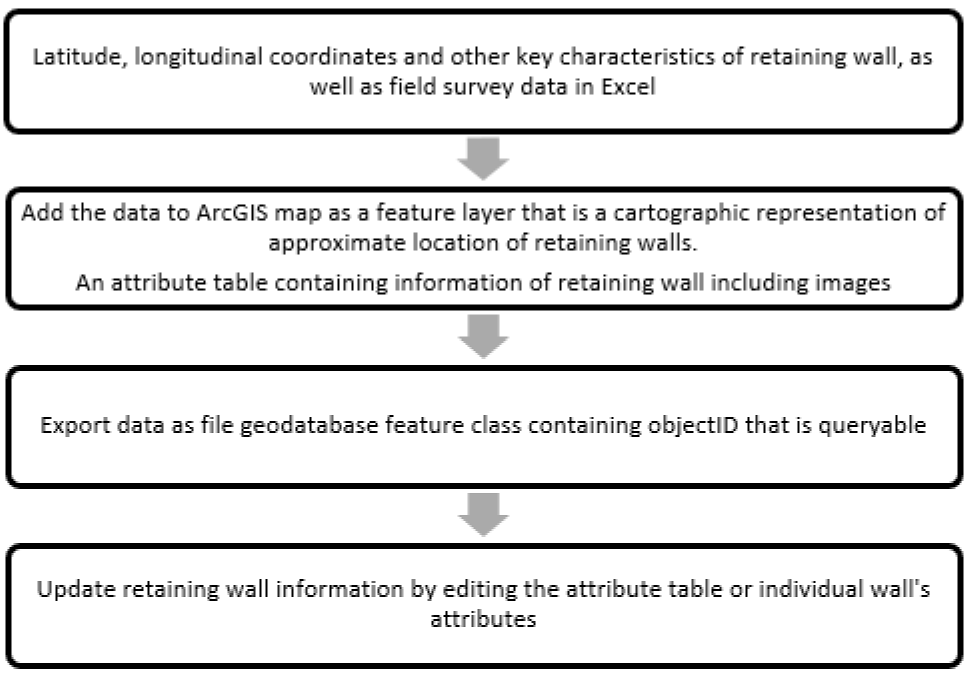


Figure 4.11 Process to Build a Retaining Wall ArcGIS Queryable Feature Class Layer

SR027

Wall_Drains_Rating	4
Down_Slope	Good
Down_Slope_Rating	4
Lateral_Slope	Good
Lateral_Slope_Rating	4
Upslope	Good
Upslope_Rating	4
Traffic_Barrier	Good
Traffic_Barrier_Rating	4
Vegetation	Good
Vegetation_Rating	4
Overall_Performance	Excellet
Overall_Performance_Rating	4
Weighted_Average_Overall_Rating	4
Composite_score - average	4
Composite_Score - Worst	4
Composite_Score - Hybrid	4
Remaining_Service_Life_years	100
Overal_Performance	Good
Overal_Performance_Rating	4
Img1	
Img2	
Img3	
Img4	
Img5	
Predicted_Condition_Ratings_After_10_30_50_Years	4,3.5,3,2
Remaining_Service_Life	100
Failure_Consequence	Catastrophic
Recommended_Maintenance_Action	No action needed
Repair_Cost_dollar	$1.00

Figure 4.12 Retaining Wall Attribute Table for A Sample Wall Not All Fields Shown

The data currently available in the feature layer and attribute table include data collected from selected retaining wall the research team visited and the basic information of location, length, and height for the rest of the walls were obtained using Google Maps. The research team visited a total of thirty-retaining walls across the different regions in the state of Tennessee.

After the retaining wall data was imported into ArcMap, each retaining wall will be displayed in the layer by a symbol that can be customized as different shapes and sizes (Figure 4.12). After the database being deployed, the properties of a wall will be displayed as a table of visible fields when users click the symbol of a wall. With the objectID generated by ArcGIS, the database is searchable/queryable by selecting using a single or multiple key characteristic of a wall.

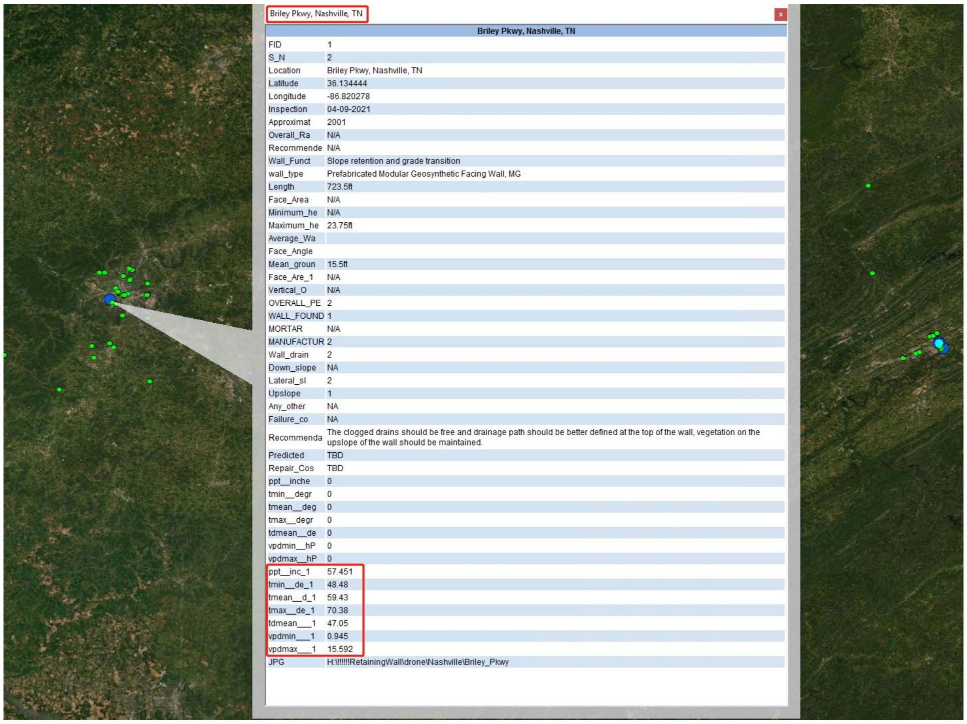


Figure 4.13 Importing Weather Data into ArcGIS

The TN retaining wall geodatabase also allows engineers to upload and save evidence such as images and videos collected from site visits, which can be realized by different approaches. Multiple images for a retaining wall can be integrated and saved in a single file, users can get access to the image webpage by using the hyperlink tool in ArcMap as shown in Figure 4.13.

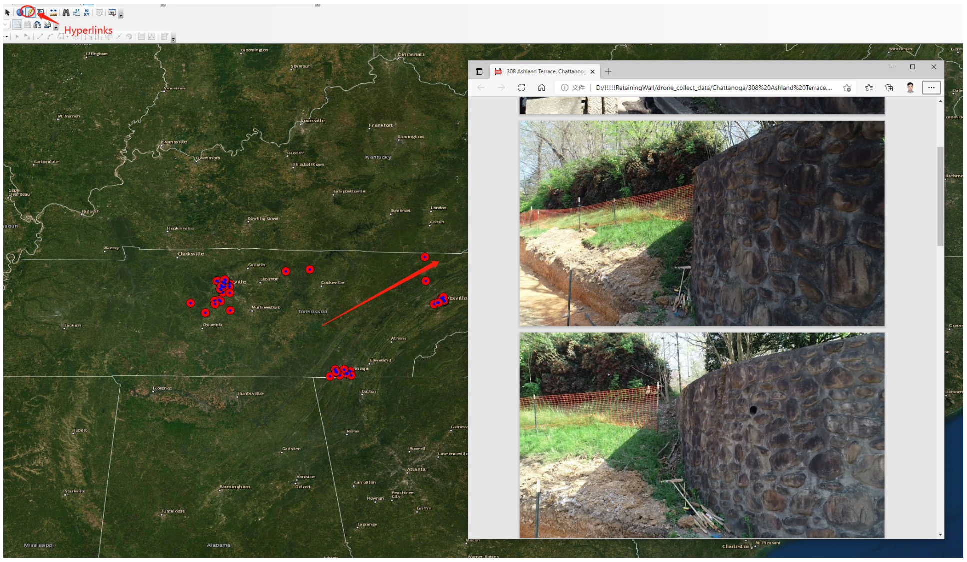


Figure 4.14 Images Stored as Html Formatted Webpage Containing Retaining Wall Field Survey Pictures

An alternative approach to store evidence images in the attribute table is through defining a field in the attribute table and specifying the image hyperlink in the field. Figure 4.14 shows the procedure to store images. Multiple fields can be created in the table if more than one image need to be saved.

