Asset Management for Retaining Walls

Final report

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16. Abstract

The work described here represents an attempt to develop a comprehensive risk management framework for the asset management of retaining wall structures. The work presented includes the development of a sensing strategy that can be used by structural inspectors to assess the coupled performance of the wall structure and the geotechnical system it supports. A reliability framework was developed using first-order reliability methods (FORM) to assess the reliability factor (β) for wall components and incorporates the consequences of failure with the estimated structural reliability factors to provide a basis for risk assessment of retaining walls. A new inspection manual was developed to reflect the instrumentation strategies and risk analyses developed.

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β	Reliability index
h_{sat}	Level of soil saturation
q	Optimal surcharge load
ε	Strain
σ	Stress
T	Temperature
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of steel
F	Fahrenheit
μ	Microns
ρ'	Submerged density of soil
ρ_b	Bulk density of soil
ρ_{sat}	Saturated density of soil
M	Flexural moment in wall element
psi	Pounds per square inches
ksi	Kilo-pounds per square inches
θ	Tilt
E_{eff}	Effective modulus of elasticity
I_{cr}	Cracked moment of inertia
y	Depth to Neutral Axis (NA) of section
f_y	Yield strength of steel
f_c	Compressive strength of concrete
R	Risk of failure
P_f	Probability of failure
$C_\$$	Consequence of failure
C	Capacity
D	Demand
G	Limit state function
A_s	Area of steel, on tensile side
$A_s{}'$	Area of steel, on compressive side
C_{rain}	Cumulative rain
k_a	Rankine's earth pressure coefficient
w	Lateral pressure intensity
c/c	Center to center
ϑ	Poisson's ratio
GF	Gage factor
V_{in}	Input voltage
V_{out}	Output voltage
^oC	Degree Celsius
g	Gravitational acceleration
$ft.\ or\ '$	Linear feet
$in\ or\ ''$	Linear inches
#	Bar size number

℄	Center line
MHz	Mega hertz
kB	Kilo bytes
∅	Internal angle of friction

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADC	Analog-to-Digital Converter
DTM	Digital Terrain Model
F.S.	Far Side
FHWA	Federal Highway Administration
FORM	First order reliability method
GAM	Geotechnical Asset Management
GPR	Ground Penetrating Radar
GWT	Ground Water Table
LiDAR	Light Detection and Ranging
LRFD	Load Resistance Factor Design
LVDT	Linear Variable Displacement Transformer
MAP-21	Moving Ahead for Progress in the 21st Century Act
MI	Michigan
MiBEIM	Michigan Bridge Element Inspection Manual
MiERSEIM	Michigan Earth Retaining Structure Element Inspection Manual
MiSIM	Michigan Structure Inspection Manual
MSE	Mechanically Stabilized Earth
N.S.	Near Side
NCHRP	National Cooperative Highway Research Program
RC	Reinforced Concrete
SAMI	System for Asset Management and Inspection
SB	South Bound
SfM	Structure from Motion
SMS	Structure Management Section
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver Transmitter
UAV	Unmanned Aerial Vehicle
VII	Visual Inspection Information

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EXECUTIVE SUMMARY

The purpose of transportation asset management is to meet life-cycle performance goals through the management of physical assets in the most cost-effective manner (FHWA, 2013). Currently, many agencies manage geotechnical features on the basis of "worst-first" conditions, reacting to failures and incurring significant safety, mobility, environmental, and other intangible costs. Whereas, this may be an appropriate response for failures following natural hazards, the goal of geotechnical asset management is to implement project planning and selection on the basis of "most-at-risk" for the asset class with consideration of collective and site specific risks throughout the system life cycle. This report presents results of a research project focused on developing a comprehensive risk management framework for the asset management of retaining wall structures, as well as a new inspection manual for retaining walls.

An instrumentation strategy was proposed for monitoring highway retaining wall systems. Emphasis was placed on a strategy suitable for rapid installation after wall construction to provide data on wall behavior. The project considered instrumentation that can be installed on exposed wall surfaces and that is easy to deploy. The instrumentation strategy adopted tiltmeters to measure wall tilt, long-gage strain gages to measure thermal and flexural strains, and thermistors to measure wall temperatures. 11 wireless sensor units were installed on the retaining wall systems along the I-696 (two wall panels) and M-10 (one wall panel) freeway corridors that collected a total of 16 measurements from the three wall panels and the performance of the instrumented retaining wall systems was assessed using the data collected. An aim of this project was the development of a risk assessment framework that utilized structural monitoring data to define the reliability of the retaining wall system. Combined with the consequence of exceed the limit state obtained from the reliability analysis, the risk of the asset can be determined. Quantifying risk in this way established for the first time, a clear pathway of using monitoring data within a broader GAM strategy. An especially valuable feature of the proposed risk assessment procedures was the explicit inclusion of visual inspection information to define structural conditions critical to the evaluation of structural capacity.

Finally, the report includes the newly developed Michigan Earth Retaining Structure Element Inspection Manual (MiERSEIM). As part of its development, ten sites from a list of 74 provided by the Michigan Department of Transportation (MDOT) were chosen based on factors including type, size, condition, risk/consequence view, past monitoring information, and ease of access. A t eam of personnel from the MDOT, University of Michigan, and the Mannik & Smith Group (MSG) visited each site to determine inspection criteria and methods through hands-on inspection. After all the investigation and data layout was finalized, the MiERSEIM was developed using a format that mirrors the Michigan Bridge Element Inspection Manual (MiBEIM) for its familiarity.

1. INTRODUCTION

1.1 Organization of Report

Chapter 1 presents the objectives of this research report and an extensive literature review. Chapter 2 provides details on the instrumentation deployed at the two MDOT sites, and the collected data. Chapter 3 provides a detailed overview of how the wireless monitoring systems performed over the one-year monitoring period. Chapter 4 presents the process of developing the new inspection manual (MiERSEIM). Chapter 5 discusses a data-driven risk assessment methodology based on long-term monitoring data and visual inspection information. Chapter 6 lists research conclusions and recommendations for future research. Finally, Chapter 7 provides a recommended implementation plan as a product of this research and Chapter 8 includes all references for the report.

1.2 Objectives

The overarching goal of this study is to define an inspection process and develop a comprehensive risk assessment framework for the asset management of MDOT's vast inventory of retaining wall structures. To accomplish this goal, the project has 7 research and implementation objectives:

<u>Objective #1:</u> Conduct Detailed Review of Reported Retaining Wall Management Methods and Failure Case Studies: A detailed review of identified retaining wall failures in Michigan (Jansson, 2007; Jansson, 2013) in addition to other failure case studies in other states will illuminate retaining wall system parameters that should be monitored for health assessment.

<u>Objective #2:</u> Conduct Field Review of MDOT Retaining Wall Systems: A detailed field review to be performed of 10 retaining wall systems in Michigan.

<u>Objective #3:</u> Assess the State-of-Practice in Retaining Wall Monitoring and Repair: Multiple monitoring methods have been proposed for monitoring retaining walls ranging from stationary wired, to stationary wireless, all the way to mobile monitoring platforms (such as those mounted on UAVs and cars).

Objective #4: Propose an Effective Monitoring Strategy: A monitoring strategy is developed for MDOT that feeds quantitative data directly to the proposed risk management framework. A permanent monitoring and inspector-operated non-destructive evaluation (NDE) methodologies is proposed as part of the larger risk management framework.

Objective #5: Development of Data-Driven Risk Management Framework: The team will develop a reliability assessment methodology to assess the factor of safety and probability of failure of retaining wall systems. Coupled with a quantification of failure consequences, a risk assessment methodology is developed to aid MDOT decision making.

Objective #6: Develop Structure and Appraisal (SI&A) Items for Retaining Walls: To acquire detailed records of the MDOT inventory of retaining walls, items required to index retaining wall assets to be added to MDOT's SI&A Codes. Existing codes for bridges and other highway assets to be used as much as possible. The code set proposed for retaining walls will ensure data is available for the risk management procedures developed.

Objective #7: Develop Inspection Procedure for Retaining Walls: A detailed and in-depth inspection procedure will be developed and incorporated in the Michigan Structure Inspection Manual (MiSIM). A stand-alone inspection manual (similar to MiBEIM) to also be written. Procedures will include recommended instrumentation, inspection frequencies according to the type of wall, condition, design, functionality, consequences and other factors relevant to the risk assessment.

Retaining walls are important infrastructure assets which are generally overlooked compared to bridges and pavements in terms of asset management practices. To date, there are several highway agencies that have established retaining wall inventory and inspection programs and very few that have retaining wall asset management programs. Most of the agencies are currently trying to develop their own asset management programs. With the Moving Ahead for Progress in the 21st Century Act (MAP-21 2012), state highway agencies are required to "develop a risk-based asset management plan for the National Highway System to improve or preserve the condition of the assets and the performance of the system, including signs and sign structures, earth retaining walls and drainage structures". An earth retaining structure and a retaining wall are defined as:

Earth Retaining Structure (ERS): Any structure intended to stabilize an otherwise unstable soil mass by means of lateral support or reinforcement (Sabatini et al. 1997).

Retaining wall: A wall which face makes an angle of 70 degrees or more with the horizontal and retains earth (National Highway Institute). Recognizing that earth retention structures other than cut and fill walls may need to be captured in the Inspection and Inventory (I&I) program, some groups have changed this criterion to a 1:1 face angle to also include earth retention structures such as rock buttresses, gabion walls, rockeries, etc. that don't directly meet the NHI design definition but are nonetheless critical assets.

As indicated by the Federal Highway Administration (FHWA), ERSs are "constructed in challenging site conditions, including mountainous terrain, soft ground, and sites that are below water". Newer ERS systems "require that engineered materials such as plastics, concrete, and steel be buried in harsh underground environments…that may adversely influence the long-term engineering properties of the materials. ERSs often have assumed design lives of 100 years, but knowledge of actual design life for these structures is minimal and failures that have occurred to date have happened without warning. Repairing these failed structures is very expensive, complex, and difficult".

In addition, a large number of the ERSs in the United States date from the major Interstate Highway construction in the late 1950s through the 1970s. The earliest of these Interstate-era walls are approaching the end of their anticipated service lives. In the case of the U.S. National Park Service (NPS), most of the walls date to the 1930s through 1940s, when most of the major parks were developed (Brutus and Tauber 2009).

Inspections of ERS should be based, to the extent possible, on the relevant techniques and procedures used in bridge inspection. These are described in detail in the FHWA's "Bridge Inspector's Reference Manual 2006" (Ryan et al. 2012). These techniques reflect decades of experience and there is no need to reinvent them (Brutus and Tauber 2009).

1.3 Review of Existing Guidelines

An extensive literature review was conducted to identify guidelines followed at the State and National level for inspection and assessment of the performance of retaining wall systems.

Currently, 23 transportation agencies have implemented inventory and/or inspection programs for their earth retaining systems in the United States and abroad:

1. Federal Highway Administration (FHWA)/US National Park Service (NPS)
2. California Department of Transportation
3. Colorado Department of Transportation
4. Kansas Department of Transportation
5. Maryland Department of Transportation
6. Minnesota Department of Transportation
7. Missouri Department of Transportation
8. New York State Department of Transportation
9. Oregon Department of Transportation
10. Pennsylvania Department of Transportation
11. The City of Cincinnati
12. New York City Department of Transportation
13. British Columbia Ministry of Transportation (Canada)
14. Alaska Department of Transportation
15. Kentucky Transportation Cabinet
16. Nebraska Department of Roads
17. North Carolina Department of Transportation
18. Ohio Department of Transportation
19. Utah Department of Transportation
20. Vermont Agency of Transportation
21. Wisconsin Department of Transportation
22. The City of Seattle
23. VicRoads, Victoria State Department (Australia)

The data is based on the highway agency programs for which full access was granted and a summary is presented in Table 1.1 and the following sections. Details of individual highway wall inventory and inspection programs will be discussed in subsequent sections.

Table 1.1. Summary of agencies with Inventory or Inspection Program

AGENCY	YEAR	ROUTINE INSPECTION FREQUENCY (years)	HEIGHT (ft)	WALL FACE ANGLE (degrees)	DISTANCE FROM ABUTMENT (ft)	DATABASE	RATING SYSTEM
National Parks Service	2010	10	4	45	40	Visidata, Access	5-100
Alaska DOT	2013	5	4	45	100	Access	Good, Fair, Poor
Colorado DOT	2016	6	4	45	40	SAMI	0-9
North Carolina DOT	2015					Access, Oracle	1-4
Pennsylvania DOT	2010	5			100	iForms	2-8
Nebraska DOR	2009						0-9
New York City DOT	1998	5	6				Safe, Safe w/minor repair, Safe with repair and monitoring, Unsafe
New York State DOT	2015		6		33	ArcMap	1-7
Wisconsin DOT	2011	6	5				Good, Fair, Poor, Severe
Oregon DOT	2007	5	4			Access	Good, Fair, Poor
Utah DOT	2009					MAP Window GIS, Access	Yes or No
Ohio DOT	2007						Yes or No
City of Cincinnati	1990	6	2			FoxPro, Oracle, ArcGIS	0-4
City of Seattle	2009		4			Access, Hanson	0-100
British Columbia MOT	2013	TBD	6.5	45		DataBC, ArcGIS	Excellent, Good, Fair, Poor, Very Poor
VicRoads-Australia	2014	2-5	4.9	45	16.4		1-4

WALL CLASSIFICATION

Retaining walls can be divided in different categories based on their function and type. Walls that are constructed from the bottom up are fill walls, while walls built from the top to the bottom are cut walls. Most inventories include all wall types. Some agencies have inventory programs only for Mechanically Stabilized Earth (MSE) walls because of resource constraints or just because MSE walls represent the majority of the wall types in the State. Agencies that fall into the latter category are: Nebraska DOR, Ohio DOT, Pennsylvania DOT and Utah DOT. Table 1.2 depicts different wall functions and types used by the FHWA-NPS (DeMarco et al. 2010) and the Wisconsin DOT (2017). Some agencies include walls associated with bridges and culverts.

WALL ACCEPTANCE CRITERIA

Agencies use different criteria when determining which retaining walls to include in their inventory program. A summary of different guidelines that are used is presented in Table 1.1. The main criteria are:

- Minimum exposed height of wall (visible or total): 2-6 ft
- Minimum height of retained earth
- Minimum length of wall (PennDOT)
- Minimum face slope greater than 45 degrees
- Wall batter, location relative to roadway, association with bridge/culvert
- Walls with distance from roadway bridge abutment: 16.4 ft to 100 ft
- Wall ownership

Noise walls do not retain earth, thus are usually under another inventory program. Bridge and culvert walls are usually part of the Bridge and Culvert Inspection Program, respectively. Agencies use a specific distance from the bridge abutment to decide whether to include a wall to the Earth Retaining Wall Program. For example, 40 ft is used by the FHWA-NPS and Colorado DOT, 100 ft is used by Alaska DOT and Pennsylvania DOT, 10 m is used by New York State DOT and 5 m is used by Victoria State Department in Australia. New York State and New York City DOTs do not include railroad-owned walls in their programs. It is suggested that an ERS Inventory include all walls regardless of ownership, since a potential failure (e.g. New York City

Department of Buildings (2007) and Tennessee Department of Transportation (2003)) might impact the highway facility (Brutus and Tauber 2009).

RANKING METHODS OF ERSs

The following methods are used by different agencies to identify and locate retaining walls:

- Physically locating the wall in the field by walking or driving to the wall
- Using aerial surveys
- Using as-built drawings or records
- Using roadway video surveys
- Using Google Maps, Bing Maps
- Using Asset Identification
- Through LiDAR and ARAN surveys
- Flood insurance, drainage, public utility maps
- Using a Geographical Information System
- Using staff knowledge
- Adding new walls as constructed

WALL ATTRIBUTES

Brutus and Tauber (2009) compiled a list of 96 possible attributes from inventory forms provided by several agencies that currently maintain inventory or inspection programs (Table 1.3). Some of the data is to be collected in the field and some can be completed back in the office. The level of detail in the database is to be decided by the highway agency according to its needs, budget and other factors.