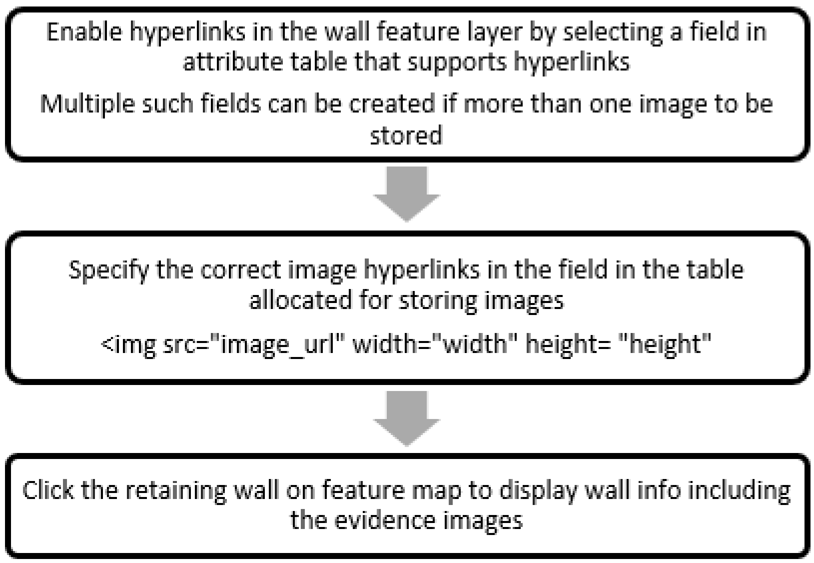


Figure 4.15 Procedure to Create a Hyperlink to Images to Store in the Attribute Table

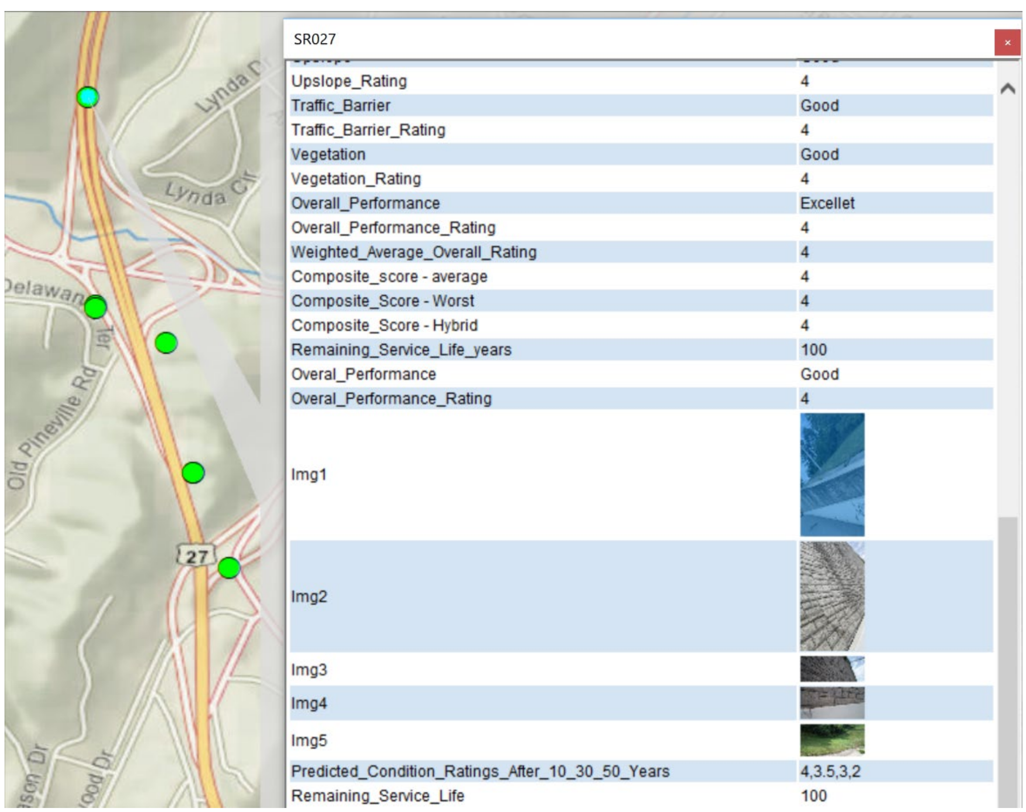


Figure 4.16 Multiple Images from Site Visits Stored as Hyperlink Listed in Attribute Table Opened by HTML Popup Tool

iii. Weather data

As part of the transportation assets, there are potential impacts of weather on condition and service life of retaining wall [34]. To obtain local weather data, the research team downloaded the meteorological data from PRISM group [36, 37] through the local weather station for 10 years between 2010-2020 and used python code to calculate the 10-year average climate data. The Meteorological data extraction interface is shown in Figure 4.17. The raw data in the same coordinates, different years' data are vertically aligned together. A framework was reconstructed to retain the 10-year average at each coordinate. The 10-year average for each location were obtained and are directly imported into ArcGIS.

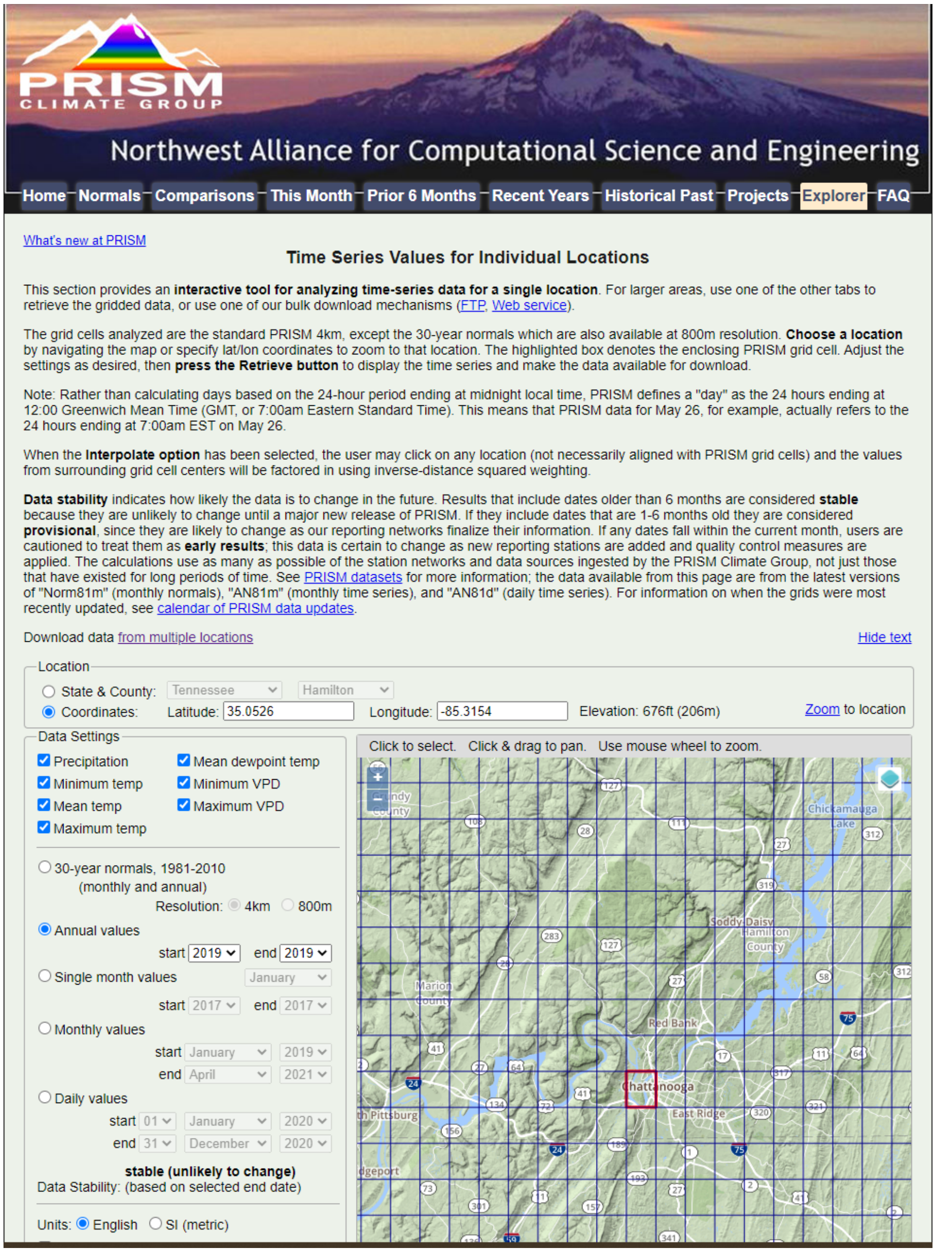


Figure 4.17 Meteorological Data Extraction Interface [37]