Table 1.2. Classification of Wall Function and Type according to the FHWA-NPS and Wisconsin DOT programs

Wall Function		Wall Type	
FHWA-NPS	**Wisconsin DOT**	**FHWA-NPS**	**Wisconsin DOT**
Fill Wall	Fill Wall	Anchor, Tieback H-Pile	Anchor, Sheet Pile
Cut Wall	Cut Wall	Anchor, Micropile	Anchor, Soldier Pile
Bridge Wall	Dockwall	Anchor, Tieback Sheet Pile	Anchor, Secant/Tangent
Head Wall		Bin, Concrete	Cantilever, Sheet Pile
Switchback Wall		Bin, Metal	Cantilever, Soldier Pile
Flood Wall		Cantilever, Concrete	Cantilever, Secant/Tangent
Slope Protection		Cantilever, Soldier Pile	Cast-in-place, Gravity
		Cantilever, Sheet Pile	Cast-in-place, Cantilever
		Crib, Concrete	Gravity, Gabion
		Crib, Metal	Gravity, Modular Block
		Crib, Timber	MSE, Modular Blocks
		Gravity, Concrete Block/Brick	MSE, Precast Panel
		Gravity, Mass Concrete	MSE, Wire Face
		Gravity, Dry Stone	Soil Nail
		Gravity, Gabion	
		Gravity, Mortared Stone	
		MSE, Geosynthetic Wrapped Face	
		MSE, Precast Panel	
		MSE, Segmental Block	
		MSE, Welded Wire Face	
		Soil Nail	
		Tangent/Secant Pile	

Table 1.3. ERS Data Attributes (after Brutus and Tauber 2009)

SURVEY LOG DATA	FUNCTION DATA	STRUCTURAL DATA, PRELIMINARY	CONDITION DATA FROM INSPECTION	CONSEQUENCES OF FAILURE FACTORS
ID number	Functional type	Wall face material	Inspection report	Critical wall height
Date of Survey	Supported feature	Apparent wall type	Inspection date	Critical distance
Times of arrival and departure	Protected feature	Wall surface treatment	Name of inspector	Roadway type and lanes
Surveyed by	Photo(s) of supported and/or protected features	Wall top feature	Prior documentation reviewed	Sensitive facility supported
Weather	**DIMENSION DATA, GENERAL**	Top of wall attachments	Potential failure type	Sensitive facility protected
Soil Moisture	Exposed height	Wall face attachments	Condition rating	COF rating
Work-zone safety devices or measures	Total length	**STRUCTURAL DATA, VERIFIED**	Performance rating	Traffic volumes
Special access equipment	Wall face slope	Structural type	Projected replacement date	Interchange distances
LOCATION DATA	Total height	Total wall face	Recommended action type	Utilities near top of wall
GPS location coordinates	Estimated area of exposed face	Estimated replacement cost per square foot	Recommended action summary	Utilities near base of wall
Location	Exposed height at beginning point	Cost estimate reference	**HISTORY AND OWNERSHIP**	Utilities on wall face
Offset	Exposed height at end point	Estimated total replacement cost	Year built	Detour length
Location photos	Height above retained soil	Wall face angle as built	New or retrofit	Affected locations
District/political subdivision	Upslope angle	Foundation type	Design service life	**ACTION PRIORITY**
End coordinates	Downslope angle	Proprietary type	Current owner	Action approved
Bridge/culvert association	Criterion length	Fill material	Owner contact information	Action priority
Other related feature	Offset criterion portion	**CONDITION DATA, PRELIMINARY**	Original owner	Action date scheduled
Access constraints	Photo(s) of top profile	Checklist conditions	Original contract number	Action completed
Did constraints affect accuracy?	Roadside features above	Inspection priority	Original cost	
Block and lot number	Roadside features below	Condition photos and sketches	Maintenance/repair /modification record	
Photo(s) of access constraints	Photos of roadside features		Original designer	
			Original contractor	

INSPECTION FREQUENCY

The frequency of inspection varies on the conditions found. Routine wall inspections range from two to ten years (Table 1.1), with the most common being a 5-year interval. More frequent inspections may be triggered by (Brutus and Tauber 2009):

- Walls exhibiting poor performance
- The environmental setting (regional climate, geology, etc.). In cold climates, for instance, walls susceptible to freeze-thaw cycles may require more frequent inspections
- The age of the wall. Older walls may require more frequent inspections
- Certain recent wall types (e.g., steel reinforced earth retaining structures or MSEs) where long-term performance records are not available
- The consequence of failure
- Occurrence of an event, such as flood or weather-related damage, or a vehicle impact, or an earthquake, etc.

WALL ELEMENTS ASSESSMENT

The FHWA-NPS WIP divides the wall elements that need to be evaluated into primary and secondary. Other agencies use a simple check list to assess the overall wall condition. The following wall elements are assessed by highway agencies:

- Wall type
- Foundation
- Wall alignment
- Facing structure/treatments
- Surface coatings
- Attachments
- Guardrails/parapets
- Backfill material
- Backfill slope
- Drainage
- Erosion

- Vegetation
- Roadway
- Curb/Berm/SW/shoulder
- Adjacent features

CONDITION OBSERVATIONS

After the wall elements are identified, their condition is assessed in terms of observed element distress or deterioration. The FHWA-NPS WIP evaluates the elements in terms of type, severity, extent and urgency. Brutus and Tauber (2009) recommend checking the following conditions when inspecting a retaining wall:

1. Wall or parts of it, out of plumb, tilting or deflected
2. Bulges or distortion in wall facing
3. Some elements not fully bearing against load
4. Joints between facing units (panels, bricks, etc.) are misaligned
5. Joints between panels are too wide or too narrow
6. Cracks or spalls in concrete, brick, or stone masonry
7. Missing blocks, bricks, or other facing units
8. Settlement of wall or visible wall elements
9. Settlement behind wall
10. Settlement or heaving in front of wall
11. Displacement of coping or parapet
12. Rust stains or other evidence of corrosion of rebars
13. Damage from vehicle impact
14. Material from upslope rockfall or landslide adding to load on wall
15. Presence of graffiti (slight, moderate, heavy)
16. Drainage channels along top of wall not operating properly
17. Drainage outlets (pipes/weep holes) not operating properly
18. Any excessive ponding of water over backfill
19. Any irrigation or watering of landscape plantings above wall
20. Root penetration of wall facing
21. Trees growing near top of wall

22. Any other observations not listed above

Since it is easier to identify drainage problems by inspections during or after heavy rains, the inspection engineer should arrange for such inspections, if the adequacy of the drainage system is in doubt.

RATING SYSTEM

The types of rating systems used to evaluate ERSs can vary between qualitative assessments and quantitative assessments. The FHWA-NPS program uses a “Condition narrative” which is a descriptive narrative of element condition. These narratives are then converted to a numerical “Condition rating” ranging from 1 to 10. A wall performance rating is also determined along with the element condition ratings, using again a scale from 1 to 10, and the combination of these two create an overall wall performance rating ranging from 5 to 100. Conversion of this numeric rating to a qualitative description can be approximately achieved by dividing the rating by 10 and comparing it to the element and wall performance definitions.

Some agencies, e.g. North Carolina DOT and VicRoads simply follow the four-level rating scale that is used in AASHTO’s “Manual for Bridge Evaluation” (AASHTO 2010a). The City of Cincinnati uses a scale from 0 to 4. Nebraska DOR and Colorado DOT follow the 0 to 9 scale found in the “Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges” published by FHWA (US DOT 1995). Oregon DOT has a three-level rating system based on Good, Fair and Poor condition ratings. Ohio DOT and Utah DOT have simple “yes” or “no” condition rating responses. The New York City DOT and the New York State DOT use a scale from 1 to 7. A summary of the different rating systems utilized is shown in Table 1.1.

RISKS ASSOCIATED WITH ERS FAILURE

After the wall condition is evaluated, risk of the likelihood and consequences of an adverse event is assessed. Most of the agencies do not have a risk-based asset management plan for retaining walls with the exception of FHWA-NPS, Colorado DOT and North Carolina DOT. Some of the consequences of failure to be considered are:

- Failure potential

- Extent of failure
- Threats to life safety
- Budget impacts for wall repair
- Link criticality/redundancy
- Average Daily Traffic (ADF) impacts
- Disruption of adjacent utility lines (water mains, electrical conduits)
- Impact to environmental resources

Recommendations for further actions are then provided. Depending on the level of risk that is determined the inspector can recommend:

- No action is needed
- Monitor of the wall is required to determine what action should be followed
- Maintenance: routine maintenance activities are required to delay wall deterioration
- Repair: non-routine restoration of wall elements is required
- Rehabilitation: replacement of wall elements or the entire structure is required

DATABASE/MAPPING SOFTWARE

Agencies maintain their retaining wall databases through different platforms. A single interface that would provide access to inventory, inspection and geospatial data, as well as photographs, drawings and documents would be the best approach. Some agencies use the PONTIS bridge management system to inventory their walls. Other popular databases that are used are Microsoft Access, Oracle, ESRI GIS and other GIS software (Table 1.1).

Some agencies link their Wall Management System to other management systems. For example, Minnesota’s DOT system is linked to the permitting department, Pennsylvania’s DOT system is linked to Roadway Management, Planning & Programming System, and Maintenance Management System and British Columbia’s system is linked to its road inventory management system.

PERSONNEL REQUIREMENTS

Data collection and condition assessment can be a one-step or two-step process. Data collection consists of recording wall attributes and condition assessment is the evaluation of the wall condition. Most agencies use a two-step process, inventory and evaluation of the walls are done in two separate steps. Once the data collection is performed, the wall is scheduled for inspection if it meets the inventory criteria. Data collection can be performed by surveyors or technicians who will check and complete the field survey forms. Condition assessment must be done by a civil, structural or geotechnical engineer or certified bridge inspector. The offices that are usually responsible for conducting and managing retaining wall inventories and condition assessment are the bridge or structures unit, the geotechnical unit, the maintenance unit and the district offices (Brutus and Tauber 2009).

Findings that are followed by different agencies in terms of retaining wall inventory, inspection and asset management programs are provided in detail in the following sections. Some parts are taken directly from the agency guidelines.

An Asset Management Plan should include the following components according to AASHTO (2011):

- Data management
- Inventory and condition surveys
- Levels of Service
- Service Life
- Performance measures and condition indices
- Risk management
- Life cycle and benefit and costs analyses
- Decision support

An example of processes for a proposed geotechnical Asset Management Plan is presented in Figure 1.1.

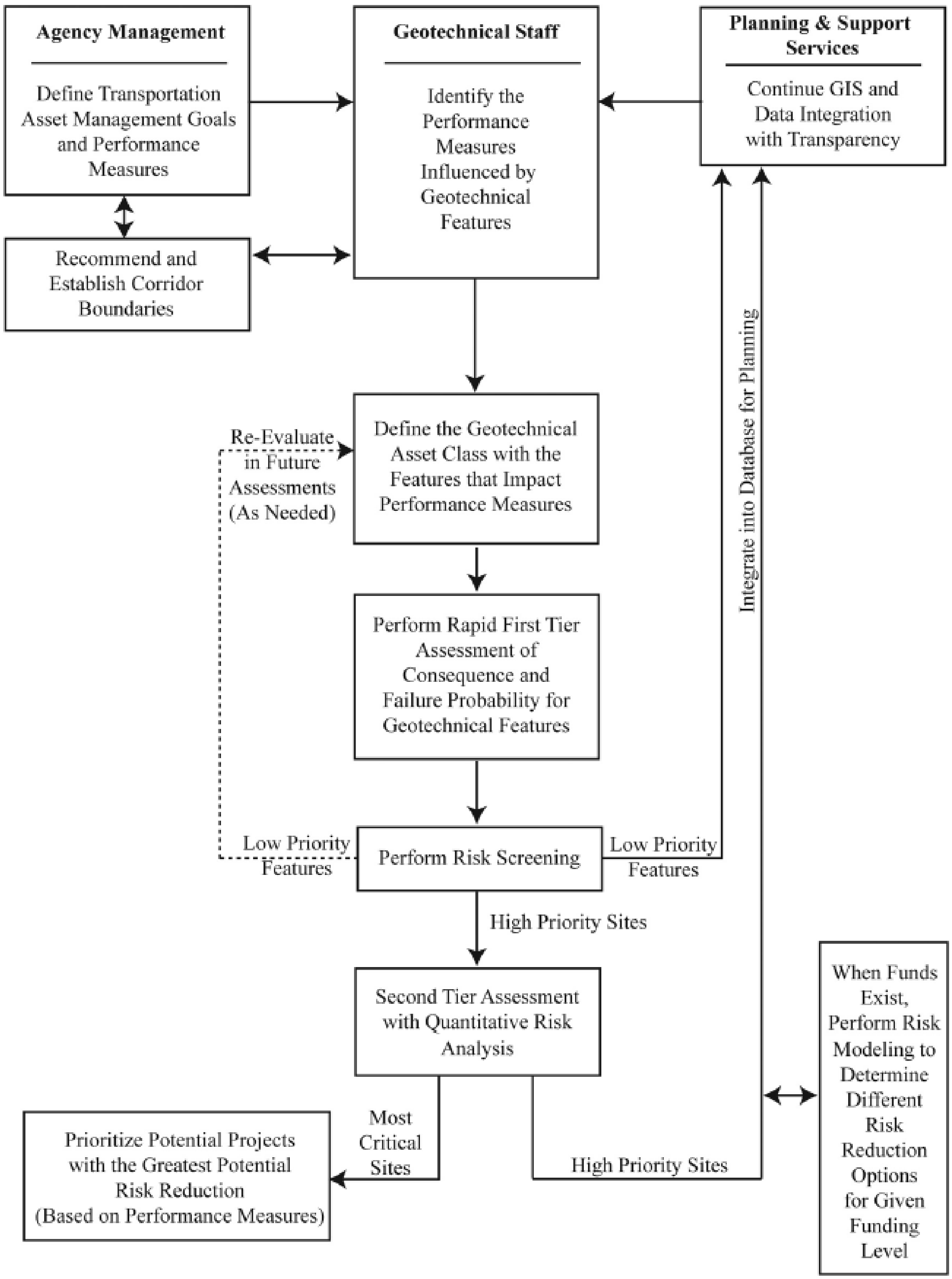


Figure 1.1. Proposed processes for a geotechnical asset management plan (from Vessely 2013)

1.3.1. Brutus and Tauber (2009) Synthesis Report and recommendations

This publication presents methodologies aimed to help transportation agencies establish asset management programs for earth retaining structures, and specifically Inventory and Inspection (I&I) programs. The programs would then provide the essential information for a broader Asset Management program. A five-year interval for routine inspections is recommended.

A five-point **rating scale** is suggested as a sample rating system, as follows:

1. **Excellent:** No significant indication of distress or deterioration
2. **Good:** Some indications of distress/deterioration, but wall is performing as designed
3. **Fair:** Moderate or multiple indications of distress/deterioration affecting wall performance.
4. **Poor:** Significant distress/deterioration with potential for wall failure.
5. **Critical:** Severe distress/deterioration. Indications of imminent wall failure.

The **consequences of failure** that are considered in the performance of risk assessment include:

- Death or injury to persons, including facility users and those on adjacent properties or facilities
- Damage to property including vehicles, highway property or facilities, and adjacent property or facilities
- Disruption of highway operations, including full or partial closure of the roadway, or appurtenant facilities
- Disruption of adjacent utility lines, such as water mains or electrical conduits
- Environmental consequences, such as damage to a significant wildlife habitat or blockage of a watercourse
- Damage to cultural assets or sensitive land uses

A three-level consequence of failure rating system is suggested:

1. **Severe**: High likelihood of injuries or death from debris falling on a heavily traveled roadway, on other heavily used adjacent areas, or from collapse of structures near top of wall. High likelihood of extensive or total-loss damage to vehicles or structures. Complete closure of a heavily traveled roadway requiring lengthy detours.

2. **Significant**: Low probability of injury to persons but likelihood of any of the following: (a) substantial property damage, (b) interruption of water or other utility service to a large area, (c) lengthy blockage of access to business properties or public facilities, (d) long-term damage to environmental or cultural resources, (e) closure of two or more lanes of a heavily traveled roadway, (f) full closure of any roadway with no alternative access or requiring lengthy detours.
3. **Minor:** Low probability of either injury to persons or of damage to vehicles or non-highway property or facilities. Full roadway closures where alternative access is available. Closure of a single lane on a heavily traveled roadway.

It is recommended to collect information from ERSs that are being demolished because of a highway widening or alignment. A careful investigation can yield useful information for the design of future structures.

1.3.2. Minnesota DOT Synthesis Report (2013)

The Minnesota DOT prepared a synthesis report (CTC and Associates 2013) of asset management programs followed by other transportation agencies. Three agencies provided guidance to most of the MnDOT's questions: FHWA for the National Park Service (NPS), Alaska Department of Transportation & Public Facilities (DOT&PF) and Oregon DOT. The main findings can be characterized as:

- **Inventory Methods:** FHWA relied on maintenance staff guidance to conduct its inventory of retaining walls. Alaska DOT&PF thus far has used only internal records, but in its next phase will recruit technicians to collect data in the field. These technicians will systematically target critical routes and interview district maintenance personnel to find concealed walls. Alaska DOT&PF hopes eventually to use such technologies as Light Detection and Ranging (LiDAR). Oregon DOT uses Google Maps and Bing Maps for visible walls and field visits for others.
- **Attributes:** Height, length, location, condition and wall type are typical attributes. FHWA suggests keeping data collection simple initially, although it collected data for an extensive number of attributes for its program.
- **Inspection:** Interviewees agreed on five years as an appropriate interval for routine inspection.
- **Useful Life:** This is a difficult topic that even FHWA is unsure how to manage in its database. Alaska DOT&PF and Oregon DOT have not yet addressed this topic.
- **Performance Measures:** FHWA has data collection forms and libraries in their Wall Inventory Program (WIP). Oregon DOT and Alaska DOT&PF have not yet developed performance measures.
- **Risk Management:** None of the interviewees had conducted an extensive risk analysis.