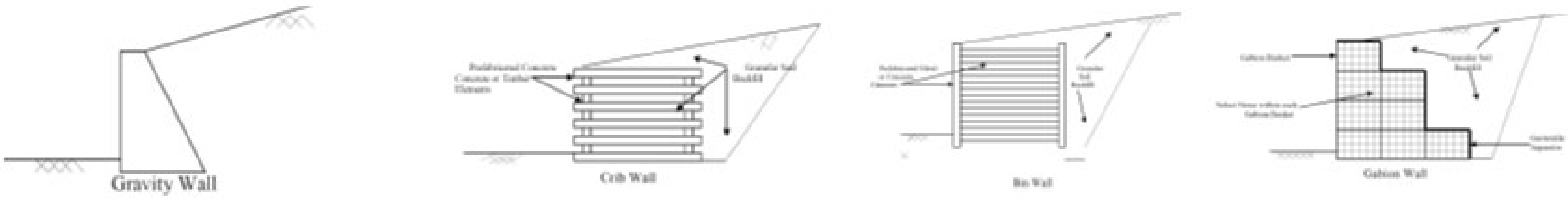
iv. Restoration/Maintenance Costs Estimation

The maintenance cost of different forms of retaining walls at different time junctions can be very different due to their components and designs. It is necessary to briefly discuss retaining wall category.

In general, retaining walls are divided into two categories, gravity retaining walls and non-gravity retaining walls, from the method of maintaining the stability of retaining walls. TABLE 4.C is a summary of RW category given by Wisconsin DOT. The design of different types of walls is shown in Figure 4.19 [38].

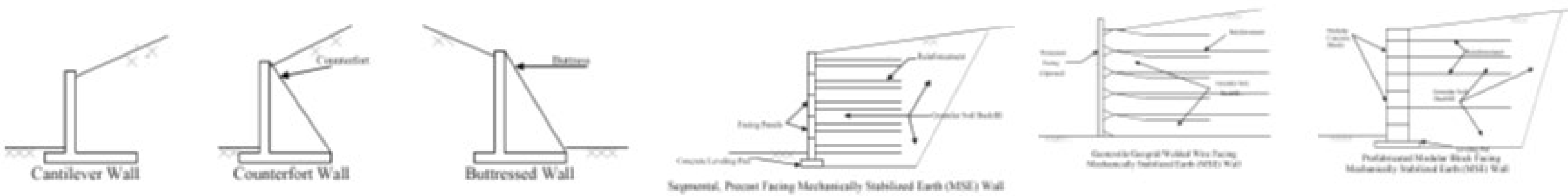
TABLE 4.C RETAINING WALL CATEGORY (WISDOT STRUCTURE INSPECTION MANUAL)

Category	Sub-Category	Typical Construction	Type
Gravity	Mass Gravity	Bottom Up (Fill)	CIP Concrete Gravity
	Semi-Gravity		CIP Concrete Cantilever
	Reinforced Earth		MSE-Precast Panels
			MSE-Modular Blocks
			MSE-Wire Face
	Modular Gravity		Modular Block
			Gabion
	In-Situ Reinforced	Top Down (cut)	Soil Nailing
Non-Gravity	Cantilever	Both	Sheet Pile
			Soldier Pile
			Secant/Tangent
Non-Gravity	Anchored	Top Down (cut)	Sheet Pile
			Soldier Pile
			Secant/Tangent



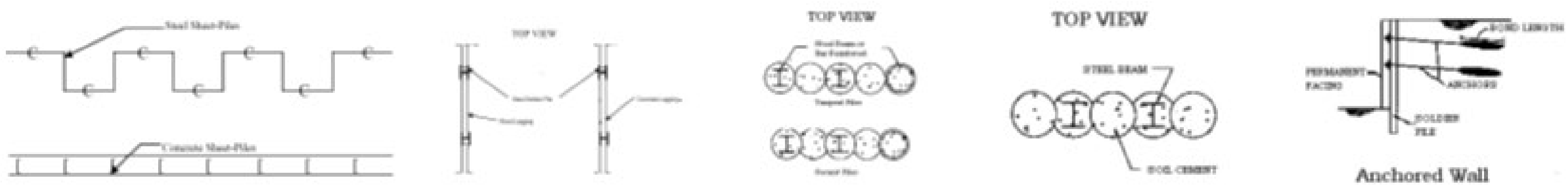
Mass gravity wall

Prefabricated Modular Gravity Walls

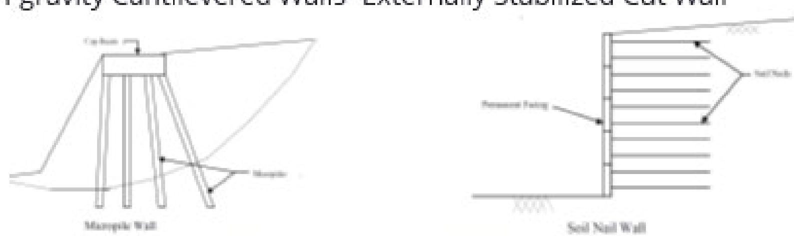


Semi-gravity wall

Mechanically Stabilized Earth (MSE) Wall



Non-gravity Cantilevered Walls- Externally Stabilized Cut Wall



In-situ Reinforced Wall- Internally Stabilized Cut Wall

Figure 4.18 Design of Retaining Walls [38]

There are a wide variety of factors that will influence the cost of replacing an existing retaining wall. Ideally, it would be best to use TDOT's historical data as the construction cost, unfortunately such data is currently not available.

The costs of different types of walls vary greatly. Typical total costs for permanent transportation Mechanically Stabilized Earth (MSE) walls range from \$30 to \$65 per ft^2 (\$320 to \$650 per m^2) of face [39]. The actual cost of a specific MSE wall structure will depend on the cost of each of its principal components. For segmental precast concrete faced structures, typical costs are[40]:

- Erection of panels and contractors' profit - 20 to 30 percent of total cost.
- Reinforcing materials - 15 to 30 percent of total cost.
- Facing system - 20 to 40 percent of total cost.
- Reinforced wall fill including placement - 30 to 60 percent of total cost, where the fill is a select granular fill from an off-site borrow source.

The project team proposes to use RSMeans data [41, 42] to calculate the wall maintenance cost. RSMeans data is used by construction professionals across North America for estimating and budget projects. RSMeans data features an online database that is convenient to be integrated.

RSMeans' database will return a unit price given a construction location and project type. The RSMeans online database is seen in Figure 4.20.

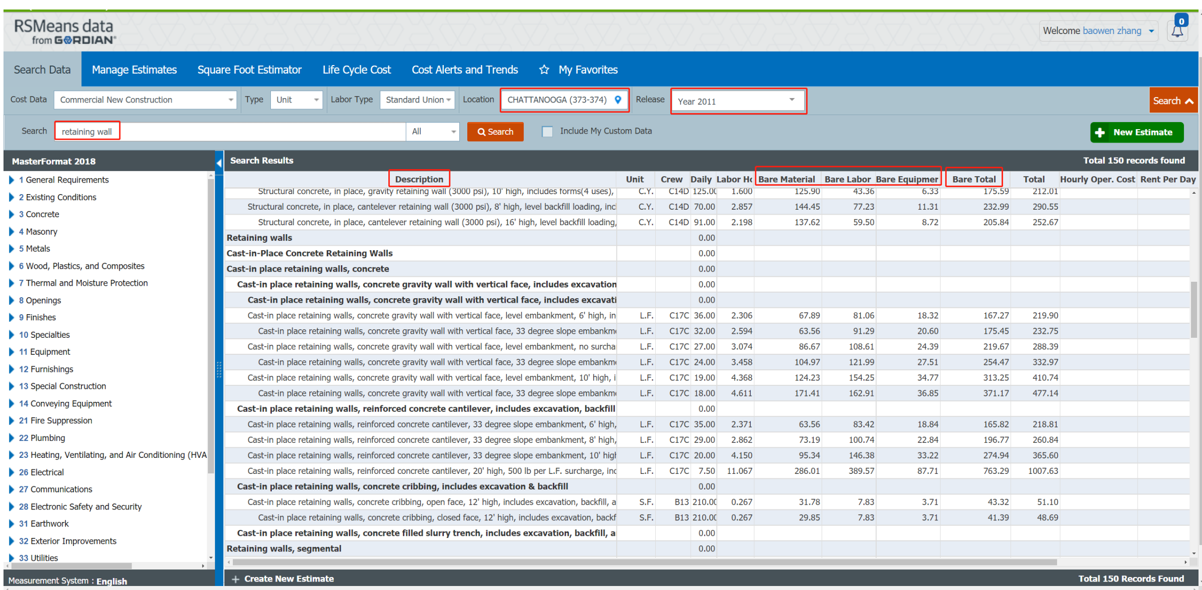


Figure 4.19 RSMeans Online Database Interface [43]

The original value of selected retaining walls can be estimated by multiplying the length and width data of the wall with the unit price retrieved from RSMeans online database. They are given in TABLE 4.D.