1.3.3. National Park Service (NPS) Wall Inventory and Condition Assessment Program (WIP) (2010)

The FHWA Wall Inventory Program (WIP) is the best documented wall inventory program in the United States to date. Assessment of 3,500 retaining walls in 32 NPS properties across the US was conducted. The overall performance was very good despite the 60+ year age of the majority of the walls.

Concrete walls (1940s and 1950s era) are showing signs of deterioration, and many needed repair. Corrugated steel bin walls (1960s era), surprisingly used in near-coast applications, were rotting and failing from corrosion. MSE walls were still in good shape for the most part. FHWA has only conducted one inventory and condition assessment, so it doesn't have data on life-cycling. Stone walls were working the best, with more modern wall designs (steel elements) degrading the most and heading toward replacement quickest.

In the WIP database, less than 1% of the walls required replacement or substantial repair. About 3% required replacement of some elements. The bulk of the rest of the maintenance recommendations primarily involved drainage cleanouts, stone resetting/repointing and vegetation removal. No risk analysis has been completed. FHWA examined rate failure consequence, but did not roll up in the wall condition rating.

The best approach to creating a program is to develop a simplified inventory and condition screening method to locate and describe walls (type, size and location) on any given route using the cheapest labor available. The VisiData software was used, which is a program to view data collected along roadways. The VisiData Wall Location Form has information about:

- Road Inventory Program (RIP) route name and/or number
- Side of wall in which the wall is located when travelling in the direction of increasing RIP milepoints
- Approximate VisiData wall start and end milepoints
- Apparent wall function
- Apparent wall type
- Comments regarding wall accessibility, general wall condition, etc.

A team of two members, led by a Geotechnical, Structural or Geological Engineer is responsible for the following during the wall assessment:

- Accurately locate the wall (park, route number/name, milepoint, etc.)
- Describe wall dimensions and features
- Acquire descriptive photos
- Rate the condition of the wall and its key elements, as well as the reliability of the data supporting the wall rating
- Assess if further investigations are required
- Determine the design criteria used to construct the wall (if any)
- Determine the consequences of wall failure
- Determine whether the wall is a cultural resource or not
- Determine the appropriate repair/replace actions (no action/monitor, maintenance, repair element, replace element, replace wall, and/or investigate)
- Develop an appropriate work order, as needed, estimating investigation, maintenance, repair, replacement costs
- Conduct all aspects of the inspection in a manner promoting safety amongst the team and traveling public

The current WIP database was developed as a Microsoft Access application allowing migration to an Oracle platform for database management, rapid queries and future developments.

DeMarco et al. (2010) also recommended a robust location method. FHWA did not use GPS for the NPS program because it is unreliable in many park settings. Instead it used milepoints from Automatic Road Analyzer (ARAN) pavement surveys (which also had roadway GPS). This system worked well, but not without some issues while new ARAN cycles come online.

For the NPS WIP, 65 different attributes were collected to define, quantify, and assess the different variety of ERSs included in its database. As a result, their database application uses three forms for entering data collected during field inspections. The first form contains general descriptions including the ERS's location, function, type, age, facings, and surface treatments. The second form is used to enter condition assessment data for each individual wall element. The third form is used to enter action assessment data such as an overall wall condition rating, a wall descriptions, and repair recommendations. The forms can be found in Appendix A, while some key parameters can be found below.

Re-inspection is based on:

- Total asset performance
- Wall type (metal and wire-faced walls need shorter inspection cycles due to deteriorating metal face elements)
- Wall location (walls subject to coastal marine environments, high annual precipitation, extreme freeze-thaw cycles, rapid vegetation growth)
- External event/park request (emergency relief events, landslides, rapidly developing wall failures, recent wall construction in the park)

Maximum of <u>10-year inspection cycle</u> and re-inspection of the total asset if condition rating is <u>less than 70</u>.

WALL ACCEPTANCE CRITERIA

- Qualifying roads; walls located on paved park roadways and parking areas
- Relation to roadway asset
- Wall height **≥ 4 ft**; culvert headwalls/wingwalls ≥ **6 ft**
- Wall embedment; fully or partially buried retaining walls are included in the inventory (e.g. patterned ground anchor walls and buried portions of tieback soldier pile walls)
- Wall face angle **≥ 45 degrees** (applies to tiered walls considered as single wall system)
- General acceptance; wall protects roadway or parking area and where failure would significantly impact the roadway

WALL FUNCTION

Refers to the purpose of the retaining structure:

- Fill wall; supports specified soil or aggregate backfill
- Cut wall; supports natural ground
- Bridge wall; wingwalls that continue more than 40 ft beyond the abutment
- Culvert/Head wall; ≤ 20 ft total span

- Bridge wall; wingwalls that continue more than 40 ft beyond the abutment
- Culvert/Head wall; ≤ 20 ft total span
- Switchback wall; between upper and lower roadway on the inside of a switchback curve
- Flood wall; constructed along flood channels, inland surge walls and seawalls
- Slope protection (e.g. rock buttresses, riprap, stacked rock inlays)

WALL TYPES

- Anchor (Tieback H-Pile/Soldier pile tieback, Micropile, Tieback Sheet Pile)
- Bin (Concrete, Metal)
- Cantilever (Concrete, Soldier Pile, Sheet Pile)
- Crib (Concrete, Metal, Timber)
- Gravity (Concrete Block/Brick, Mass concrete, Dry stone, Gabion, Mortared Stone)
- MSE (Geosynthetic wrapped face, Precast panel, Segmental block, Welded wire face)
- Soil nail
- Tangent/Secant Pile

ARCHITECTURAL FACINGS

Elements that do not contribute to the support capacity of the structure include brick veneer, cementitious overlay, fractured fin concrete, formlined concrete, plain concrete, planted face, sculpted concrete, shotcrete, steel, stone, simulated stone, stone veneer and timber.

SURFACE TREATMENTS

Coatings or treatments used to color, preserve or protect wall elements include bush hammer, color additive, galvanization, paint, preservative, silane sealer, stain, tar coatings and weathering steel.

PHOTOS TO CAPTURE KEY WALL ELEMENTS

- Wall approach
- Wall frontal elevation
- Top of wall/roadway

- Wall face alignment
- Wall face detail
- Wall failure/deficiency detail

WALL CONDITION ASSESSMENT

Primary and secondary elements are evaluated, first by descriptive condition narratives and then a 1-10 numerical "Element Condition Rating". The overall performance of the wall is evaluated and rated. Wall performance includes global wall distresses and evidence of prior repairs that may indicate component problems. Weighting Factors are applied to the Primary Elements and Wall Performance condition ratings. Once the overall wall performance and pertinent primary/secondary wall elements have been assessed and rated, the inspecting engineer rolls up the weighted element ratings into a "Final Wall Rating". This value ranges from 5-100 and is representative of the overall wall condition.

Consequence of Failure

- **Low**: No loss of roadway, no-to-low public risk, no impact to traffic during wall repair/replacement;
- **Moderate**: Hourly to short-term closure of roadway, low-to-moderate public risk, multiple alternate routes available; or
- **High**: Seasonal to long-term loss of roadway, substantial loss-of-life risk, no alternate routes available.

Recommended Action

Consideration is given to the Final Wall Rating, any identified requirements for further site investigations, the apparent design criteria employed at the time of the construction, any cultural concerns and the consequences of failure to determine a recommended action:

- **No Action**: The wall is fully functioning, with no action required at the time of the inspection.
- **Monitor:** The wall requires regular monitoring and/or investigation to determine the nature of observed distresses and what action may be required.

- **Maintenance**: Routine or cyclic maintenance is required to correct minor or low severity recurring deficiencies spanning a single wall element or the entire structure in order to minimize or delay further wall deterioration.
- **Repair Elements**: Minor to extensive repair of wall element(s) is required in the near-term to prevent rapid element deterioration, loss of performance or failure.
- **Replace Elements**: Replacement of specific wall element(s) or an entire section of wall is required in the near-term to preserve wall stability.
- **Replace Wall**: Replacement of the entire wall structure is required to reestablish the intended function of the wall.

1.3.4. North Carolina DOT (2015)

This research study (Rasdorf et al. 2015) included a literature review, an identification of ERS data attributes and critical elements of data collection, the development of data collection forms for inventory and condition assessment, the identification of five predominant retaining wall types of greatest interest to the North Carolina Department of Transportation (NCDOT), a study of existing rating systems, a pilot study of 15 geographically distributed ERS locations, the development of a condition assessment system for various retaining wall types, a field application study, and the development of a prototype database. 32 ERSs were inventoried and field surveyed with the database philosophy emphasizing simplicity.

The NCDOT has implemented an integrated asset management system (AMS), which is comprised of Pavement, Maintenance, and Bridge Management Systems and includes Asset Trade-Off Analyst in a single Oracle database utilizing an interactive user interface (Microsoft Access). The NCDOT's Bridge Management System (BMS) has functions that can be applied to ERSs.

Some of the data, such as the retaining wall type, location, and configuration details are static in nature while others, such as geometry are dynamic as the ERS is subjected to tilt, lateral deformation, and differential movement.

A total of 15 ERS sites containing a variation in the distribution of ERSs, with respect to location, retaining wall type, and condition were investigated (MSE, Soil nail, Anchored, Gravity, Cantilever). The data collected was utilized to develop a rating system for a quantitative condition assessment of various retaining wall types.

Two data collection forms were developed: the Wall Identification and Data Attributes Form and the ERS Field Condition Inspection Data Collection Form (Appendix A.2). For the first form, data fields were programmed with drop-down menus in order to minimize errors made by the inspectors. The condition assessment criteria of the second form included four categories: facing, movement, drainage and exterior. There are a total of 17 condition evaluation criteria among the four category observations:

1. **Facial Deterioration:** Missing facing units, spalling, delamination, weathering (splitting or rotting), other deterioration of the wall facing, or graffiti.

2. **Staining:** Discoloration of the facing of the wall from water, efflorescence, rust, or other evidence of corrosion.

3. **Damage:** Damage to the wall from vehicle impact or root penetration.

4. **Cracking:** Structural cracking that penetrates the facing of the wall.

5. **Joint Alignment:** Joints between facing units (panels, bricks, etc.) and/or adjacent wall sections that are inconsistent, misaligned, or uneven across the facing of the wall.

6. **Joint Spacing:** Joints between facing units (panels, bricks, etc.) that are too wide (exposing organic material) or too narrow (removing proper spacing).

7. **Material Loss:** The loss of backfill material through the facing of the wall.

8. **Defection/Rotation:** Wall or parts are visually out of plumb, tilting, or deflecting resulting in a negative or positive inclination beyond the wall's original batter.

9. **Bulges/Distortion:** Local bulges (outward bend or curve) or distortion in the wall facing.

10. **Settlement:** Settlement of wall, visible wall elements, or tension cracks behind wall.

11. **Heaving:** Upward movement or swelling of soil in front of wall.

12. **Erosion**: Disruption or loss of soil or backfill material over a wide area within the sphere of influence of the wall.

13. **Scour**: Evidence of localized material loss specifically at the wall or around the foundation.

14. **Internal/External Drains:** Evidence of improper passage of water through or over the facing of the wall (i.e., clogged drainage outlets (pipes or weepholes) or drainage channels along top of wall that are not operating properly).

15. **Wall Top Attachment:** Displacement, misalignment, or deterioration (staining, cracking, damage, etc.) of the wall top attachment (Fence or Handrail, Coping, Concrete Barrier Rail, Guardrail, etc.).

16. **Road/Sidewalk/Shoulder:** Cracks, depressions, heaves, and any other evidence of active earth movement within the sphere of influence of the wall.

17. **Vegetation:** Evidence of excessive vegetation on or around the wall.

If the findings from the field condition assessments indicate that an ERS is showing signs of failure, then the additional field evaluations should be undertaken immediately. For critical safety problems, a more detailed means of measurement may include LiDAR measurements taken at some point in time or at other regular intervals as determined by the NCDOT. For noncritical ERSs, LiDAR measurements could be taken only if and when an ERS element is distorted, deflecting, or settling.

To design and develop the WICAS, the North Caroline State University (NCSU) research team used the Microsoft Access database management software tool. A platform such as Sharepoint (web application) can be used in conjunction with MS Access services to create a database that is accessible via the internet. Figure 1.2 shows the main menu of the WICAS, which has six menu options.

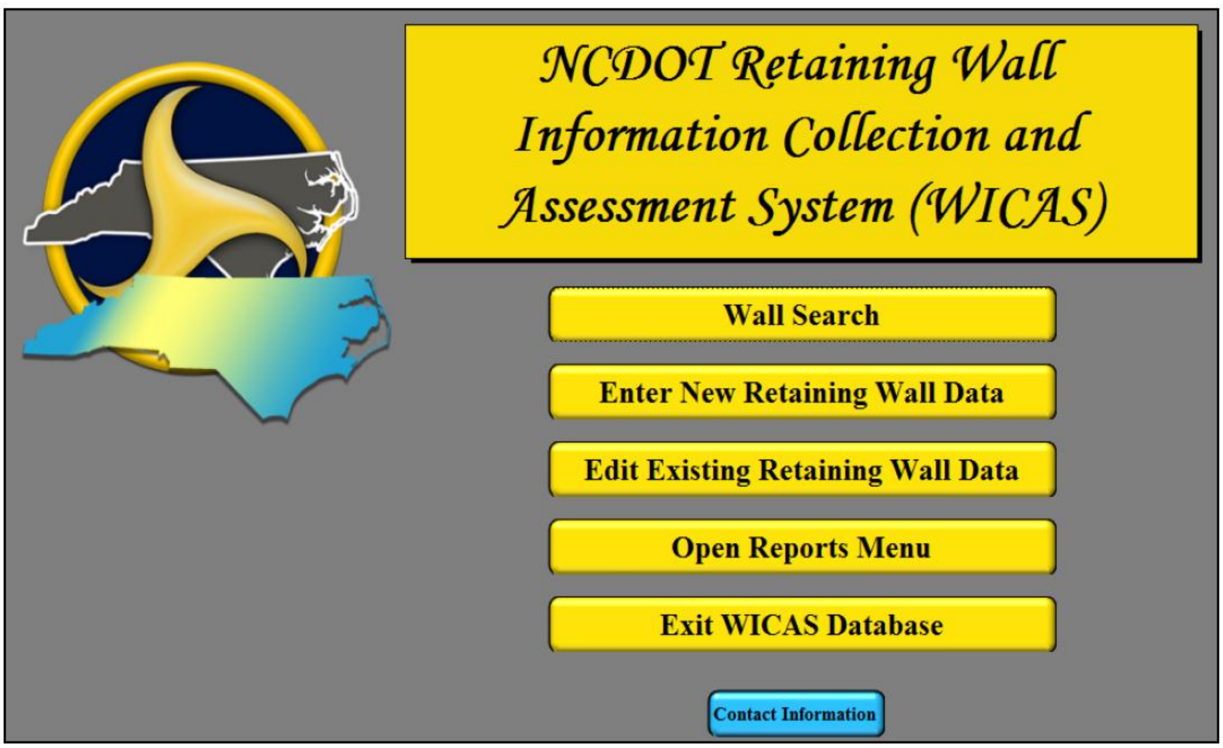


Figure 1.2. WICAS home screen (from Rasdorf et al. 2015)

Wall search provides basic information of a wall; location, wall type and condition (Figure 1.3). Every wall is assigned a unique six-digit identification number. The first two digits indicate the county where the ERS is located and the last four digits identify the individual records created and stored in the database for that ERS.

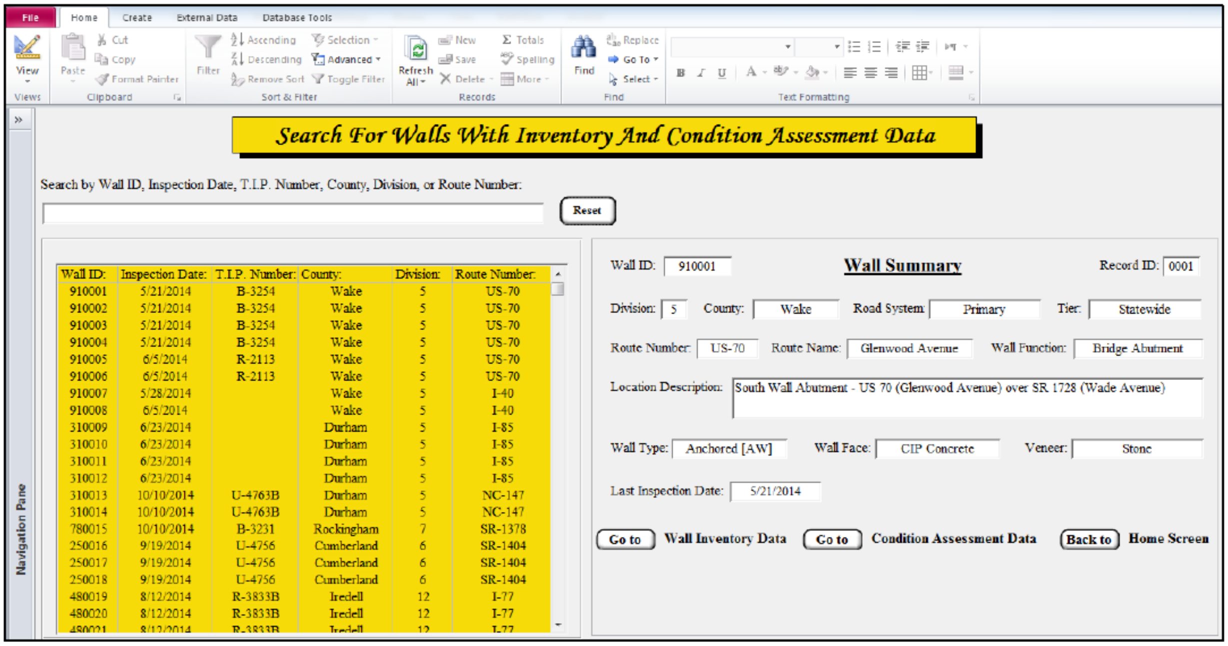


Figure 1.3. Wall Search menu (from Rasdorf et al. 2015)

The NCSU research team recommends the same rating approach outlined in AASHTO's "Manual for Bridge Element Inspection". The rating method is very similar to the one for VicRoads Technical Consulting in Victoria Australia (1 to 4 rating). Two inspectors surveyed the 32 ERSs to determine whether or not they could obtain similar average criteria ratings for the same ERSs.