TABLE 4.D ORIGINAL COST ESTIMATION OF SELECTED RETAINING WALL

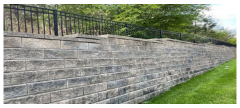
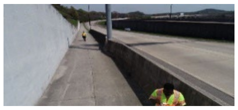
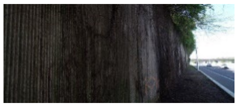
Wall Location	Type	Wall Heights	RSMeans Unite Price	Total
308 Ashland Terrace, Chattanooga, TN	Prefabricated Modular Geosynthetic Facing Wall, MG	7'9"	$10.9/S.F. 	215'(Length) × 8'(Heights) × 10.9 = $18,748
7244-7254 E Brainerd Rd., Chattanooga, TN.	Segmental Retaining Wall	5'9"	$15.83/S.F. 	149'(Length) × 6'(Heights) × 15.83 = $14,152.02
TN-153, Off Bonny Oaks Dr, Chattanooga, TN	Concrete Cantilever Wall, CL	14'9"	$288/ L.F. 	692'(Length) × $288 = $199,815
1301 Washington Avenue	Mechanically Stabilized Modular Block Facing, MS	7'2"	$1.97/ SFCA 	192'(Length) × 7'2"(Heights) × 1.97 = $2,688
Hall of Fame Dr	Mechanically Stabilized Modular Block Facing, MS	7'1"	$1.97/ SFCA 	144'5"(Length) × 7'1"(Heights)* 1.97 = $2,016
James White Pkwy	Concrete Cantilever wall, CL	15'7"	$288/ L.F. 	1173'10"(Length) × $288 = $337,824
N Broadway ramp to I40, Knoxville, TN	Mechanically Stabilized wall, MS	16'9"	$1.97/ SFCA 	952'7"(Length) × 16'9"(Heights) ×1.97 = $32,368
Briley Pkwy	Prefabricated Modular Geosynthetic Facing Wall, MG	15'6"	$10.9/S.F. 	723'(Length) × 15'6"(Heights) × 10.9 = $123,271.5

TABLE 4.E lists some common retaining wall deterioration problems and suggested solutions.

TABLE 4.E COMMON RETAINING WALL DETERIORATION PROBLEMS AND SUGGESTED SOLUTIONS

Root Issue	Resulting Damage	Solution
DIY or low-quality construction	Wall fails	Possible rebuild Dig out behind wall to install anchors
Load exceeds design	Full or partial destruction	Foundation repairs Dig out behind wall to install anchors
Inadequate drainage	Wall bulging	Uphill soil regrading Install landscape fabric barrier Install drainpipe & weep holes
Inadequate footing implemented	Failure or signs of future failure	Increase base or slabs

The research team decided to estimate restoration/maintenance costs based on the lifetime of different parts of the retaining wall combined with the data collected in the field. In TABLE 4.F, the National Concrete Masonry Association [44] lists some life span information about the different component in retaining walls, which leads to the assumptions of residual percentage (TABLE 4.G) used in this project.

TABLE 4.F ESTIMATED LIFE OF MATERIALS [44]

Material	Estimated Life (years)
Concrete Masonry Units	100+
Caulking	5-15
Coping/flashing	25+
Mortar	100+
Paint	5-10
Post-applied water repellent	5-10
Stucco on masonry	100+

TABLE 4.G ASSUMPTION OF RESIDUAL PERCENTAGE BASED ON RATING SCORE

Current Rating Score	Residual Percentage
4	80%
3	60%
2	40%
1	20%

Considering the time value of money, the present value of wall after t years is given by original cost of retaining wall x (1 + 30 years average inflation rate)^t. The 30-year average inflation rate for nonresidential buildings adopted in this project is 3.5% [45].

As a demonstration, the team chose a wall located at 308 Ashland Terrace in Chattanooga TN to estimate its maintenance cost. The wall was built in 2003 at a total cost of approximately $18,748.

Present value after 30 years= $18,748 x $(1 + 0.035)^{30}$ = $52,621.77

The current overall condition rating score for the wall is 3, which indicates around 40% (i.e. 100% -60%) of this wall will need to be reconstructed after 30 years (TABLE 4.G). The repair cost of the wall computed as:

$52,621.77 x 40% = $21,048.71

The repair cost for selected retaining wall is shown in TABLE 4.H.

TABLE 4.H ORIGINAL COST OF RETAINING WALL

Wall Location	Total Original Cost	Wall Condition Rating Score	Repair Cost Estimated
308 Ashland Terrace, Chattanooga, TN	$18,748	3	$21,048.71
7244-7254 E Brainerd Rd., Chattanooga, TN.	$14,152.02	4	$7,944.36
TN-153, Off Bonny Oaks Dr, Chattanooga, TN	$199,815	4	$112,167.90
1301 Washington Avenue	$2,688	4	$1,508.93
Hall of Fame Dr	$2,016	4	$1,131.70
James White Pkwy	$337,824	3	$379,280.91
N Broadway ramp to I40, Knoxville, TN	$32,368	2	$54,510.18
Briley Pkwy	$123,271.5	2	$207,598.60

Chapter 5 Conclusion and Recommendations

5.1 Benefits to TDOT

The research results from this project will provide TDOT with a comprehensive rating and inventory system to inspect, assess and record the condition of all retaining walls throughout the State to meet part of the MAP-21 requirements. More specifically,

1) This project built an ArcGIS feature layer for mapping and inventory of retaining wall in the state of Tennessee. The inventory data and condition rating can assist TDOT in better understanding the spatial distribution and current condition of selected retaining walls in the state of Tennessee.
2) The dynamic condition prediction, remaining service life estimate, and risk analysis, methods developed in this project can assist TDOT better manage the TDOT walls thus preventing catastrophic failures of retaining wall/catchment systems. Action cost analysis can be beneficial for accurate budget and allocation of available funds.
3) The user-friendly queryable ArcGIS database aligns with the TDOT current GIS data and enables TDOT to easily update the information on retaining walls in the future. The detailed information presented in this report on how the ArcGIS database was built will allow TDOT to have a full understanding of the database.
4) The software tools developed and delivered allow TDOT to easily estimate current and future wall condition scores and remaining service life, enable TDOT to practically apply AHP and Markov model in retaining wall management.

Overall, with the deliverables of this project, TDOT will be able to better manage retaining wall structures in terms of maintenance, repair and replacement through well-informed decisions within tight budget. They can also help to shape both short-term and long-term strategic plans on retaining wall asset management.

5.2 Implementation

The main audience for these project results includes TDOT's geotechnical engineers and consultants. Audiences may also extend to other state DOTs, government agencies and even students and researchers in universities who are working in the field of transportation asset management. This research project is the first that integrates AHP and Markov model to estimate condition and service life in a systematic approach. With more and more state DOTs building their database of condition wall ratings, the approach proposed in this project will be able to make better predictions about the condition and service life of retaining wall. Other than application in retaining walls, the method used in this study can be easily extended to management of other infrastructure assets such as bridges. A research article developed from this research is currently being reviewed, the research team expects the publication will be circulated among engineers and researchers in geotechnical and transportation practice and research.

Many transportation agencies lack practicable tools that can be used to estimate wall condition ratings and service-life [11], the research findings and tools from this project will enable TDOT and other agencies to better execute and implement retaining wall management programs to achieve their goal of more effectively managing their walls as well as other transportation assets.

The team will continue improving the computer tools and database, soon an updated version of the software, if desired, will be delivered to TDOT.

5.3 Conclusion Justifications

As an important part of asset management for retaining walls, reliably estimating the condition and life expectancy will guide transportation agencies to better maintain retaining walls. This project proposed a framework that integrated AHP with Markov chain to rate the current condition and estimate future conditions as well as service life of retaining walls. The application of AHP for weighting the relative importance of wall elements can use the knowledge from experts or experienced people with respect to engineering principles. Markov chain provides a more realistic solution to service life prediction since it considers the practical condition of retaining walls.