The condition of an ERS is determined by performing field inspections and recording quantities for criteria with defects that correlate to a prescribed condition state (GOOD = 1, FAIR = 2, POOR = 3, and SEVERE = 4). The condition assessment is complete when the appropriate portion of the total quantity is stratified over the defined condition states (e.g., with respect to cracks in the wall facing 25% of the wall may be in FAIR condition and the remaining 75% in POOR condition). As with VicRoads and AASHTO, the sum of the individual condition percentages assigned to each criterion has to equal 100%. Once the appropriated percentages are assigned to the 17 criteria listed on the "Field Condition Assessment Data Collection Form", they are then used in a weighted averaging process to determine a single value rating for each criterion. Table 1.4 shows the rating definitions and examples of the four condition states.

For example, for the "staining" criteria, the inspector determines that roughly 10% of the entire ERS showed signs of staining corresponding to a "Fair" condition state, 40% in a "Poor" condition state, and 50% in a "Severe" condition state. In this example, the majority of staining (roughly 90%) was deemed to be in a "Poor" or "Severe" condition because the steel sheet piles were severely rusted allowing groundwater to seep through the wall facing. As a result, when all the percentages (by rating) were aggregated together (using a weighted average), the overall criteria rating (average rating) was determined to be 3. The calculation for the "Average Rating" was determined in the following manner:

CATEGORY OBSERVATIONS	PERCENT BY RATING				AVERAGE RATING	COMMENTS
	1	2	3	4		
Facial Deterioration	0	0	50	50	4	Severely weathered sheet piles.
Staining	0	10	40	50	3	The steel sheet piles are severely rusted allowing groundwater to seep through the wall.

Example Average Rating Calculation: (**1** x 0%) + (**2** x 10%) + (**3** x 40%) + (**4** x 50%) = **3.4**

In accordance with the element condition rating definitions outlined in Table 1.4, this means the distressed "staining" criterion may result in a wall failure without near-term repair or replacement.

Table 1.4. Proposed condition rating system (from Rasdorf et al. 2015)

Condition State	Description	Example
1 "GOOD"	**Low Severity Distress** The distress does not significantly compromise the wall's function, nor is there significant or severe distress to major structural elements. An average criteria rating of 1 indicates a criterion that is showing no distress whatsoever or is only beginning to show the first signs of distress or weathering.	A soldier pile wall may have moderately extensive minor surface corrosion on piles where protective paint has weathered and peeled, and may have wood lagging beginning to split. Distresses are very low overall, present over a modest amount of the wall, and do not require immediate or near-term attention.
2 "FAIR"	**Low-to-Medium Extent of Medium Severity Distress** The distress does not compromise wall function, but lack of treatment may lead to impaired function and/or elevated risk of wall failure in the long term. An average criteria rating of 2 indicates a criterion with specific distresses that need to be mitigated in the near-term to avoid significant repairs or replacement in the longer term.	Numerous anchor struts holding MSE wire facing elements in place are beginning to break due to corrosion and suspected over-stressing of the connections at the time of construction. Although the overall function of the reinforced earth wall is not in jeopardy, failing wall facing baskets are allowing facing fill to spill out. If several overlying baskets experience this isolated element failure, significant wall face sag, and deformation may result at the top of wall, eventually impacting the overlying guardrail installation. The element should be inspected carefully along the entire wall and repaired as needed to forestall further facing basket deterioration.
3 "POOR"	**Medium-to-High Extent of Medium Severity Distress** The distress threatens wall function, and strength is obviously compromised and/or structural analysis is warranted. The criteria condition does not pose an immediate threat to wall stability and roadway closure is not immediately necessary. An average criteria rating of 3 indicates a distressed criterion that may result in a wall failure without near-term repair or replacement.	Mortar throughout a stone masonry wall is cracked, spalling, highly weathered, and often missing. Individual stone blocks are missing from the wall face, and adjacent blocks show signs of outward displacement. Although not an immediate threat to overall wall stability, stone block replacement and repointing throughout the wall in the near term are necessary to forestall rapid wall deterioration.
4 "SEVERE"	**High Severity Distress** The criteria condition is compromising the wall's performance and is threatening the overall stability of the wall at the time of inspection. The wall is in danger of failing, requiring the roadway be closed to all traffic until the wall can be replaced or stabilized. An average criteria rating of 4 indicates a severely distressed criterion that may result in a wall failure.	A 15-ft-tall cast-in-place concrete cantilever wall has a large open horizontal crack running the full length of the wall at the base of the stem. Vertical cracks are also beginning to open up in the wall face. Water is seeping from most wall cracks, and is running from the basal horizontal crack at several locations. The wall face has rotated outward, resulting in a negative batter of several degrees. The overlying guardrail is highly distorted above the wall and the adjacent roadway is showing significant settlement above the retained fill.

Note: This table was adopted and modified from FHWA-CFLHD's, "Retaining Wall Inventory and Condition Assessment Program (WIP): National Parks Service Procedure Manual."

Risk Assessment

To assist the NCDOT with defining the relationship between qualitative ratings and time sensitive actions, the NCSU research team has developed a risk assessment matrix. In Table 1.5, risk is evaluated qualitatively as a function of both criticality ratings (i.e., whether the consequence of failure (COF) is “High” or “Low”) and condition ratings (i.e., whether the likelihood of failure (LOF) is “Very High,” “High,” “Moderate,” or “Low”). Definitions for the COF criteria and the LOF criteria are presented in Table 1.6 and Table 1.7, respectively. Table 1.8 and Table 1.9 present the recommended actions and inspection frequencies as a function of risk.

Table 1.5. Risk Assessment Matrix (from Rasdorf et al. 2015)

Condition Rating (Likelihood) / Criticality Rating (Consequence)	Low	Moderate	High	Very Likely
High	Moderate	Moderate	High	High
Low	Low	Low	Moderate	Moderate

Table 1.6. Consequence of Failure Criteria Definitions (from Rasdorf et al. 2015)

Criticality Criteria Rating	Definition of Failure Consequence
Low	No threat to people or property. No loss of roadway or impact to traffic during wall repair or replacement.
High	Severe injuries to people or fatalities. Total-loss damage to structures or long-term damage to the environment, cultural resources, or other property. Complete closure (long-term) of heavily traveled roadways.

Table 1.7. Failure Likelihood Criteria Definitions (from Rasdorf et al. 2015)

Condition Criteria Rating	Failure Likelihood Criteria Definitions [FHWA, 2013]
Low	A failure could occur but would require a remote circumstance to trigger failure.
Moderate	A failure could occur but evidence suggests the event could be either unlikely than likely.
High	There is evidence a failure will occur with only a minor triggering event.
Very High	There is significant evidence that failure has occurred or will occur without any further triggering events.

Table 1.8. Action Assessment Table (from Rasdorf et al. 2015)

Risk	Actions
High	Remedial action is required in the short term.
Moderate	Remedial action is required in the long term.
Low	No action is required.

Table 1.9. Inspection Assessment Table (from Rasdorf et al. 2015)

Risk	Inspection Frequency
High	Frequent Inspections.
Moderate	The inspection frequency should be based on the likelihood of failure (LOF). If the LOF is "Low-Moderate," the inspection frequency can be infrequent. Conversely, if the LOF is "High-Very High," inspections should occur more frequently.
Low	Infrequent Inspections.

1.3.5. Colorado DOT (2003)

Wall management includes the functions of inventory, inspection, condition assessment, maintenance, performance evaluation, and asset valuation. Wall management can be similar to bridge management, and indeed existing data organization and software tools for bridges can be adapted to use for walls.

The CDOT inventory contained 640 retaining walls (110 are MSE walls) and 110 sound barriers at the time; there were around 1250 walls in Colorado. MSE walls are the most common in Colorado.

CDOT defines walls as structures that retain fill and have width of at least 100 ft and height of at least 5 ft. Eight wall types are defined in the CDOT structure number coding guide: Cast-in-Place concrete, MSE, Masonry, Pre-Cast Elements, Pre-Cast Elements prestressed, Tie-back and Others. Wall elements were not established.

CDOT had no program for periodic inspection of walls, no standards and no rating system. The Inventory was for new walls only (built after 1998). The most frequent maintenance activity is removal of graffiti. Failures in walls are rare, and most walls serve with no maintenance beyond cleaning. The Guidance in Governmental Accounting Standards Board Primer (GASB) is used for asset management. A management system such as Pontis was suggested to be adapted to management of walls.

Table 1.10 presents elements and components of walls. Table 1.11 shows some of the wall actions. Table 1.12 presents some observations that should be made in the course of a routine inspection of retaining walls and Table 1.13 illustrates conditions states for elements.

Table 1.10. Properties of Elements and Components (from Hearn 2003)

		Quantities	Conditions	Actions
Elements	Feature at Top	Yes	Yes	No (1)
	Top attachment	Yes	Yes	Yes
	Facing	Yes	Yes	Yes
	Bottom attachment	Yes	Yes	Yes
	Feature at front	Yes	Yes	No (1)
Components	Membrane	Yes	No	Yes (2)
	Backfill	Yes	No	Yes (2)
	Fill Reinforcement	Yes	No	Yes (2)
	Anchors/other tensile inclusion	Yes	No	Yes (2)
	Drainage blanket	Yes	No	Yes (2)
	Internal drains	Yes	No	Yes (2)
	Foundation	Yes	No	Yes (2)

(1) – A wall management system is not directly concerned with maintenance of adjacent features, but the system will indicate that actions at walls can affect adjacent features.
(2) – Invasive actions are needed to replace or repair internal components.

Table 1.11. Maintenance Actions (from Hearn 2003)

Action		Walls & Barriers
Maintenance	217.01	Graffiti removal
	217.02	Removal of vegetation
	217.03	Clearing of drains
	217.04	Replacement of riprap or other random slope or channel protections
Repairs	217.11	Repairs to railings and barriers damaged by collision
	217.12	Sealing cracks in facing elements
	217.13	Patching concrete elements
Rehabilitation	217.21	Replacement of facing panels
	217.22	Replacement of drains or membranes
	217.23	Replacement of anchors for facing
	217.24	Replacement of fill reinforcements
	217.25	Shoring

Table 1.12. Routine Inspection Tasks (from Hearn 2003)

Area	Element	Observations
Feature at top	Slope	Note any evidence of movement. May be evident as disruption of vegetation, as depressions or heaves, as scars as slumps or settlements. Note evidence of water movement causing erosion or otherwise disturbing the slope.
	Pavement	Note cracks, depressions, heaves, and any other evidence of movement, especially note movement along the edge of pavement nearest to the retaining wall.
Wall Top Attachment	Railing, Sidewalk	Note deterioration wall attachments such as surface rust, minor cracking, rot in timber, etc. that may require maintenance. Note rooting of vegetation that may disrupt wall attachments. Note cracking, misalignment, tilting or other evidence of movement. Note loss of fill or exposure of foundations for wall attachments
Wall Facing Barrier Facing		Note graffiti on facing. Note deterioration in wall/barrier facing such as surface rust, cracking, rot in timber that may require repair of facing elements. Note evidence of water drainage over the wall, or emerging from the facing in joints or cracks. Note vegetation rooted in joints or cracks. Note settlement, tilt, or cracking related to movement of wall. Observations of water infiltration or movement. Loss of fines Other settlement, tilt movement of the walls or barrier.
Wall Bottom Attachment	Railing, Sidewalk, Splash Block	Note evidence of movement at cover for toe of wall. May be evident as depressions, heaves, scars, damage to pavements, railings or barriers at toe.
Sound Barrier	Posts	Note deterioration in posts such as rust and rot. Note any collision damage to posts Note evidence of movement of posts such as settlement or tilt. Note any exposure of foundations for posts, or other distress in foundations.

Table 1.13. Condition States for Elements (from Hearn 2003)

	State	Description
1	Good	No deterioration of elements. No movement, settlement, or misalignment.
2	Fair	Minor, repairable deterioration of elements. Minor movement settlement or misalignment
3	Poor	Deterioration that may require replacement of elements. Significant movement, settlement or misalignment that is not (yet) a threat to safety or stability of the wall.
4	Serious	Deterioration that impairs function of elements. Movement, settlement or misalignment that may threaten to safety or stability of the wall.
5	Critical	Deterioration or movement, etc., that requires emergency shoring, anchoring or closure of lanes adjacent to the wall

- **<u>MSE wall case</u>**

Bulging of ramp connecting WB I-70 to NB I-25 was observed. Distress in MSE wall resulted in cracking on the ramp's concrete roadway pavement that was several hundred feet long with sections of differential settlement up to 0.75 in. A bulge was also noticed at the facing of MSE wall. Investigation was done with survey targets and video system to inspect storm drainpipes. This problem, if inspected properly, could have been detected early (from information of movement with time) and the drainage system could have been fixed a long time ago to avoid the significant bulging of the wall that occurred over the last few years.

1.3.6. Colorado DOT (2016)

This report (Walters et al. 2016) compiles inventory data and provides consistent inspection condition rating and coding guidelines to facilitate management of transportation needs. Inspection data are captured using a tablet (quick and easy) and works together with the online application System for Asset Management and Inspection (SAMI). The Bridge Branch of CDOT manages retaining walls, noise walls and bridge retaining walls.

Criteria for wall definition:

- **Noise wall:** ≥8 ft in height
- **Retaining wall:** ≥4 ft in height
- **Bridge wall:** The bridge retaining wall is located entirely within the bridge zone as shown in Figure 1.4. The bridge zone is a rectangular boundary created by measuring **40 ft** perpendicular from the edge of the bridge on either side and 40 feet perpendicular from the face of the abutment (or abutment wall) along the approaches on either end of the bridge.

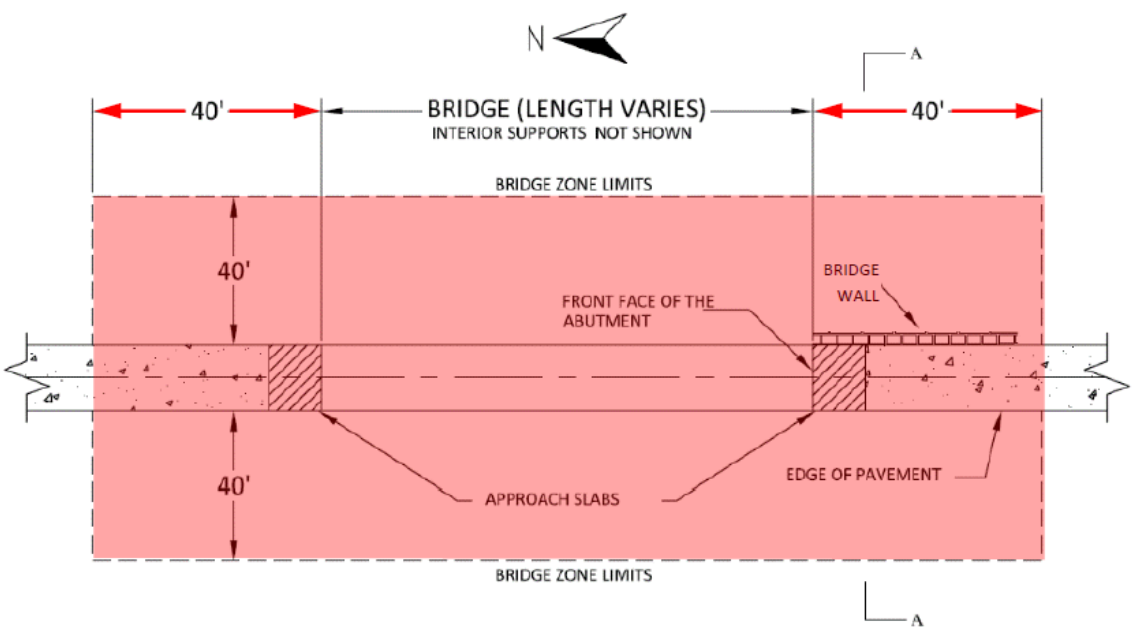


Figure 1.4. Bridge zone (from Walters et al. 2016)

One end, or corner, of the wall starts at the face of the abutment of the bridge and the entire length of the wall face is no greater than **200 ft**. Walls that fit this criterion should be inspected as a single bridge wall to prevent the creation of additional smaller walls. Figure 1.5 shows the Effective bridge zone.