For the first time, the research team introduces AHP complex decisions making technique and the latest research of two-part condition rating into retaining wall condition assessment. Markov model was applied to predict both future condition ratings and service-life for retaining wall. The team managed to collect basic location information of nearly 100 retaining walls and visited about 30 different retaining walls equipped with modern drone technology. An ArcGIS feature layer visually maps the walls and information including site visit pictures associated with each wall can be easily accessed by TDOT ArcGIS users.

The team found that application of UAV in retaining wall data collection made it possible to survey 30 geographically distributed retaining walls with a tight budget.

With the Excel based tools developed through this project, and the retaining wall component rating scores collected in the field, the research team was able to predict future conditions in 10, 30 and 50 years for selected retaining walls, as well as the remaining service life if no maintenance action is taken.

The Research Team did not have a TDOT cost history to reference. The employment of the RSMeans database afforded the means of demonstrating the capability of the database generated by this Research Project.

5.4 Recommendations

It is recommended to have more than one TDOT engineer perform pairwise comparison of different wall elements. Every engineer may have different opinions on the importance scores and most critical wall components when applying AHP to estimate weights. TDOT personnel should conduct an in-house evaluation of 1) critical wall components, 2) the important scores used for AHP, 3) transition probability matrix used for Markov model, 4) field survey form, and 5) all fields that should be included in the attribute table in ArcGIS database.

As for data collection, the team recommend collecting both static and video images using an inspection drone especially for large scale wall that is not easily accessible, or a wall located in very busy roadway. A Thermal camera, ultrasound or ground-penetrating radar may be used if more detailed information including potential damage inside the wall or the condition of a wall. The research team was not able to obtain information about the ages of retaining wall, the imagery date in Google Earth was leveraged to observe the presence of a retaining wall in the specific location as the year of construction. The wall ages in the initial inventory ArcGIS database should be double-checked by searching construction drawings or records.

Additionally, the initial inventory database developed in this project should be refined by making necessary changes to attribute values. It is also recommended that TDOT use vehicle mounted LiDAR sensors and digitally captured photos to collect more accurate information of all retaining walls in the state, add to the inventory database and map them in the retaining wall layer.

Unlike bridges, currently, no sufficient condition rating data for retaining walls is available, which makes more accurate estimation of service life and future condition of wall difficult. The condition ratings and service life predicted using the method proposed in this project should be used together with periodic field survey. Moreover, the condition rating and service life prediction software produced in this research needs to be further developed to make it more user friendly and a web-based interactive version is highly recommended.

As for the maintenance cost, the research team relied on RSMeans database, which may not reflect the true cost. A construction cost database and cost estimation tool for transportation assets maintenance is recommended.

Finally, due to data unavailability, accurate estimation of a transition probability matrix is impossible. Transition probability matrices in NCHRP report 713 [26, 46] for highway assets and in Morcous et al. [20] for concrete bridge decks for the moderate environment category was adopted in this research. It is acknowledged that environmental category, as well as age group, has impact on transition probability matrix. As more condition rating data is expected in the future, a variety of such matrices should be used for different age retaining wall groups.

References

[1] O. Brutus, Tauber, G., and Gandhi, K., "Guide to asset management of earth retaining strucrures," in *2011 Bridge Conf.*, Washington, DC, 2011: Federal Highway Administration, pp. 1-12.

[2] C. J. Butler, M. A. Gabr, W. Rasdorf, D. J. Findley, J. C. Chang, and B. E. Hammit, "Retaining wall field condition inspection, rating analysis, and condition assessment," *Journal of Performance of Constructed Facilities,* vol. 30, no. 3, p. 04015039, 2016.

[3] M. A. Gabr, W. Rasdorf, D. J. Findley, C. J. Butler, and S. A. Bert, "Comparison of Three Retaining Wall Condition Assessment Rating Systems," *Journal of Infrastructure Systems,* vol. 24, no. 1, p. 04017037, 2018.

[4] M. DeMarco, D. Keough, and S. Lewis, "Retaining wall inventory and condition assessment program (WIP): National Parks Service procedure manual," *FHWA Publication No. FHWA-CFL/TD-10-003, Federal Highway Administration, Lakewood, CO,* 2010.

[5] U. Congress, "Moving ahead for progress in the 21 st century act," *Washington, DC,* 2012.

[6] ASCE, "2021 report card for America's infrastructure," 2021: American Society of Civil Engineers, 2021.

[7] S. A. Anderson, D. Alzamora, and M. J. DeMarco, "Asset management systems for retaining walls," in *Geo-Velopment: The Role of Geological and Geotechnical Engineering in New and Redevelopment Projects*, 2009, pp. 162-177.

[8] AASHTO, *AASHTO Transportation Asset Management Guide: A Focus on Implementation*. AASHTO, 2011.

[9] W. Jensen Ph D, "Inspector's Manual for Mechanically Stabilized Earth Walls," 2009.

[10] K. L. Sanford Bernhardt, J. E. Loehr, and D. Huaco, "Asset management framework for geotechnical infrastructure," *Journal of infrastructure systems,* vol. 9, no. 3, pp. 107-116, 2003.

[11] W. Rasdorf, Mohammed A. G., Cedrick J. B., Daniel J. F., Steven A. B., "Retaining Wall Inventory and Assessment System," NCDOT Project 2014-10 FHWA/NC/2014-10, 2015.

[12] O. Brutus and G. Tauber, *Guide to asset management of earth retaining structures*. US Department of Transportation, Federal Highway Administration, Office of ..., 2009.

[13] A. Athanasopoulos-Zekkos *et al.*, "Asset Management for Retaining Walls," 2020.

[14] (2016). *Colorado Retaining and Noise Walls Inspection and Asset Management*

Manual.

[15] CTC and Associates, "Asset management for retaining walls," ed: Minnesota Department of Transportation Saint Paul, 2013.

[16] (2018). *Retaining Wall Inventory and Inspection Program Manual*.

[17] T. L. Saaty, "What is the analytic hierarchy process?," in *Mathematical models for decision support*: Springer, 1988, pp. 109-121.

[18] (1999). *Asset Management Primer*.

[19] E. Wang, Z. Shen, J. Neal, J. Shi, C. Berryman, and A. Schwer, "An AHP-weighted aggregated data quality indicator (AWADQI) approach for estimating embodied energy of building materials," *The International Journal of Life Cycle Assessment,* vol. 17, no. 6, pp. 764-773, 2012.

[20] G. Morcous, Z. Lounis, and M. Mirza, "Identification of environmental categories for Markovian deterioration models of bridge decks," *Journal of Bridge Engineering,* vol. 8, no. 6, pp. 353-361, 2003.

[21] E. Wang and Z. Shen, "Lifecycle energy consumption prediction of residential buildings by incorporating longitudinal uncertainties," *Journal of Civil Engineering and Management,* vol. 19, no. sup1, pp. S161-S171, 2013.
[22] Y. Jiang, M. Saito, and K. C. Sinha, *Bridge performance prediction model using the Markov chain* (no. 1180). 1988.
[23] D. Chimba, E. Kidando, and M. J. J. o. T. E. Onyango, Part B: Pavements, "Evaluating the service life of thermoplastic pavement markings: stochastic approach," vol. 144, no. 3, p. 04018029, 2018.
[24] N. K. W. Wellalage, T. Zhang, and R. J. J. o. B. E. Dwight, "Calibrating Markov chain–based deterioration models for predicting future conditions of railway bridge elements," vol. 20, no. 2, p. 04014060, 2015.
[25] A. A. Butt, M. Y. Shahin, K. J. Feighan, and S. H. Carpenter, *Pavement performance prediction model using the Markov process* (no. 1123). 1987.
[26] K. M. Ford *et al.*, "Estimating Life Expectancies of Highway Assets. Volume 2," *NCHRP Report,* vol. 2, no. Project 08-71, 2012.
[27] J. Zink and B. Lovelace, "Unmanned aerial vehicle bridge inspection demonstration project," 2015.
[28] J. L. Wells, B. Lovelace, and T. Kalar, "Use of unmanned aircraft systems for bridge inspections," *Transportation Research Record,* vol. 2612, no. 1, pp. 60-66, 2017.
[29] J. Wells and B. Lovelace, "Improving the quality of bridge inspections using unmanned aircraft systems (UAS)," 2018.
[30] B. F. Spencer Jr, V. Hoskere, and Y. Narazaki, "Advances in computer vision-based civil infrastructure inspection and monitoring," *Engineering,* vol. 5, no. 2, pp. 199-222, 2019.
[31] D. Laefer and D. Lennon, "Viability assessment of terrestrial LiDAR for retaining wall monitoring," in *GeoCongress 2008: Geosustainability and Geohazard Mitigation*, 2008, pp. 247-254.
[32] P. Oskouie, B. Becerik-Gerber, and L. Soibelman, "Automated cleaning of point clouds for highway retaining wall condition assessment," in *Computing in Civil and Building Engineering (2014)*, 2014, pp. 966-974.
[33] K. D. Goepel, "Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises–a new AHP excel template with multiple inputs," in *Proceedings of the international symposium on the analytic hierarchy process*, 2013, vol. 2, no. 10: Creative Decisions Foundation Kuala Lumpur, pp. 1-10.
[34] E. Rowan *et al.*, "Assessing the sensitivity of transportation assets to extreme weather events and climate change," *Transportation research record,* vol. 2326, no. 1, pp. 16-23, 2013.
[35] G. TDOT. "Concrete Barrier Wall." https://tn-tnmap.opendata.arcgis.com/datasets/784fdeb5348c418fac9fa8a95b9d8e30_0/explore?location=37.303745%2C-87.827111%2C14.86 (accessed August 1, 2021, 2021).
[36] C. Daly and K. Bryant, "The PRISM climate and weather system—an introduction," *Corvallis, OR: PRISM climate group,* 2013.
[37] O. S. U. PRISM Climate Group, "PRISM climate data," 2021.
[38] (2012). *Tennessee Department of Transportation Earth Retaining Structures Manual*.
[39] R. R. Berg, B. R. Christopher, and N. C. Samtani, "Design and construction of mechanically stabilized earth walls and reinforced soil slopes–Volume I," *Federal High Way Administration (FHWA),* 2009.
[40] (2015). *GEM-16, Geotechnical Engineering Manual: Mechanically Stabilized Earth System Inspection Manual*.

[41] M. Doheny, *Building construction costs with RSMeans Data 2021*. Gordian RSMeans Data, 2021.
[42] G. Gordian. https://www.rsmeans.com/ (accessed.
[43] G. Gordian. RSMeans data [Online] Available: https://www.rsmeansonline.com/
[44] N. NCMA, "Maintenance of Concrete Masonry Walls, TEK 08-01A," ed, 2004.
[45] E. R. Zarenski, "Construction Inflation Analysis for Natonal Data," in "Construction Analytics 2021 Construction Economic Forecast," 2021.
[46] P. D. Thompson and K. M. Ford, *Estimating life expectancies of highway assets: Guidebook*. Transportation Research Board, 2012.

Appendices

Appendix A: Field Survey Data

<u>Field survey sample report #1: Washington Avenue, Knoxville, TN</u>

FIELD SURVEY FORM FOR RETAINING WALL INSPECTION				
Wall Identification Number	47XXXX			
Route Name/Location	I0040 1301 Washington Avenue, Knoxville, TN			
Wall ownership				
Inspection Date	04-07-2021	**Approximate Year Built**	2005	
Wall Description Data				
Wall Function (fill, cut, head, bridge, slope protect)	Slope retention and grade transition	Wall Type	Mechanically Stabilized Modular Block Facing, MS	
General Description				
Wall Measurement Data				
Wall Length(ft)	192’2”		Face Area (sq.)	
Average Wall Height(ft)	7’2”		Face Angle (deg.)	
Maximum Wall Height(ft)	11’3”		Vertical Offset (ft.)	
Mean ground elevation (ft)				
Wall Location Data				
Latitude and Longitude	35°59’03” N 83°54’50” W			
Weather Data				

<table>
<tr><td>10-year Mean Temp</td><td colspan="3"></td></tr>
<tr><td>10-year Max Temp</td><td colspan="3"></td></tr>
<tr><td>10-year Min Temp</td><td colspan="3"></td></tr>
<tr><td>10-year PPT</td><td colspan="3"></td></tr>
<tr><td>Td Mean</td><td colspan="3"></td></tr>
<tr><td>VPD Max</td><td colspan="3"></td></tr>
<tr><td>VPD Min</td><td colspan="3"></td></tr>
<tr><td colspan="4">Condition Assessment of Wall Elements</td></tr>
<tr><td>Structural Elements</td><td colspan="3"></td></tr>
<tr><td>Element Assessed</td><td>Sample Narrative</td><td colspan="2">Condition Rating (1-4)</td></tr>
<tr><td>Pile and shafts</td><td></td><td></td><td rowspan="4">Other structural elements
3</td></tr>
<tr><td>Lagging</td><td></td><td></td></tr>
<tr><td>Anchor</td><td></td><td></td></tr>
<tr><td>Wire/Geosynthetic</td><td></td><td></td></tr>
<tr><td>Facing</td><td></td><td></td><td rowspan="8">Wall
3</td></tr>
<tr><td>Bin or crib</td><td></td><td></td></tr>
<tr><td>Concrete</td><td></td><td></td></tr>
<tr><td>Shotcrete</td><td></td><td></td></tr>
<tr><td>Mortar</td><td></td><td></td></tr>
<tr><td>Block/Brick</td><td>• Few blocks bear hairline to moderate cracks
• Few cases of scaling observed
• Few visible markings on the wall
• No open joints
• Breakages at the top coping of the wall</td><td>3</td></tr>
<tr><td>Placed Stone</td><td></td><td></td></tr>
<tr><td>Stone Masonry</td><td></td><td></td></tr>
<tr><td>Foundation material</td><td>• No tension cracks behind wall observed
• Foundation soil appears compact and adequate to support wall
• No loss of fill or exposure of foundation</td><td>4</td><td>Foundation material
4</td></tr>
<tr><td>Auxiliary Elements</td><td colspan="3"></td></tr>
<tr><td>Element Assessed</td><td>Sample Narrative</td><td colspan="2">Condition Rating (1-4)</td></tr>
</table>

<table>
<tr><td>Wall drains</td><td>• Clear drainage path on top of the wall
• Two clogged drainage holes out of six (6)</td><td>3</td><td>Drain
3</td></tr>
<tr><td>Upslope</td><td>• Fairly good vegetation at the upslope
• Presence of trees and shrubs</td><td>3</td><td rowspan="3">Slope
3</td></tr>
<tr><td>Downslope</td><td></td><td></td></tr>
<tr><td>Lateral slope</td><td>Moderate disturbance for the slope possibly due to water movement</td><td>3</td></tr>
<tr><td>Architectural facing</td><td></td><td></td><td rowspan="4">Other Auxiliary Elements
3</td></tr>
<tr><td>Road/shoulder</td><td></td><td>3</td></tr>
<tr><td>Culvert</td><td></td><td></td></tr>
<tr><td>Curb/Berm/Ditch</td><td></td><td></td></tr>
<tr><td>Surrounding Setting</td><td colspan="3"></td></tr>
<tr><td>Element Assessed</td><td>Sample Narrative</td><td colspan="2">Condition Rating (1-4)</td></tr>
<tr><td>Traffic barrier/fence</td><td></td><td>2</td><td rowspan="2">2</td></tr>
<tr><td>Vegetation</td><td></td><td>4</td></tr>
<tr><td>Service functionality</td><td colspan="3"></td></tr>
<tr><td>Element Assessed</td><td>Sample Narrative</td><td colspan="2">Condition Rating (1-4)</td></tr>
<tr><td>Wall Overall Performance</td><td>• No stability problems
• No combination of element distresses observed
• No history of remediation or repair to wall</td><td colspan="2">4</td></tr>
<tr><td>Wall Action Assessment/Repair Recommendations</td><td colspan="3"></td></tr>
<tr><td>Failure consequence</td><td colspan="3"></td></tr>
<tr><td>Recommended Maintenance Action</td><td colspan="3">Overall, the condition of the wall does not warrant any immediate rehabilitation action. However, the drain pipes should be devoid of weed growth, and the crack growth on the wall should be monitored closely if possible.</td></tr>
<tr><td>Overall Ratings</td><td colspan="3"></td></tr>
<tr><td>Predicted Ratings</td><td colspan="3"></td></tr>
<tr><td>Predicted Service Life</td><td colspan="3"></td></tr>
<tr><td>Repair Cost</td><td colspan="3"></td></tr>
</table>