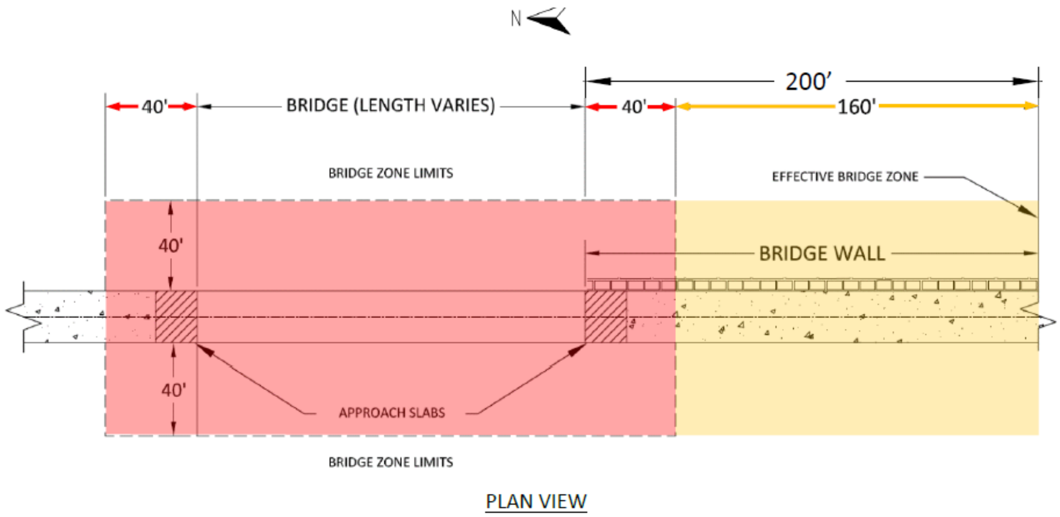


Figure 1.5. Effective Bridge Zone (from Walters et al. 2016)

For a wall that begins within the bridge zone, but extends beyond the effective bridge zone, the wall should be separated into two walls at the 40-foot bridge zone mark. Figure 1.6 shows the Separation of wall at bridge zone.

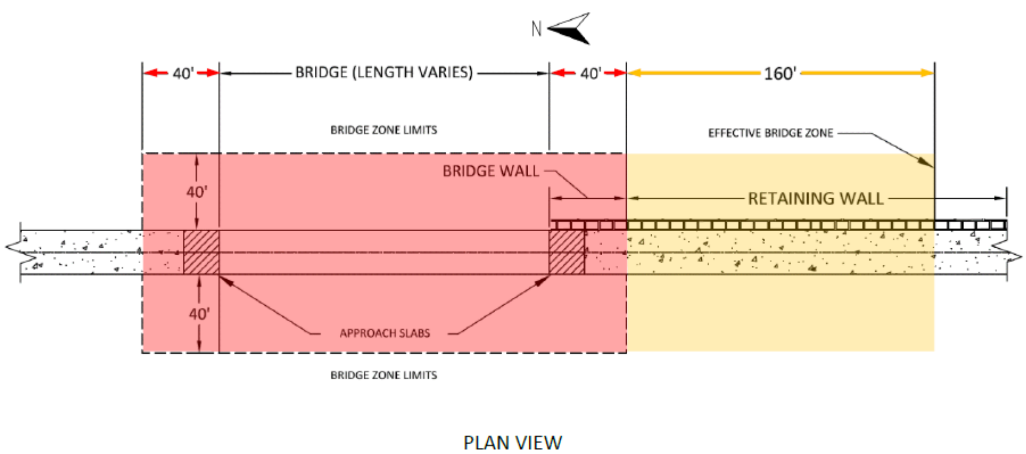


Figure 1.6. Separation of wall at bridge zone (from Walters et al. 2016)

A wall that is associated with two different bridges whose abutments are less than or equal to 200 ft apart should be inventoried as a single bridge wall.

Wingwalls or headwalls for bridges or culverts are not inspected. These structural elements are considered part of a bridge or culvert and would be addressed in CDOT's Routine Bridge or Minor Structure Inspections Programs.

Routine Inspection

- Retaining and Noise walls: 6 years
- Bridge walls: 4 years

The **System for Asset Management and Inspection (SAMI)** is composed of two inter-dependent pieces; mobile and in-office. Field data is collected using a mobile tablet device, and then uploaded to a web-based database at the end of each inspection day. The mobile unit collects photographs as well as location, condition, and appraisal data in accordance with the guidelines described in this manual. Once this data is uploaded to the web-based database, SAMI can be used to generate and submit reports, analyze data, budget, and schedule inspections in-office. Figure 1.7 shows the "Structures Map" in the mobile SAMI application including line geometry, associated photos and defect locations. The "Elements" tab provides a list of appropriate defects based on the element type, which reduces any errors when an inspector notes defects associated with an element.

The inventory categories for wall structures are: (1) Structure identification, (2) Location and (3) Structure data. The condition ratings for the structure level inspection follow closely the language found in the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges", published by the US DOT (1995). A similar 0-9 scale, as seen in the Condition Ratings section should be used to rate the condition of the Main Wall Facing, Foundation, and Channel and Channel Protection. This evaluation data assists in the calculation of Condition Risk Rating for the wall, and should be recorded in the "Overall Structure Rating" field in the Inspection Report. Materials from the Colorado DOT can be found in Appendix A.3.

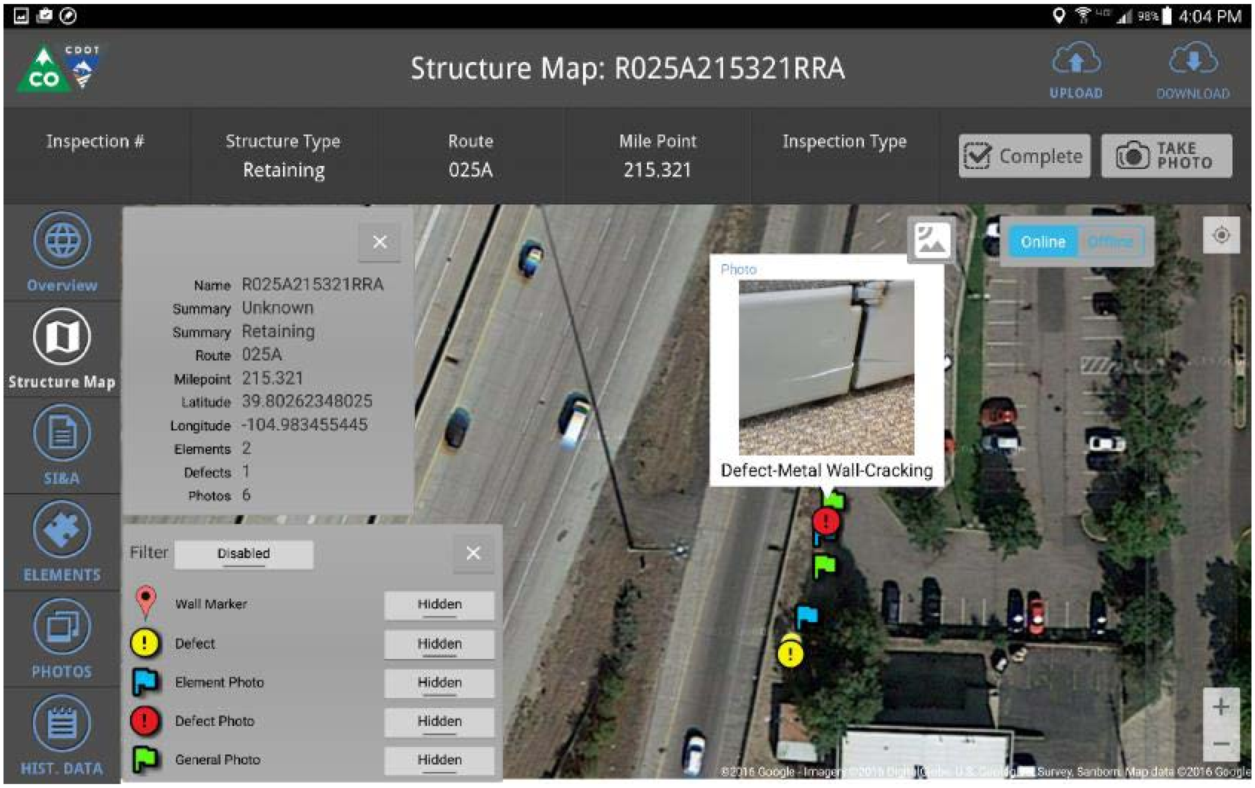


Figure 1.7. Structure Map in SAMI application (from Walters et al. 2016)

Condition ratings are used to describe the existing, in-place wall as compared to the as-built condition. A scale of 0-9 is used to rate the condition of the Main Structure, Foundation, and Channel and Channel Protection.

Wall element inspection: Primary elements, Secondary elements, Incident elements

Maintenance categories: Do nothing, protect, repair, rehabilitate, replace

The defects are classified into two categories, National Bridge Element (NBE) Defects or Agency Defined Element (ADE) Defects, denoting the origin of the condition state language.

Defect condition rating: Good, Fair, Poor, Severe

Environmental Factors: Benign, Low, Moderate, Severe

Wall Elements

- **Primary Elements:** Primary Elements are the main structural features of a wall, including the wall face, vertical supports, foundations, and anchors. They are subject to distress and deterioration and are the most important features rated during the wall condition assessment.
- **Secondary Elements:** Secondary Elements include the attachments, appurtenances, and surrounding features that can impact the performance of the wall. They exhibit a lower degree of distress and deterioration from the Primary Element and are also rated during the wall condition assessment. Secondary Elements include coping, drainage elements, architectural facings, protective coatings, slopes and backfill, railings, and joints.
- **Incidental Elements**: Some elements are considered incidental to primary or secondary wall elements and the location of these incidental elements should be noted under the general description of the parent element. If an incidental element is damaged or deteriorated, an appropriate work candidate should be created to address the issue.

Common Wall Structures

- MSE segmental block retaining wall
- Precast panel MSE retaining wall
- Cast-in-place cantilever retaining wall
- Cantilever, Soldier Pile
- Post-and-Panel noise wall
- Free-standing noise wall

Material Defects

- Corrosion of material elements
- Cracking in material elements
- Connection distress in material elements
- Delamination/Spall/Patched area in material elements
- Exposed rebar/Welded wire/Fabric/Strands in concrete elements
- Exposed prestressing steel in concrete elements
- Cracking in prestressed concrete elements

- Efflorescence/Rust Staining in concrete and masonry elements
- Decay/Section loss in timber elements
- Check/Shake in timber elements
- Split/Delamination in timber elements
- Abrasion/Wear in material elements
- Deterioration in elements such as fiber reinforced plastics
- Mortar breakdown of masonry mortar
- Split/Spall in stone
- Masonry displacement
- Distortion from original line or grade of the element
- Bulging of wall facing elements
- Vertical rotation of elements
- Horizontal rotation of elements
- Separation of wall facing elements
- Graffiti on wall element
- Vegetation growth
- Blockage of drainage elements
- Effectiveness-Anchors
- Freeze-Thaw damage
- Leakage through/around sealed joints
- Loss of seal adhesion
- Seal damage
- Seal cracking
- Debris impaction
- Metal deterioration/Damage
- Joint material; deterioration, missing, loose or other defect
- Chalking in metal/concrete/masonry protective coating
- Peeling/Bubbling/Cracking in metal/concrete/masonry protective coatings
- Oxide film degradation color/Texture adherence in metal protective coatings
- Loss of effectiveness of metal/concrete protective coatings

- Wearing of concrete/timber protective coatings
- Effectiveness of internal concrete/timber protective system
- Backfill loss
- Water retention
- Erosion of any material adjacent to the wall
- Settlement in foundation elements
- Scour in foundation/facing elements
- Impact damage
- Temporary support on wall facing/vertical support/foundation
- Alkali-Silica reactivity

CDOT retaining wall asset management plan

Considers the seven National Performance Areas under MAP-21/FAST legislation:

- Safety
- Infrastructure condition
- Congestion reduction
- System reliability
- Freight movement and economic vitality
- Environmental sustainability
- Reduced project delivery delays

<u>Consequences initially considered for plan development:</u>

- Condition loss and damage to the wall
- Safety hazards to travelling public
- Potential traveler delay, congestion and mobility impacts
- CDOT maintenance expenses for wall repair
- Impacts to environmental resources
- Economic loss to users
- Private property damage

The risk analysis in the plan can be performed at multiple plan levels ranging from **qualitative** (subjective) levels of accuracy for higher level plan decisions to more rigorous **quantitative** (numerical) evaluations for specific wall assets. In both instances, the risk process can assign values to various conditions, the extent of infrastructure vulnerability and the measures used to manage adverse consequences.

Goals of risk-based asset management plan

- Shift the process towards a more proactive approach with a long-term view of the overall health of the statewide wall system and develop a multi-year investment plan that will support wall assets to optimize life-cycle costs.
- Routine maintenance activities intended to preserve wall assets and slow deterioration rates to obtain the anticipated life-cycle
- Wall system as a statewide asset class with long-term financial plans to maintain the system and reduce risk statewide

The risk-based asset management plan identifies walls with a high risk to mobility and economic consequences to provide CDOT the opportunity to manage risks using a **lowest life-cycle cost approach**. CDOT uses wall condition data from wall facing repair plans to manage similar deterioration conditions with a lower life cycle cost goal. A failure example was considered in the development of the plan approach in order to give CDOT the ability to identify, prioritize, and invest in mitigation efforts than can prevent a larger adverse event with economic consequences that exceed the required investment for preventive rehabilitation.

Areas of interest for risk-based management plan

- detailed inventory and appraisal of each wall asset
- internal CDOT operating costs to maintain the wall structure
- user costs associated with wall maintenance and/or adverse events

Risk concept for wall assets

Multiple plan tiers are used to prioritize wall assets on the basis of higher risk:

1. **Tier 1 Level**: inventory of retaining walls and subjective determination of likelihood and consequence of potential failure
2. **Tier 2 Level**: based on data collected during field inspections, assessment of risk to mobility and maintenance
3. **Tier 3 Level**: higher risk walls and cost-benefit analysis to determine preferred investment strategy; continued monitoring, rehabilitation or replacement

Tier 1 Risk Score = [Wall Condition] x [Failure Consequence x AADT Factor x Height Factor]

Low: risk score of 8 or less
Medium: risk score between 8 and 12
High: risk score of 12 or higher

Tier 2 Maintenance Risk Score = Weighted Maintenance Risk Costs/Raw Maintenance Costs

Primary elements have greater priority and are weighted more heavily.

<u>Roadway Impact (RI) score</u>: estimates the potential mobility consequence associated with the wall structure.

RI = (Avg. Wall Height – Distance from Roadway In Front) +
(2 * Avg. Wall Height – Distance from Roadway Carried)

User Costs = (Delay Time/3600) x (AADT Actual – AADT During the Delay) / 2)/24 x User Value x Occupancy Rate

- Delay time is assumed to be 2 hours for all walls
- AADT during any delay is assumed to be 33 percent of actual AADT
- User cost value = $30.50 per hour
- Occupancy rate = 1.67 per vehicle

The **user costs** represent the consequence estimate in the determination of mobility risk. The likelihood (or probability) of an event based on the condition score is based on input from CDOT and consultant staff and reflect past experience and professional judgment.

The final mobility risk calculation is found as:

Tier 2 Mobility Risk Score = User Costs x Wall Condition

645 walls have been inspected to date and their data were used to complete Tier 2 analysis.

Tier 3 Plan Level

Targets of the wall management program:

- 95% of walls with a Level of Risk grade of C or worse
- Less than 1% of walls with CS4 (Condition State 4) defects at or above the C level
- Less than 1% of walls with deterioration accelerator condition states

<u>Performance target:</u> reduce and maintain number of walls with a level of risk of D or F to 5% of the total wall inventory.

1.3.7. Wisconsin DOT (2017)

Wisconsin DOT started a wall inventory program in 1999. Retaining walls with height greater than 5 ft should be inspected at intervals not to exceed 4 years. Four main types of retaining walls include: Rigid or Gravity, Cantilever, Anchored and MSE.

Structural Material Failure

Primary causes of in-service retaining wall failures include poor drainage, corrosion, facing deterioration, inadequate connection details, and latent construction defects. Failure of the construction material is frequently observed in older earth retention structures due to deterioration. Newer walls may exhibit structural material failure due to structural overstresses or poor material properties. Inadequate drainage behind the wall or an unexpected surcharge load can often cause material overstress. Impact damage may also fail the material, and is typically a result of a collision between a moving object and the earth retention structure.

Geotechnical Failure

Vertical movement: soil bearing failure, soil consolidation, erosion and foundation material deterioration

Lateral movement: slope failures, seepage, changes in soil characteristics and consolidation.

Rotational movement: saturation of backfill due to clogged drains, embankment erosion along the front of the wall and improper design.