Field survey sample report #1: Washington Avenue, Knoxville, TN

Table A.1 AHP Condition Rating scores: Washington Avenue, Knoxville, TN

#	1st - level element	2nd - level element	Weight of 2nd - level element	Global weight of 2nd - level elements	Rating score of 2nd - level element	Weighted average rating of the 1st - level element
1	Structure	Foundation materials	60.0%	33.7%	4.0	3.6
2		Wall	20.0%	11.2%	3.0	
3		Other structural	20.0%	11.2%	3.0	
4	Auxiliary	Drainage	47.4%	6.9%	3.0	3.0
5		Slope	47.4%	6.9%	3.0	
6		Other auxiliary elements	5.3%	0.8%	3.0	
7	Surrounding setting	Traffic barrier	16.7%	0.7%	2.0	3.7
8		Vegetation	83.3%	3.4%	4.0	
9	Functionality	Functionality	100.0%	25.2%	4.0	4.0

Table A.2 Condition Rating Scores: Washington Avenue, Knoxville, TN

Composite Scores			Weighted Overall Rating
Rating by average	Rating by worst	Rating by hybrid	
3.57	3.00	3.57	3.62

Table A.3 Predicted Condition Scores and Service Life: Washington Avenue, Knoxville, TN

Estimated Future Condition Ratings			Remaining Service Life
In 10 years	30 years	50 years	
2.2	1.3	1.1	55

Figure A. 1 Vertical crack on wall facing

Figure A. 2 Cracks observed on top of the wall

Figure A. 3 Cracks observed on top of the wall, clear drainage path on top of the wall

Figure A. 4 Fairly good vegetation at the upslope, presence of trees and shrubs

Field survey sample report #1: Washington Avenue, Knoxville, TN cont'd

Figure A. 5 Fairly good vegetation at the foot, no soil erosion and deflection/displacement observed

Figure A. 6 Moderate cracks observed on the face of the wall blocks

Table A.4 Condition Scores for Selected Retaining Walls

Wall	Retaining Wall Locations	Age§	Weighted Overall Rating
1	7244-7544 E Brainerd Chattanooga, TN	14	3.74
2	TN-153, Off Bonny Oaks Dr., Chattanooga, TN/TN-153N Near Exit 5A	21	2.10
3	308 Ashland Terrace, Chattanooga, TN	22	2.45
4	Northpoint Boulevard, Chattanooga, TN	13	2.91
5	Riverside Drive, TN-58, Chattanooga	27	2.21
6	Signal Mountain Road, Chattanooga, TN	18	3.49
7	1727 Dayton Blvd, Chattanooga, TN	16	2.95
8	222 Baker Street, Chattanooga, TN/Barton Ave Near GPS	24	2.95
9	918-998 Cherokee Blvd, Chattanooga, TN	22	2.84
10	I-75 N, Chattanooga, TN/I-75 N Exit Ramp to Hampton Place Mall, Chattanooga TN	35	2.66
11	1201-1261 Dayton Blvd, Chattanooga, TN	27	2.97
12	I-75 S, Chattanooga/I-75 S Near Exit 4, Chattanooga, TN	36	2.43
13	US-11, Birmingham Hwy Cross Railway, Chattanooga, TN	38	1.85
14	6401 Lee Hwy/US 64 & Lee Hwy Exit Ramp to TN-153N	47	2.41
15	4177 Willard Dr/Bonny Oaks Dr to TN-153S	48	2.77
16	6828 Northside Dr/I75 Exit 3 Ramp Merges US 153 E. Brainerd Exit Ramp , Chattanooga, TN	17	3.74
17	US-27 N/US-27N Exit to Signal Mountain, Chattanooga, TN	6	3.90
18	US-27 S/US-27S Dayton Blvd Entrance, Chattanooga, TN	6	3.78
19	US-27 S/US-27S Near Manufacturers Road Exit, Chattanooga, TN	6	3.93
20	9303 E Brainerd Rd/E Brainerd Rd between Hamlet Dr. and Bel-air Rd,Chattanooga, TN	15	3.75
21	6312 Fisk Ave/US-153N Near Fisk Ave,Chattanooga, TN	16	3.32
22	1701-1899 Meharry Dr/US-153N Near Meharry Dr,Chattanooga, TN	45	2.40
23	US-27 N/US-27N between Red Bank Exit and R.R.Olgiati Bridge,Chattanooga, TN	6	3.88
24	1301 Washington Avenue, Knoxville, TN	21	3.62
25	Hall of Fame Drive, Knoxville, TN	19	3.10
26	James White Pkwy, Knoxville, TN	31	2.59
27	N Broadway Ramp to I40, Knoxville, TN	15	2.16
28	Briley Pkwy, Nashville, TN/US70S exit to I440	35	2.03
29	Elm Hill Pike, Nashville, TN/Briley Pkwy Elm Hill Pike Exit Ramp	24	3.01

§ Age is estimated through Google Earth

Additional retaining wall reports are available upon request.

Appendix B: Retaining Walls Rating Criteria Narratives

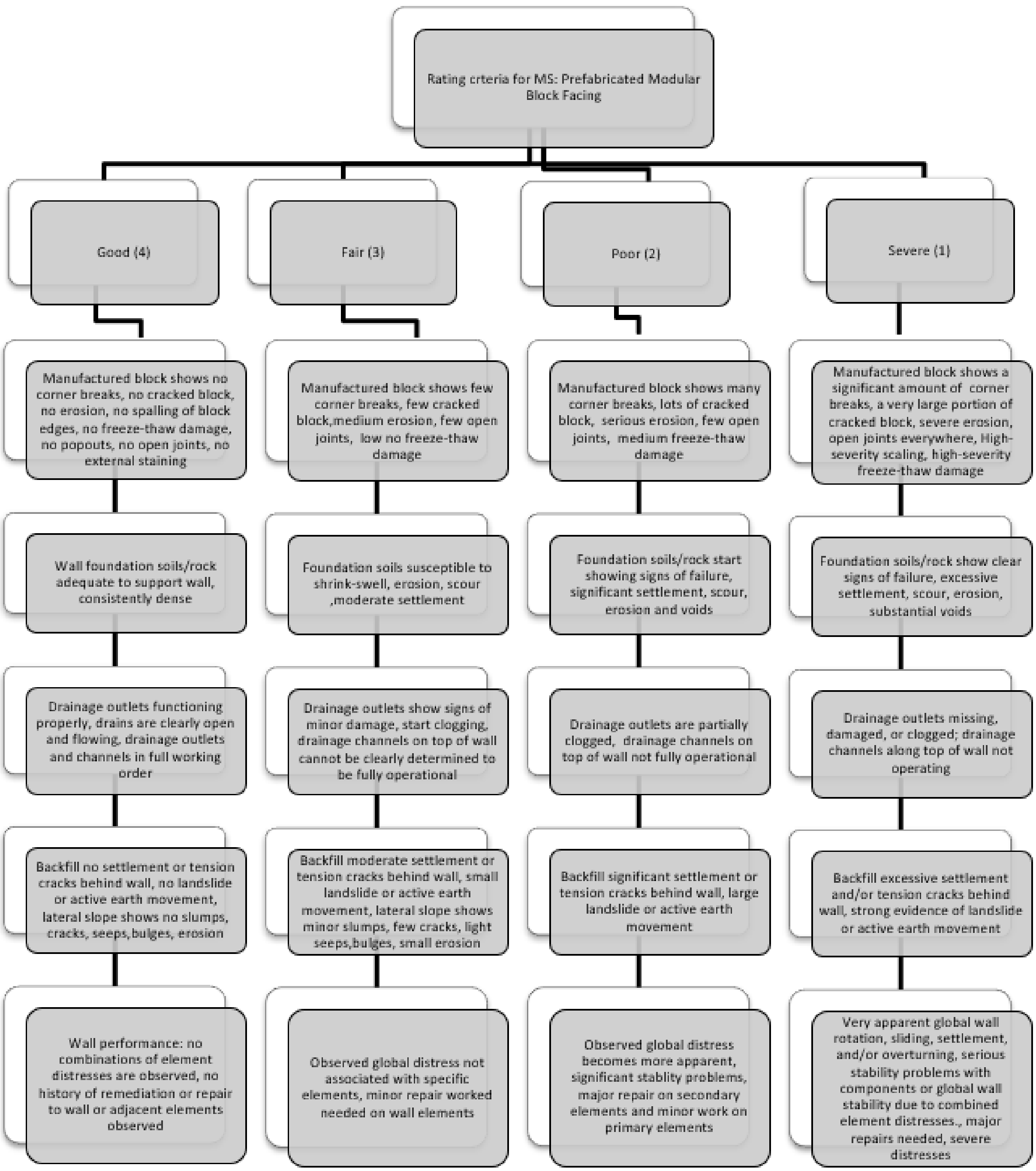


Figure B. 1 Rating criteria for MS: Prefabricated Modular Block Facing

Additional narratives for other types of retaining wall are available upon request.