Table 1.14 shows common material flaws observed during retaining wall inspections.

Table 1.14. Common material defects (from Wisconsin DOT 2017)

Stone/Concrete Masonry Units	Concrete	Timber	Metal	Other Materials
Construction defects	Cracking	Decay	Corrosion	Ultraviolet deterioration
Corner breaks	Scaling	Insect Infestation	Cracking	Material incompatibility
Cracked block	Fraying/Spalling/Exposed Reinforced Steel	Vermin damage		Corrosion damage
Efflorescence	Abrasion	Fire damage		Overstress damage
Embedded vegatative growth				
Abrasion				
Fraying/Spalling (Block edges)				
Freeze-thaw damage				
Manufacturing flaws				
Popouts				
Positioning-Guide damage				
Scaling				
Staining				
Structural Distress				
Wash Through				

Only the visible features of the wall including the front face (facade), top, and sides of a wall will typically be inspected during a normal routine inspection. It is the inspector's duty to discern from distress through the observable components if other unseen issues are at play.

<u>Recommended Inspection Procedures</u>

1. Arrive at site and set-up traffic control (if required)

2. Identify Structure Number

3. Perform Inspection

- Check wall for signs of settlement, rotation or bulging
- Inspect the vertical alignment of the wall with a plumb-bob. (Note: Most walls are constructed with a battered or sloped face)
- Examine the opening of the construction joints between sections of the wall
- Inspect joints near ground line for any fill material washing out from between panels or joint
- Inspect for erosion of the embankment material in front of the wall
- Inspect for heaving of the embankment material in front of the wall
- Inspect for settlement of the fill material behind the wall
- Examine the wall for deterioration of the material, such as cracking, spalling, and/or corrosion, noting the width, length, depth, and/or orientation of the deterioration
- Some wall types (post and panel) may require the inspector to randomly select a few posts and dig down 3-6 in below ground line to see if piling is deteriorating at the soil level
- Lagging or cribbing should be checked for excessive deflections. Excessive deflections may allow the solid behind to spill or wash out, causing settlement in the retained material above
- Examine previous areas of repair for soundness
- Check wall façade for evidence of water seepage, efflorescence or rust staining
- Examine anchorage systems if present. Fasteners and connections to the wall components should be checked for tightness and distress.
- Examine and probe drains for signs of clogging. Examine drainage around ends of wall and note if embankments have been experiencing erosion.
- Examine site grading for any locations that may prohibit proper drainage from behind the wall. Look for evidence of ponding above the wall, such as debris accumulation in the lower spots. Attempt to ascertain why water is not draining properly, and note in the inspection.
- Inspect sidewalk or roadway components above wall for signs or joint separation, potholes and areas of settlement.
- Examine vegetation growth along and above the wall. Root infiltration may create undesirable stresses on the wall and may induce cracking, bulging or failure.
- Examine the wall system for vehicular damage. Document the location and degree of damage.
- Note previous inspection frequency and recommend inspection frequency

4. Determine and record the overall rating of structure based on inspection findings
5. Determine and record all applicable maintenance items and a level of priority
6. Determine if an underwater dive inspection or an in-depth inspection needs to be scheduled to supplement the routine inspection and provide more information on the condition and performance of the wall. If determined to be needed, schedule in the HSI System
7. Review of inspection notes to ensure completeness and correctness
8. Document all CS3 and CS4 defects with a photo and/or a sketch
9. Remove any traffic control

Components are divided into Elements (Primary) and Assessments (Secondary). Both require that the inspector quantify specific conditions states, but Elements take it a step further and also require that the inspector define Defects specific to each Element for asset management purposes. WisDOT simplifies wall inspection into the following Defects: Wall deterioration, Wall movement, Masonry or Panel displacement and Scour.

The rating system is based on a four level scale: Good, Fair, Poor and Severe:

- ***Good***: No, or very low distress observed in the wall elements and assessments. Defects are minor, and within the normal range for newly constructed or fabricated elements. Highly functioning wall that is only beginning to show the first signs of distress or weathering.
- ***Fair***: Overall, the condition is satisfactory. Distress is present in wall elements and/or assessments, but does not compromise the wall function. Localized drainage issues, settlement, staining, washing of fines from backfill material that are minor.
- ***Poor***: Overall condition of the wall is poor. Distress is present, but does not pose an immediate threat to wall stability and closure of facilities adjacent to structure is not necessary. Repair and/or replacement is needed in the near future.
- ***Severe***: Critical condition. Major structural defects, or components have rotation, sliding, settlement, and/or overturning that is close to possible collapse. Wall is no longer serving the intended function, or is unstable and needs repair/replacement as soon as possible. Facilities adjacent to wall may need to be closed.

Upon completion of a wall inspection, the inspector is tasked with assigning an overall condition rating to the structure. This is a global evaluation and is used to determine inspection frequency and other asset management functions. Therefore the inspector must take into account all elements and assessments noted during the inspection and the functionality of the entire structure.

Determining the priority level for each item depends significantly on how the functionality of the wall is impacted. Table 1.15 describes the repair timeline associated with each priority level. The inventory data sheet that is used by the Wisconsin DOT is provided in Appendix A.4.

Table 1.15. Repair timeline depending on priority level (from Wisconsin DOT 2017)

Priority Level	**Timeline Expectations**
Low	Repair prior to next inspection, as funding allows
Medium	Repair within one year as funding allows
High	Repair within 90 days
Critical	Repair within the timeline specified by the inspector in the notes, but not to exceed 30 calendar days

1.3.8. Alaska DOT (2013)

At present, the Alaska Department of Transportation and Public Facilities (AKDOT & PF) is in the first phase of the process for developing an inventory and inspection system which involves a survey of internal records to catalog ERS locations and gather basic information (CTC and Associates 2013). In the second phase, AKDOT & PF plans to validate and augment their in-house data with data collected in the field. As part of the second phase, the AKDOT & PF will also rely on the guidance of FHWA-CFLHD to develop an ERS condition assessment process and establish a rating system to measure ERS performance.

Criteria for determining if a wall should be inventoried:

- Serves as an earth retention structure
- Belongs to a roadway asset that is owned and/or maintained by AKDOT&PF
- Culvert headwalls/wing walls ≥6 ft (total height, exposed plus embedded)
- Face angle ≥45°
- Identify tiered wall system as one wall

Wall information is to be entered into a GIS-based database via a web interface. This preliminary phase of the Wall Inventory relies on gathering information from internal AKDOT&PF records, including-but not limited to- the following:

- As-built
- Road viewers, e.g. Google
- AKDOT&PF Digital Roadway Viewer Alaska
- DOT Highway Data Port
- Bridge Inventory/PONTIS
- Statewide Culvert Inventory
- Compilation of Bids (COB) sheets

Figure 1.8 shows the bridge zone limits.

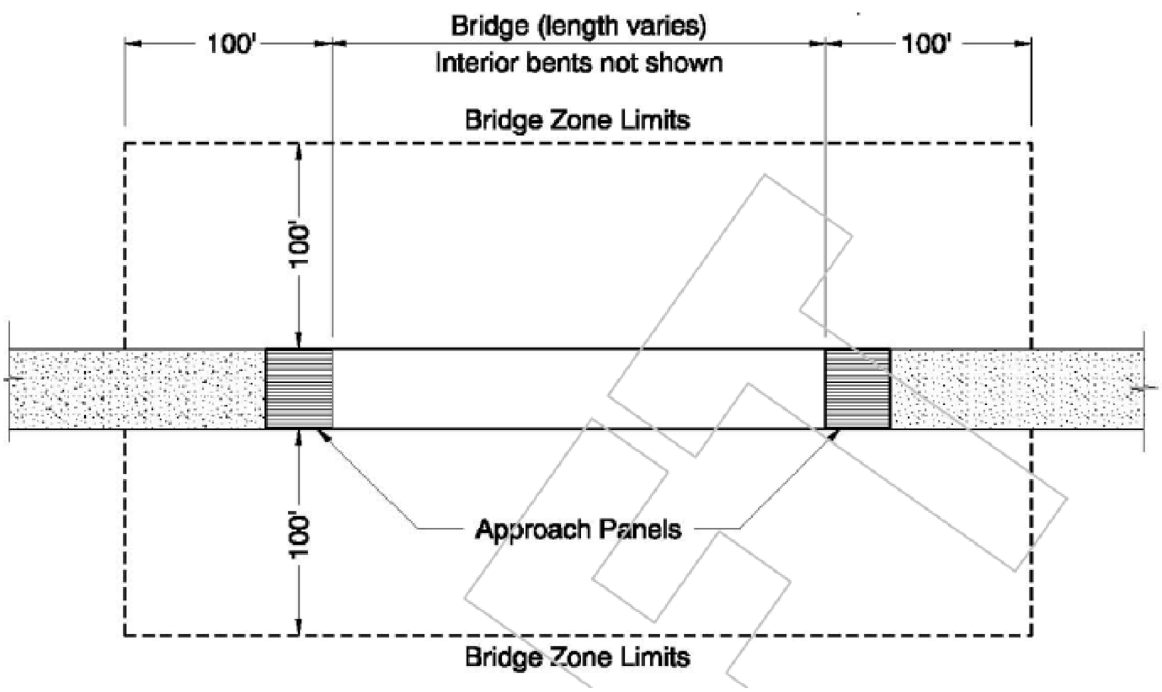


Figure 1.8. Bridge zone limits (from AK DOT & PF 2013)

1.3.9. Pennsylvania DOT (2010)

The inspection typically consists of an examination and recording of signs of damage, deterioration, movement, and if in water, evidence of scour.

PennDOT takes a tiered approach, with a "routine" wall inspection every five years and an "in-depth" inspection (which includes a three-dimensional survey for MSE walls more than 100 ft long and more than 20 ft high) at either 10 or 15-year intervals. Unscheduled "special" inspections are to be performed after a significant event, such as a vehicular collision, extreme weather, or indication of wall movement.

Neither reinforcement nor backfill can be inspected; therefore, a close visual inspection of the facing panels and drainage facilities is required to provide information on all three of the major components. This includes visual inspection of the roadway surface (i.e., pavement) above the MSE wall for tension cracking. Inspection of the leveling pads, if visible, can provide information on scour, erosion or settlement. Inspection of the barriers can also provide important information regarding movement of the MSE wall.

Field Inspection Procedures

Many of the techniques from the bridge inspection are also applicable to retaining wall inspections. Establishing a baseline condition for retaining walls is crucial for effective future inspections.

- Inspect exposed wall faces, barriers and moment slabs, footings and joints for: arching, spalling, movement of joints, corrosion of members, locations of entrapped water/improper drainage, evidence of impact, condition of riprap, and/or indications of scour.
- Inspect wall for movement, rotation or settlement.
- Inspect crest of sloping backfill for evidence of soil stress or failure as an indication of settlement or wall movement.
- Inspect drainage facilities in the wall and in proximity of the wall (above and below the wall) to ensure proper function of drainage.

MECHANICALLY STABILIZED EARTH WALL FIELD INSPECTION PROCEDURES

The critical factors affecting the long term performance of MSE walls are: corrosion of the soil reinforcement, improper drainage, improper backfill material and compaction, freezing of entrapped water, and movement of the entire MSE Mass (global stability).

Mechanically Stabilized Earth (MSE) retaining walls should be inspected for evidence of wall movement.

- Examine barrier and moment slab for evidence of movement as well as the MSE wall for evidence of bulging, bowing or panel offset.
- Perform a survey if movement is suspected to compare to initial inspection data to gauge amount of movement.
- Examine the roadway above MSE walls for indications of failing pavement or tension cracking. These may indicate a loss of fill.
- For MSE walls in front of sloping backfill, the crest of the embankment should be investigated for soil stress or failure, both of which may indicate settlement or wall movement.

The **joints** between panels of MSE Walls are to be inspected and examined for loss of backfill, change in spacing, and indications of settlement. The specification requirement for joint spacing is a maximum ¾ in.

- Inspect walls for evidence of backfill loss (piles of aggregate at the base of the wall).
- Indicate visibility of backfill or fabric behind the panel through joints.
- Examine for evidence of damage to the geotextile fabric, if visible.
- Look for variation in joint spacing. Note vegetation growing in joints.
- Vertical slip (expansion joints) used on long lengths of walls should be investigated similar to panel joints. The initial spacing at the slip joint should be determined from design, shop or as-built drawings.

Wall panels shall be checked for cracking, spalling, other forms of deterioration, and collision damage.

Drainage systems through or along MSE walls should be inspected to verify water is free flowing into and out of the appropriate facility.

- Ensure that weep holes are free draining.
- Inspect all inlets to verify water is draining into the inlet, and flowing freely to the inlet and out of the outlet. Examine inlets for cracks.
- Inspect visually or use down-hole cameras (as appropriate) for all culverts and pipes contained or having portions in, behind, or above the MSE wall mass and for pipes or culverts which run above, adjacent to, or outlet through the MSE walls to verify pipes are free draining and water is flowing through (and not under or around) the pipe. Examine drainage pipes for cracking or damage with emphasis on areas where water may flow, or is flowing, into the MSE wall soil mass. Inspect outlet ends to verify free drainage or for evidence of migration of fill or other material.
- Inspect swales above the MSE wall. Verify rock fall or other materials (trees, etc.) are not blocking, redirecting, or restricting the flow of water through the drainage ditch above the MSE wall to the appropriate receptacle.
- Inspect collection and outlet basins to verify water is draining freely. Look for any signs of infiltration or migration of material which may prevent water from draining from the wall.
- Identify inappropriate appearance of water along the base of the wall (i.e., if water is appearing when weather conditions have been particularly dry). Note areas where there is inappropriate collection and/or lack of drainage for water along the length of the MSE Wall.
- Note erosion of soil along the base of the wall exposing or undermining the leveling pad.

Observed conditions are translated into ratings, as shown in Table 16, that are assigned to MSE wall elements:

- Anchorage
- Backfill
- Wall conditions such as bulging, joints, deterioration of face panels, connection of the backs, etc.
- Panels

- Drainage
- Foundation
- Parapets

Table 1.16. Performance ratings assigned to wall elements in Pennsylvania DOT inspection process (from Pennsylvania DOT 2010)

Rating	Rating Definition
8	Good condition. No apparent problems.
6	Satisfactory condition. Structural elements sound. Localized drainage problems, settlement, staining, washing of fines from backfill material.
4	Poor condition. Localized buckling, deteriorated face panels, joint problems, major settlement, ice damage.
2	Critical. Major structural defects, components have moved to point of possible collapse.

1.3.10. Nebraska DOR (2009)

This project (Jensen 2009) developed a condition rating system for MSE walls, in which rating criteria are specific to each element or wall condition. The MSE wall features that are assessed are:

- Wall tilting
- Structural cracking
- Facial deterioration
- Bowing of the wall
- Panel staining
- Exposure of fabric
- Loss of backfill
- Erosion in front of wall
- Erosion in back of wall
- Joint spacing
- Condition of “v-ditch” (i.e., drainage way at top of wall)
- Coping deterioration
- Drainage runoff
- Drainage at the front of the wall

A **rating scale** ranging from 0 to 9 (consistent with most bridge assessment procedures) is provided to describe the extent or severity of each feature. Rating criteria are specific to each element or wall condition rather than being generic. The database will then use the numbers from each inspection to create a Wall Performance Index (WPI) that allows NDOR to rate how each retaining wall is performing.

MSE Wall ID Numbering Convention

M008018215L

1. 2. 3. 4.

1. Indicates the type of wall present. "M" indicates a MSE wall, while "R" indicates a retaining or gravity wall.

2 Indicates the highway number associated with a specific wall. The MSE wall(s) form(s) one lateral boundary of this highway. Four spaces are provided. If the highway number is a 2 digit number, add two "0" as placeholders before the highway number (as illustrated above for I-80).

3. These five digits indicate the Reference Post location closest to the center of the wall.

4. The last digit is used to designate which side of the highway the wall is located on when the inspector is facing in the direction of ascending reference posts.

1.3.11. British Columbia Ministry of Transportation - Canada (2013)

The British Columbia Ministry of Transportation has both expanded its Bridge Management and Information System (BMIS) and revised its maintenance specification to include ERSs.

Condition Rating: Excellent, Good, Fair, Poor, Very Poor

Wall Components and Conditions

- **Hydrotechnical**
  - Channel bed conditions, Channel bank conditions, Skew, Adequacy of waterway
  - Erosion Protection
  - Substructure Scour
- **Foundation**
  - Wall Foundation
- **Structure**
  - Movement of Wall
  - Retaining Wall
  - Embankment
  - Tiebacks/Connectors
  - Wall drainage system
  - Coating
  - Railings
  - Roadway Flares

Examples of **instrumentation** used to monitor walls include slope indicators (drill holes with special casing installed), tell-tales (simple movement monitors across cracks in walls), surface monitoring hubs, piezometers (drill holes for monitoring groundwater levels), tilt meters, etc. Retaining wall inventory and inspection forms used by the British Columbia Ministry of Transportation are provided in Appendix A.5.

1.3.12. Victoria Highway Department - Australia (2014)

VicRoads Technical Consulting of Victoria, Australia, records its inspection data in a road asset system (RAS), which is an information system for all structures' inventory and condition data managed by the Network and Asset Planning Division (VicRoads, 2014). They produced the "Road Structures Inspection Manual" which applies to retaining walls, visual walls, and noise walls, along with many other roadway structures including bridges and culverts.

Retaining Wall: A structure with the primary purpose of retaining soil that is 1.5 m or greater in height and steeper than 1 to 1.5 or a structure that would result in a traffic or pedestrian hazard or damage to neighboring property upon failure. A retaining wall within 5 m of a bridge abutment is to be considered part of the bridge structure. Beaching (rock, paved or other) on cuttings or embankments where the slope of the cutting or the embankment is less than 1 to 1.5 is not considered to be a retaining wall but the 'surfacing' of the roadside.

Level 1 – Routine Maintenance Inspection: it is used to check the general serviceability of a structure and to ensure the safety of road users. Level 1 inspections may be completed in conjunction with routine road maintenance. Structures are subjected to two inspections per year.

Level 2 – Structure Condition Inspections: they are used to assess the condition of structures and their components. Level 2 inspections are managed on a statewide basis. The frequency of inspections is 2 to 5 years depending on the condition.

Level 3 – Engineering Investigations: they are detailed engineering investigations and assessments of individual structures which are conducted as required. Frequency of investigations shall be determined for each structure and shall require ongoing review depending upon the performance, intensity of loading, rate of deterioration, if any, maintenance, strengthening, component replacement or similar that potentially influence safety and whole of life costing. Level 3 investigations may include non-destructive testing and/or sampling of materials for laboratory testing.

Critical components for retaining walls are shown in Table 1.17.

Table 1.17. Critical components for retaining walls (from VicRoads 2014)

Critical components for retaining walls	
Retaining wall facing components including masonry blocks or bricks, precast concrete panels, timber sleepers and similar	• Evidence of lateral tilting, bulging that might indicate excessive earth pressure from settlement of contained fill, failure of drainage system, if any, behind the wall or similar • Extended cracks through mortar and masonry components or precast concrete panels
Supporting components including vertical posts and columns, metal or geo-synthetic anchor strips for reinforced soil walls and similar	• Evidence of lateral tilting, bulging that might indicate failure or extension of retaining systems in reinforced soil walls, or failure of vertical retaining posts or their foundations • Evidence of movement of retaining walls that has caused permanent closure of expansion joints, spalling of concrete superstructure or substructure components
Strip footing and pile foundations	• Signs of substantial settlement or rotation • Significant exposure by erosion, settlement or other means
Crib wall	• Disintegration of blocks

The wall chainage is the distance measured from the Road Start. The General Location is either on the freeway or an adjacent ramp. GPS readings are required at the start and end of the wall together with the chainage at the start of the wall.

The following photographs are required:

- At the start and end of the wall
- A view along the wall
- Any components in condition states 3 or 4

Monitor inspections consist of non-destructive inspections of specific components to detect structural distress that may indicate reduced strength and include:

- Visual observation at arms-length and assessment of the condition of critical components
- Photography - in order to compare the condition of critical parts of the structure with previous records

Routine maintenance activities on bridges and other structures are presented in Table 1.18.

Table 1.18. Routine maintenance activities on bridges and other structures (from VicRoads 2014)

Routine maintenance activities on bridges and other structures	
General	• Graffiti and other damage caused by vandalism • Accident, fire or water damage • Accumulation of dirt, bird and animal droppings and other debris on components preventing drainage, ponding, rusting of steel, seizure of bearings and other moving parts • Vegetation growth in structural joints, mortar joints, cracks and other locations on and around structures
Drainage	• Blocked scuppers and side entry pits on bridges, culverts and approaches • Scour or settlement of bridge abutment batters, road approaches, behind retaining walls, foundations of bridge piers, sign structures, mast arms, retaining walls and other structures • Blocked weepholes and signs of water penetration and inadequate drainage behind retaining walls, bridge and culvert wing walls and similar
Deck joints	• Debris blocking or jamming joints • Damaged waterproofing seals • Missing or damaged bolts
Bearings	• Debris and dirt build up around bearings • Rusted steel bearings
Barriers	• Damaged, corroded and missing posts, rails, spacer blocks, and connections • Approach barrier not constructed or connected
Bituminous surfacing on structure roadway, footpaths and approaches	• Uneven surface • Settlement of approaches
Signs, lighting and roadmarking	• Missing, damaged or corroded components, supports, connections • Signs or roadmarking not legible • Lights not working
Waterways	• Blocked with debris and vegetation • Scour and subsidence requiring beaching or other maintenance

Retaining walls are generally made from timber, concrete, masonry and steel materials. Problems can occur with the foundations of the wall due to:

- Rot and termites in timber particularly at or just below ground level
- Corrosion in steel and cracked welds
- Reinforcement corrosion

- Cracking and spalling concrete
- Cracking of mortar or stone degradation in masonry walls
- Settlement, sliding or overturning of the wall
- Insufficient or ineffective weep holes to relieve pore pressure behind the wall

The inspector should also observe and record problems associated with ground movement that may be exerting unusual pressure on the walls.

Condition rating of components

ERS condition assessments are divided into four individual elements: the wall facings or panels (measured by area), the column and horizontal supports (measured by unit), the foundations or supports (measured by length), and the hold-down bolts, base plates, and fittings (measured by unit). The ERS rating is then established by evaluating each individual element and assigning a conditional percentage to the portion of the element that meets the criteria in one of the four conditional states listed below. For example, if the facing of a concrete retaining wall is 100 meters long and has a 10 meter crack, 90% of the facing would be considered condition 1 and 10% would be condition 3. The sum of the individual condition percentages assigned to each element has to equal 100%. The approach used in this rating system closely resembles the 1-4 rating system outlined in AASHTO's "Manual for Bridge Evaluation" for its bridge element ratings (AASHTO, 2010a).

The manual includes a retaining wall structure condition inspection sheet and a condition rating system for retaining wall elements, including facing panels (area), column supports (unit), foundation (length) and connections (unit). In general, the condition ratings have been developed to describe the following conditions:

Condition state 1 Component is in good condition with little or no deterioration.

Condition state 2 Component shows minor deterioration with primary supporting material showing the first signs of being affected. Intervention points for maintenance are generally as follows: Minor spalls or cracking of no real concern. Paintwork on steel components with spot rusting up to 5%.

Condition state 3 Component shows advancing deterioration and loss of protection to the supporting material which is showing deterioration and minor loss of section. Intervention points for maintenance are generally as follows: Large spalls, medium cracking and defects should be programmed for repair works. Paintwork has spot rusting of up to 10%, which is the approximate limit for overcoating.

Condition state 4 Component shows advanced deterioration, loss of effective section to the primary supporting material, is not performing as designed or is showing signs of distress or overstress. Intervention points for maintenance are generally as follows: Very large spalls or heavy cracking and defects should be repaired within the next 12 months. Paintwork beyond repair requires blasting back to bright metal and recoating.

The extent of each condition state affecting a component shall be measured as a percentage of the whole component. The percentages in each condition state (1, 2, 3 and 4) must add up to 100% of the whole component.

Each element is quantified as follows:

- Number of units making up the component (each)
- Length of the component (lin m) or
- Area of the component (m^2)

When assessing condition rating, the inspector should first determine the worst condition affecting the component (e.g. Condition 4) and its extent, and progress to the best condition (e.g. Condition 1). The condition rating and its extent, for each element shall be recorded as a percentage of each condition state in the appropriate column on the Condition rating sheet. The quantities of each element and their condition are not required unless specified elsewhere. The accuracy of the percentages determined for each condition state shall be within ± 5 %.

For example, if the facing of a concrete retaining wall is 100 m long and has a 10 m crack, 90% of the facing would be considered condition 1 and 10% would be condition 3.

Materials from the Victoria Highway Department can be found in Appendix A.6.

1.3.13. Kentucky Transportation Cabinet (1998)

In this study (Fleckenstein et al. 1998), approximately 209 walls were visually evaluated for long-term performance. The inspection included concrete crib, single-barrel and double-barrel culvert wing, metal bin, gabion, rigid concrete, keystone block, tiedback, mechanically stabilized earth, TechWall, and sound walls. Significant structural distress was observed in several of the wall systems. Table 1.19 shows the walls that were inspected in this study. Each wall system was divided into nine sections for analysis purposes. In addition, each wall system was photographed and video taped.

Several walls that were evaluated had significant problems and should be repaired. It was recommended that retaining wall structures be inspected annually by maintenance crews. It is apparent from this study that drainage plays a major role in the long-term performance of these structures. Past edge drain research indicates that 20 to 50 percent of edge drain outlets were not fully functional. It is likely that these percentages also were applicable to bridge-end drains. It was recommended that bridge-end drains be inspected during construction. It was also recommended that a full-scale study be conducted on the performance of bridge-end drainage and to evaluate the lateral earth pressures on return walls.

Materials from the Kentucky Transportation Cabinet can be found in Appendix A.7.

1. Concrete Crib Walls

Several types of distress were observed in the crib wall systems including: **1)** migration of backfill through the crib members, **2)** displaced crib members due to erosion, **3)** cracking of the crib members, **4)** spalling of the face of crib members, **5)** slight bulging or tilting, and **6)** sluffing of unanchored ends. The significance of the observed distress was ranked from “A” being slight “B” being moderate and “C” being severe.

The migration of the backfill through the cribbing appears to be the most significant problem observed in the crib wall systems. A non-erodible granular backfill should be used to prevent the migration of the backfill, and the surrounding soil, through the crib structure. If the backfill is classified as erodible or unstable it shall be protected by geotextile fabric.

2. Culvert Wing Walls

Each wall was divided into ten different sections to help quantify repeated distress patterns. Wall systems have performed well. The only distress that was recurring was slight-to-moderate cracking and staining.

Spalling occurring on the horizontal face of the top slab of the culvert was likely due to water saturating the top of the culvert. A possible solution to deter spalling on the horizontal face would be to cover or seal the top horizontal face with a waterproof geomembrane. Maintenance crews should periodically check the inlet and outlet ends of the culvert for buildup of debris or vegetation, and take any necessary actions to clean up obstructions blocking the culvert.

Table 1.19. Kentucky wall inspection study (from Fleckenstein et al. 2003)

Type	No.	Type	No.
Concrete crib walls	4	Timber lagging tied back	4
Wing walls - double barrel culverts	32	Keystone modular block retaining wall	2
Wing walls - single barrel culverts	20	Reinforced Earth Co. Open bridge abutments	9
Metal bin walls	5	Reinforced Earth Co. Wing walls	18
Gabion walls	5	Reinforced Earth Co. Closed bridge abutment	13
Rigid concrete retaining walls	13	Reinforced Earth Co. Return walls	23
Rigid concrete abutment (breast)	8	Reinforced Earth Co. Retaining walls	3
Rigid concrete abutment (non vertical)	5	VSL retaining walls	2
Rigid concrete wing walls	18	TechWall ramp embankment	2
Rigid concrete approach retaining walls	7	Sound barriers - Brick	1
CIP concrete wall tied back	6	Sound barriers - Metal sheet	1

3. Metal Bin Walls

Each wall type was divided into nine sections for inspection and analysis purposes. Significant distress was observed in the center of a wall. Five of the vertical support members had failed at the base of the wall, and bending was occurring in some of the horizontal members.

Failures in the vertical supports of the metal bin retaining wall are likely due to post construction settlement of the backfill. Further inspection and monitoring for vertical settlement were recommended at the time.

4. Gabion Walls

Bulging and/or sagging was observed in most of the walls. Consideration shall be given to placing a geotextile between the Gabion wall and the fill material if the fill material cannot be retained on the 100 mm (4-inch) sieve-the smallest size stone used to fill the Gabion baskets.

5. Rigid Concrete Retaining Walls

The majority of the distress observed with each wall type consisted of slight to moderate cracking or staining. The shrinkage cracks may be controlled by using more expansion and contraction joints.

Concrete walls used for bridge approach fill retaining walls have suffered the most severe recurring distress among the five different wall categories. Consideration is to be given to reinforcing the backfill of approach fills, and wall drains are to be placed with care. To insure proper drainage at bridge ends, the wall drains are to be inspected with a pipeline camera during the construction phase.

6. Modular Block Retaining Walls

Distress included cracking, sliding, bulging, migration of backfill between blocks and settlement behind the structure.

7. Tied Back Walls

Of the ten tied back walls inspected in this study, the group that had a cast-in-place wall in front of the tied back wall has performed the best. The two tied back walls that had used clips to hold the timber lagging in place were in need of immediate maintenance. This method of construction is not to be used in future tied back wall construction. The method of placing timber lagging between the webs of the H-Piles appears as a good alternative to using the clips. However, the tied back walls that used this type of construction were relatively new and were to be monitored further.

8. MSE Walls

Several problems were noted with the seventy-seven MSE walls. Settlement of the leveling pads was noted in several of the inspected MSE wing walls, which may be attributed to poor soil compaction. Cracking in MSE wall panels on return walls and bridge abutments had developed due to precast panels or cast-in-place blocks located between the bridge deck and the MSE wall. In future MSE wall construction, these precast panels or cast-in-place blocks are not to be used to bridge the two structures. Drainage was an additional problem that was noted during inspection of MSE bridge abutment and return walls. Water is to be diverted away from the reinforced approach fill. In areas where wall drains were installed in the approach fill, a miniature pipeline camera should be used to inspect the integrity of drainage system during construction. Also, water is not to be discharged from headwalls directly behind any retaining wall structure. Lastly, geotextile fabrics should be used in MSE wall construction.

9. Techwalls

There were two TechWalls inspected for this study. The TechWall is one of the accepted alternative walls selected by the Kentucky Department of Highways. However, this particular wall type has not been used very frequently in Kentucky. The two TechWalls that were inspected had already shown signs of distress. Newly accepted walls such as the TechWalls, and other retaining walls are to be thoroughly monitored during construction.

1.3.14. City of Seattle (2014)

The City of Seattle has more than 500 retaining walls in its inventory. Most of these retaining walls were built prior to 1970. Some were built as early as 1900. Early 1990s, Roadway Structures made a preliminary inspection of all retaining walls in its inventory. After this inspection, the retaining walls were grouped into **4 categories**:

1. Retaining walls that are in good condition
2. Retaining walls that need minor to major maintenance.
3. Retaining walls that need frequent monitoring.
4. Retaining walls that need replacement.

Later in 1999 and 2000, all retaining walls **4 feet high and above** were inspected by a consultant (Agra). A **digital protractor** was used to measure plumpness of retaining walls.

The major types of retaining walls, which are widespread throughout the City, are as follows:

- Rockfacing
- Soldier pile wall with timber or concrete lagging
- Cantilevered concrete walls
- Gravity type concrete walls
- Crib-lock wall (concrete, timber or steel)
- Gabion walls
- MSE Retaining Walls

Inspection of retaining walls may vary depending on the type of retaining wall, its condition and the area where it is located. If the retaining wall is in an area of **steep slope** or/and in an area with **slide history**, the scope of inspection may include the <u>visual reconnaissance</u> and <u>assessment of apparent slope stability</u> of the adjacent area. If the condition of the retaining wall is bad and needs frequent monitoring, it may require **establishing points of reference** (base-line) for checking rate of deterioration.

<u>Procedure of inspection:</u>

1. Pick an area and select retaining walls for inspection
2. Check out files for the selected retaining walls and review previous inspection report

3. Review appropriate plans in the vault for details of retaining wall.
4. Take out all the tools you need for inspection:

- 25 feet Tape
- 100 feet tape
- Camera
- Digital protractor (to be provided by SEATRAN)
- Hammer
- Bondo (patching paste)
- Crack comparator
- Machete

5. Assess condition of retaining wall. The following points can be used as a minimum guide line in condition assessment

- **Check alignment** and geometry and note if bulges, differential settlement, or differential tilting are apparent.
- **Check rotation** and compare with its original batter angle. Some of the retaining walls have built-in tilt measurement reference points. Using a digital protractor, measure tilt on the existing points and compare results with the previous measurement. For previous tilt measurement and location of reference points, refer to retaining wall file. If the retaining wall does not have tilt measurement reference points, establish a new one. For concrete retaining walls, use **anchor bolts**. For steel posts, make direct reading on the face of the **soldier piles**; indicating location of measurement. For timber posts, use survey tacks. Generally, tilt measurement is not required for retaining walls less than 6 feet in height subject to the inspector's judgment. It is not easy to put tilt measurement reference points on some retaining walls such as rockery or gabion. Tilt will not be measured for such walls. All new installation of reference points should be at accessible locations. Most of our previous installation was 5 feet above the ground and sometimes measured from the top.
- **Assess slope stability.** Look at the slope areas adjacent to the wall; make note of any indications of slope movement such has cracking or settlement at the top or heaving at the bottom which may indicate movement of the retaining wall.

- **Check for cracks**. Measure sizes and map their location. Assess cracks to determine if they are caused by thermal movement, shrinkage or other structural problems. If crack monitoring is required, clean a small area on the crack and patch with Bondo. Other crack monitoring methods can also be used if approved by SEATRAN.
- **Check for any concrete spalling or delamination**. Spalls with exposed rebar should be mapped and their sizes (area and depth) noted. Areas of delamination should also be mapped with approximate areas.
- **Note if retaining wall has weep holes** or other means of relief of subsurface water pressure.
- **Check other miscellaneous defects** such as rust, rot, damage, erosion, paint, rock pockets, weathering, root pressure, etc.