Appendix C: Questionnaire

Questionnaire for TDOT-RES 2019 #08

Rating and Inventory of TDOT Retaining Walls

This questionnaire is part of an effort of UTC research team to gather any available inventory and rating information TDOT regional offices and agencies may have for existing retaining walls across the State of Tennessee. To build an inventory and rating system for retaining walls in the State, we are interested in any information and opinions. Your valuable inputs will help identify the retaining walls that are most beneficial to creating a retaining wall asset management system for the State of Tennessee. Thank you in advance for your participation.
The questionnaire has 15 questions. Trial use in a survey pretest shows that the questionnaire can be easily completed within 20 minutes.
Please complete the questionnaire by (TBD).

Disclaimer Statement: Answers provided in response to this questionnaire will be compiled and presented anonymously, and the report will be written in a manner that does not expose any owner agencies or their agents to liability concerns.

1. From which TDOT regional office are you completing this survey?
   ☐ Region 1

   ☐ Region 2

   ☐ Region 3

   ☐ Region 4

2. Your contact information
   Name:Click or tap here to enter text.

   Position:Click or tap here to enter text.

   Email:Click or tap here to enter text.

   Phone:Click or tap here to enter text.

3. Does your region keep any records of retaining walls such as drawings and year built, or you know any information about retaining walls in your region?
   ☐ Yes
   ☐ No

   If your answer to question 3 is “no”, you may stop here and thank you for your participation.

4. The data types that your region has include (please select all that apply)

☐ Descriptive data
☐ Numerical data
☐ Graphical image data
☐ As-built drawings
☐ Any other type, please specifyClick or tap here to enter text.

5. The retaining wall data that your region has include information about (please select all that apply)
   ☐ Identification number
   ☐ Location
   ☐ Dimensions
   ☐ Year built
   ☐ Structure type (Tieback H-Pile, Cantilever, Gravity, MSE, Soil Nail, Crib...)
   ☐ Function (e.g., bridge wall, slope protection, fill wall, cut wall, switchback wall...)
   ☐ Ownership
   ☐ Condition and action records
   ☐ Photographs and images
   ☐ Initial construction cost
   ☐ Maintenance records and costs
   ☐ Any other information other than above, please specifyClick or tap here to enter text.

6. What are most used retaining wall types in your region. (Please select THREE or less)
   ☐ Anchor (tieback H-pile, micropile, tieback sheet-pile)

   ☐ Bin (concrete, metal)

   ☐ Cantilever (concrete, solider pile, sheet pile)

   ☐ Crib (concrete, metal, timber)

   ☐ Gravity (mass concrete, dry stone, Gabion)

   ☐ MSE (Geosynthetic face, Welded Wire Face, Segmental Block, Precast Panel)

   ☐ Soil Nail

   ☐ Others

7. Do you have any time-history rating records for retaining walls?

   ☐ Yes

   ☐ No

8. If your answer to question 7 is “yes”, what is the condition rating scale used?
   ☐ 1-10
   ☐ 1-7
   ☐ 1-4
   ☐ 0-9

☐ 2-8
☐ others, please specify Click or tap here to enter text.

9. Using a rating scale of 0-5 as shown in the table below, please rate the importance level for the following wall components to the best of your knowledge:

Importance levels	**Ratings**
No opinion	0
Not at all important	1
Slightly important	2
Important	3
Fairly important	4
Very important	5

[ ] Wall foundation material
[ ] Wall building materials (concrete, shotcrete, mortar, brick, stone, masonry…)
[ ] Backfill
[ ] Drainage
[ ] Vegetation

10. Please list 1 to 3 retaining walls that have relatively poorer condition and should be closely monitored in your region (please specify location, year built and condition if available).

Wall 1:Click or tap here to enter text.

Wall 2:Click or tap here to enter text.

Wall 3:Click or tap here to enter text.

11. Please rank the accessibility of the retaining walls you listed in question 9:

Wall 1:
☐Limited access
☐Direct access

Wall 2:
☐Limited access
☐Direct access

Wall 3:
☐Limited access
☐Direct access

12. This project aims at creating a searchable retaining wall inventory database. Which of the following platform do you prefer for the database to be built?

    ☐ Microsoft Access

    ☐ Microsoft Excel

    ☐ ArcGIS and ArcMap

    ☐ One more layer on existing TDOT GIS Data

    ☐ Others Click or tap here to enter text.

13. Can you provide us the retaining wall data your region may have?
    ☐ Yes
    ☐ No

14. If your answer to question 12 is “yes”, who will be the best contact person and how should we reach her/him?

    Name: Click or tap here to enter text.

    Email: Click or tap here to enter text.

    Phone: Click or tap here to enter text.

15. Can you provide any assistance if the research team decide to inspect the retaining walls located in your region?

    ☐ Yes

    ☐ No

The survey questionnaire is complete. Thank you for your participation.

Appendix D: Tables

TABLE D. 1 FIELD SURVEY FORM FOR RETAINING WALL INSPECTION

FIELD SURVEY FORM FOR RETAINING WALL INSPECTION				
Wall Identification Number				
Route Name/Location				
Wall ownership				
Inspection Date		**Approximate Year Built**		
Wall Description Data				
Wall Function (fill, cut, head, bridge, slope protect)		Wall Type		
General Description				
Wall Measurement Data				
Wall Length(ft)			Face Area (sq.)	
Average Wall Height(ft)			Face Angle (deg.)	
Maximum Wall Height(ft)			Vertical Offset (ft.)	
Mean ground elevation (ft)				
Wall Location Data				
Latitude and Longitude				
Weather Data				
10-year Mean Temp				
10-year Max Temp				
10-year Min Temp				
10-year PPT				

Td Mean			
VPD Max			
VPD Min			
Condition Assessment of Wall Elements			
Structural Elements			
Element Assessed	Sample Narrative	Condition Rating (1-4)	
Pile and shafts	settlement, corrosion, outward deflection		Other structural elements
Lagging	weathered or corrosion		
Anchor	heads broken		
Wire/Geosynthetic	deterioration		
Facing	joints misaligned or too wide; local bulges or distortion, out of plumb, tilting. deflecting, discolor, staining		Wall
Bin or crib			
Concrete	Vertical/transverse cracking, spalled, reinforcement corrosion		
Shotcrete	Soft, drummy, missing, lost durability and strength, pervasive cracking, spalling intercepting corroding, reinforcement corrosion		
Mortar	Soft, drummy, missing, lost durability and strength, pervasive cracking, spalling intercepting corroding		
Block/Brick			
Placed Stone	Opening of discontinuities, cracking, breaking, abrasion		
Stone Masonry	Cracking, weathering, isolated blocks missing		
Foundation material	erosion, scour, shrink-swell, voids, settlement		Foundation material
Auxiliary Elements			
Element Assessed	Sample Narrative	Condition Rating (1-4)	

Wall drains	Pipe broken, clogged, signs of seepage through wall face, trees and shrubs growth in swale		Drain
Upslope	Slumping or significant erosion, over-steepening, removing, or adding materials,		Slope
Downslope	Slumping or significant erosion, over-steepening, removing, or adding materials,		
Lateral slope	Slumping or significant erosion, over-steepening, removing, or adding materials,		
Architectural facing			Other Auxiliary Elements
Road/shoulder			
Culvert			
Curb/Berm/Ditch			
Surrounding Setting			
Element Assessed	Sample Narrative	Condition Rating (1-4)	
Traffic barrier/fence	None (rating 1 assigned if missing)		
Vegetation			
Service functionality			
Element Assessed	Sample Narrative	Condition Rating (1-4)	
Wall Overall Performance			
Wall Action Assessment/Repair Recommendations			
Failure consequence[§]			
Recommended Maintenance Action	No action/monitor/maintenance/repair wall elements/replace wall elements/replace wall		
Overall Ratings			
Predicted Ratings			
Predicted Service Life			
Repair Cost			

* Elements highlighted in red are critical elements

§ The four failure consequences are defined in Table D.2.

TABLE D. 2 FAILURE CONSEQUENCES DEFINITIONS

Consequences of Failures	**Narratives**
Negligible	No loss of roadway, very low public risk, no traffic closure
Moderate	Hourly to short-term closure of traffic, low-to-moderate public risk, multiple alternate routes available
Critical	Relatively long-term monthly or seasonal closure of traffic, high public risk, very few alternate routes available
Catastrophic	Very long-term/year closure of traffic, substantial loss-of-life risk, no alternate routes