6. Record all findings. Include **sketches** if necessary to describe deficiency and location of defects of each component of retaining wall.
7. Take **pictures** that indicate the vicinity and close detail of the defect.
8. Write condition report for each wall that documents all information and other collected data. Report should include condition **<u>rating</u>** that illustrates the relative condition of each retaining wall. For consistency with previously made inspection report, we recommend the following guidelines be used in condition rating of each retaining wall:
9. Discuss major structural problems that affect the integrity and functionality of the retaining wall with Roadway Structure's Engineer before request for repair is made.

Each retaining wall is given **<u>% condition rating</u>** that numerically portrays its relative condition. Each defect is rated from **0 to 100**. If the wall has distinct components such as rails, walers or tiebacks, each defective component is also rated. Each rating is multiplied by a **<u>weight factor</u>** to get factored condition rating. Weight factor prorates the rating of each defect based on its role to the structural integrity of the retaining wall. Weight factor varies from **0 to 1**.

The overall % condition rating of retaining wall is calculated using the following formula:

$$\textbf{\%Condition Rating} = \frac{\sum_{i=1}^{i=n} (WF)_i\, G_i}{\sum_{i=1}^{i=n} (WF)_i}$$

Where **G** = rating (0 to 100)

WF = weight factor (0 to 1)

N = number of defects rated

Rating guide table

Tilt measurement

Tilt in °	0-1	3-5	6-10	11-15	16-20	> 20
Rating (G)	100	90-100	70-90	40-70	20-40	0-20

Condition rating	**Description of rating**	**Rating**
81-100	Good condition	Good
51-80	Fair condition	Fair
31 to 50	Poor to condition	Poor

Weight Factors

Weight factors are subjective and it is up to the inspector to decide. The table below can be used as a guide to help the inspector pick a number within the described range.

Deficiency	Tilting of wall	Slope movement	Bulging of wall	Crack	Differential Settlement	Rot	Rust
WF	1	1	1	0 to 0.7	1	0.5 to 0.8	0.5 to 0.8

The Microsoft-ACCESS based application program is used to keep inventory and inspection data for the retaining walls.

Project Assumptions

The scope of work for this wall inspection is based on the following assumptions:

1. Assumes most of the retaining walls require tilt measurement;
2. Assumes some walls, especially new ones need monitoring points installed;
3. Assumes steel surface is uniformly flat and tilt reading can be taken without making reference points, such as dent.

4. Assumes segmental walls (gabion, rockery, ecology block or concrete crib) do not require tilt measurement.

Wall attributes that are collected during inspection are shown in Appendix A.8.

1.3.15. The City of Cincinnati (2015)

The Wall Stabilization and Landslide Correction Program is the specific program within The Department of Transportation and Engineering (DOTE) charged with the responsibility of maintaining the retaining walls within this transportation system. Every retaining wall within or adjacent to the right-of-way has been inventoried and is included in the Wall Inventory Tracking System (WITS) database; around 7,000 walls were inventoried with 5,125 being privately owned walls.

The Wall Inventory Tracking System (WITS) was created in 1991 and used Foxpro as the database software. In 2015, WITS was converted to a server based Oracle system and is accessed through ArcGIS. A wall inspection application was created that allows the inspector to complete the inspection documentations using a tablet in the field, eliminating the need to complete hand written documents and then reentering the data into a computer file.

Walls are inspected once every six years. Walls that are rated 3 (Poor) or 4 (Critical) condition are inspected yearly. Other inspections are performed if a wall is damaged in an automobile accident or if a complaint is received. All newly constructed, replaced or repaired walls are inventoried and inspected.

The rating system follows a five-level scale:

0 to 1 Excellent: No-to-very-low extent of very low distress. Defects are minor, are within the normal range for *newly constructed or fabricated* elements, and may include those resulting from fabrication or construction. Ratings of 0-1 are only given to elements with very minor to no distress whatsoever –conditions typically seen only shortly after wall construction or substantial wall repairs.

1 to 2 Good: Low-to-moderate extent of low severity distress. Distress does not significantly compromise the element’s function, nor is there significant severe distress to major structural components. Ratings of 1 to 2 indicate highly functioning wall elements that are only beginning to show the first signs of distress or weathering.

2 to 3 Satisfactory: High extent of low severity distress and/or low-to-medium extent of medium to high severity distress. Distress present does not compromise element function, but lack of treatment may lead to impaired function and/or elevated risk of element failure in the long term. Ratings of 2 to 3 indicate functioning wall elements with specific distresses that need to be mitigated to avoid significant repairs or element replacement in the longer term.

3 to 4 Poor: Medium-to-high extent of medium-to-high severity distress. Distress present threatens element function, and strength is obviously compromised and/or structural analysis is warranted. The element condition does not pose an immediate threat to wall stability. A rating of 3 to 4 indicates marginally functioning, severely distressed wall elements in jeopardy of failing without element repair or in need of repair to prevent further deterioration at an accelerated rate.

4 Critical: Medium-to-high extent of high severity distress. Element is no longer serving intended function. Element performance is threatening overall stability of the wall at the time of inspection. In practice, a rating of 4 indicates a wall that is no longer functioning as intended, and is in danger of failing.

Retaining Wall Inspection Criteria

Each item is rated:

0 = No Problems

1 = Minor Problems

2 = Moderate Problems

3 = Severe Problems

4 = Critical Problems

N/A = Not Applicable

Each Division – Given an Average Rating (Sum of Individual Items in Division / # of Items rated)

OVERALL WALL RATING (General Condition)

Sum of the average of the four Divisions (Structural, Drainage, Cosmetic, Misc.) Excludes any N/A Ratings

Example:

Structural Avg. - 2.0

Drainage Avg. – 3.0

Cosmetic Avg. – 2.0

Miscellaneous Avg. N/A

Overall Wall Rating = 7 (Sum of Ratings) / 3 (Number of Subjects) = 2.3 (Rating)

1.4 MSE Wall Issues and Guidelines

Gerber (2012) compiled a synthesis report with the objective to determine methods used at the time to monitor, assess and predict the long-term performance of MSE walls, where "long-term" denotes the period of time from approximately one year after the wall is in service until the end of its design life (75 to 100 years). Of the 52 US and 12 Canadian targeted survey recipients, 39 and 5, respectively, responded. Fewer than one-quarter of state-level transportation agencies in the United States have developed some type of MSE wall inventory beyond that which may be captured as part of their bridge inventories. The agencies reported the most significant lessons learned, with the more popular topics being drainage, construction, backfill and modular block issues. An important conclusion of this synthesis is that there exists a need for greater recognition of MSE walls (and retaining walls in general) as important infrastructure assets. The 14 respondents who have MSE wall inventories are:

- Alberta, Canada
- California
- Colorado
- Kansas
- Minnesota
- Missouri
- Nebraska
- New York
- North Carolina
- North Dakota
- Ontario, Canada
- Tennessee
- Utah
- Wisconsin

Ohio, Pennsylvania and Washington also have MSE wall inventories, however they were not survey respondents. Some wall inventories are also maintained by city-level agencies. The cities of Cincinnati, New York City and Seattle maintain retaining wall inventories, including MSE walls. Methods used to manage MSE wall inventories include simple spreadsheets, MS Access, Oracle and PONTIS databases.

Most agencies monitor their MSE walls in response to known incidents or adverse performance. It appears that once MSE wall inventories are initially developed, additional information relative to ongoing performance is generally either not collected or not assessed for most walls. The reinforcement of the retained soil mass, which can be geosynthetic material or metallic straps or meshes, is critical for the assessment of the performance of MSE walls. The AASHTO (2010b) metal loss model and backfill specifications are shown in Table 1.20. Several US State agencies have conducted reinforcement corrosion studies.

Table 1.21 presents a summary of various of these efforts. Corrosion monitoring of steel reinforcement is typically accomplished by either retrieval of buried coupons or non-destructive electrochemical methods. For geosynthetic reinforcement, the primary performance issue is polymer degradation. At present, the only effective means of assessment is retrieval of buried specimens. Table 1.22 depicts backfill material requirements for different DOTs.

Table 1.20. AASHTO metal loss model and backfill specifications (after Fishman and Withiam 2011)

Metal Loss Model		**Backfill Specifications**	
Component Type (age)	Loss (μm/yr)	pH	5 to 10
Zinc (first 2 years)	15	Resistivity	≥ 3000 ohm-cm
Zinc (to depletion)	4	Chlorides	≤ 100 ppm
Carbon steel (after steel depletion)	12	Sulfates	≤ 200 ppm
		Organic Content	≤ 1 %

Table 1.21. Summary of US State MSE wall corrosion assessment programs (from Gerber 2012)

Table 1.21. Summary of US State MSE wall corrosion assessment programs (from Gerber 2012)

State	Description
California	Has been installing inspection elements with new construction since 1987, and has been performing tensile strength tests on extracted elements. Some electrochemical testing of in-service reinforcements and coupons has also been performed. Linear polarization resistance (LPR) and EIS tests were performed on inspection elements at selected sites as part of NCHRP Project 24-28 and results compared with direct physical observations on extracted elements.
Florida	Program focused on evaluating the impact of saltwater intrusion, including laboratory testing and field studies. Coupons were installed and reinforcements were wired for electrochemical testing and corrosion monitoring at 10 MSE walls. Monitoring has continued since 1996.
Georgia	Began evaluating MSE walls in 1979 in response to observations of poor performance at one site located in a very aggressive marine environment incorporating an early application of MSE technology. Exhumed reinforcement samples for visual examination and laboratory testing. Some in situ corrosion monitoring of in-service reinforcements and coupons at 12 selected sites using electrochemical test techniques was also performed.
Kentucky	Developed an inventory and performance database for MSE walls. Performed corrosion monitoring including electrochemical testing of in-service reinforcements and coupons at five selected sites.
Nevada	Condition assessments and corrosion monitoring of three walls at a site with aggressive reinforced fill and site conditions. Exhumed reinforcements for visual examination and laboratory testing; performed electrochemical testing on in-service reinforcements and coupons. A total of 12 monitoring stations were dispersed throughout the site providing a very good sample distribution.
New York	Screened inventory and established priorities for condition assessment and corrosion monitoring based on suspect reinforced fills. Two walls with reinforced fill known to meet department specifications for MSE construction are also included in program as a basis for comparison. Corrosion monitoring uses electrochemical tests on coupons and in-service reinforcements.
North Carolina	Initiated a corrosion evaluation program for MSE structures in 1992. Screened inventory and six walls were selected for electrochemical testing including measurement of half-cell potential and LPR. This initial study included in-service reinforcements, but coupons were not installed. Subsequent to the initial study, NCDOT has installed coupons and wired in-service reinforcements for measurement of half-cell potential on MSE walls and embankments constructed since 1992. LPR testing was also performed at approximately 30 sites in cooperation with NCHRP Project 24-28.
Ohio	Concerned about the impact of their highway and bridge de-icing programs on the service life of metal reinforcements. Performed laboratory testing on samples of reinforced fill but did not sample reinforcements or make in situ corrosion rate measurements.
Oregon	Preliminary study including (1) a review of methods for estimating and measuring deterioration of structural reinforcing elements, (2) a selected history of design specifications and utilization of metallic reinforcements, and (3) listing of MSE walls that can be identified in the ODOT system.
Utah	Extracted 22 wire coupons from one- and two-stage MSE walls all approximately 11 to 12 years old. Galvanization thickness was found to still be greater than initial specified values. Data to provide baselines for future assessments.

After Fishman and Withiam (2011).

Table 1.22. Summary of backfill requirements for some State DOTs (from Raeburn et al. 2008)

State Name	PI or Φ	Resistivity, R (ohm-cm)	Chlorides (ppm)	Sulfates (ppm)	pH
Federal Highway (FHWA)	-	≥3000	≤100	≤200	5 to 10
California	PI ≤ 10	≥1500	<500	<2000	5.5 to 10
Florida	PI < 6	≥3000	≤100	≤200	5 to 10
Georgia	-	≥3000	≤100	≤200	6 to 9.5
New York	PI < 5	≥3000	≤100	≤200	-
Ohio	Φ > 34	≥3000	≤100	≤200	5 to 10 for steel reinforcement 4.5 to 9 for geosyn. reinf.
Washington	-	≥5000 3000≤R< 5000	Waived ≤100	Waived ≤200	5 to 10 for steel reinforcement 4.5 to 9 for geosyn. reinf.
Idaho	PI < 6	≥3000	Waived ≤100	Waived ≤200	4.5 to 9.5
Nevada	PI < 6	≥3000	≤100	≤200	5 to 10
Utah	PI < 6 Φ > 34		≤100	≤200	6 to 9
Colorado*	Φ > 34	≥3000	≤100	≤200	5 to 10
Oregon**	PI < 6	≥5000 3000≤R< 5000	Waived ≤100	Waived ≤200	4.5 to 9.5
Related Standards	ASTM D4318 for PI	AASHTO T-288-91	AASHTO T-291-91 or ASTM D-4327-88	AASHTO T-291-91 or ASTM D-4327-88	AASHTO T-289-91

* In their specs, CDOT requires backfill material to be non-aggressive, hence FHWA criteria is assumed.

**ODOT also requires the uniformity coefficient ($C_u=D_{60}/D_{10}$) of the granular backfill material to be smaller than 1.5 (*ODOT 2007*).

The most important conditions in assessing the long-term performance of MSE walls are corrosion and degradation of internal reinforcement and drainage according to the survey participants. Wall height, was surprisingly found to be among the least important features. In addition, most agencies believe that global stability and reinforcement rupture are the most likely failure modes for MSE walls in the long term. Overturning and facing failure are considered the least likely failure modes.

Once wall conditions are assessed, the assigned rating can be related to a specified action or is used to make programming decisions. For example, in the FHWA-NPS (DeMarco et al. 2010) system four additional items are considered before taking action: (1) are additional investigations required (how reliable is our assessment); (2) what design criteria may have been used in planning the structure (was the structure engineered); (3) what aspects of the wall structure are historic or contribute to the cultural context of the road asset; and (4) what are the consequences of wall failure.

Alzamora and Anderson (2009) provided a list of design and construction inspection issues and commented that poor performance of MSE walls is mainly attributed to construction, but observations related to design, wall and material selection and mitigation of weak foundations have been reported:

Design

- Geometry/Wall layout
- Obstructions
- Wall embedment
- Surface drainage
- Contractor experience

Construction/Inspection

- Claims
- Backfill placement and compaction
- Panel joints
- Leveling pad
- Durability of facing

Texas DOT has had few issues with MSE walls, which are the majority (85%) of the walls in the State of Texas (Delphia 2012). The main MSE wall can be categorized as:

- **DESIGN**
  - ➢ Global Stability
    - o Strength Conditions (short term and long term)
    - o Presence of Water

- Placement of Walls on Slopes, may be false economy

- **CONSTRUCTION/INSPECTION**
  - Embankment/Backfill Placement
  - Foundation Soil preparation
  - Obstructions – Drilled shafts, drainage features.
  - Damaged Reinforcements
  - Connections
  - Backfill Properties
  - Panel alignment and panel joint spacing
  - Loss of MSE backfill
  - Corner details
  - Hard point under MSE retaining wall leveling pad

It is recommended that the construction of the wall should be treated as a structure and not as an embankment. Texas DOT developed a shallow inlet standard 1'-10'' in depth. When inlets have to be placed behind the wall, Texas DOT uses the vertical stand pipe option and the shallow inlet standard.

Ohio DOT (Narsavage 2006) inspected 339 MSE walls. Figure 1.9 shows some of the observed problems that were identified. The Office of Structural Engineering would use the information fr om the inspections to develop an inspection program, similar to the Bridge Inspection Program. Condition ratings were developed consisting of simple "yes" or "no" responses. Inspection forms can be found in Appendix A.9.

Figure 1.9. Observed problems in MSE walls (Narsavage 2006)

Observed Problems

- Sand leaking from joints
- Settlement of panels
- Uncontrolled drainage
- Deteriorating panels
- Erosion along MSE wall
- Vegetation in joints
- Bulging
- Drainage system

Design Changes for MSE Walls

- Preference for certain MSE wall types. Acute angles should be avoided at bridge abutments and obstructions should be minimized.
- Abutments supported on spread footings only under certain conditions. All obstructions within reinforcing zone should be shown in a plan view.
- Drainage around MSE walls should be considered. The barrier should be extended past the MSE wall and catch basins should be placed beyond the MSE wall.
- Avoid utilities through or underneath MSE walls.

Utah DOT tried to locate all the MSE walls in the State and develop an inspection protocol based on the Ohio DOT inspection program, as well as an asset management database (Bay et al. 2010). Data from 104 MSE walls are contained in the database.

A team from Utah State University and another one from Brigham Young University inspected MSE walls in the State of Utah. The inspection form that was developed is separated into: 1) inspector and general information, 2) summary of key observations, 3) plan/drainage view, 4) cross-sections and 5) specific wall characteristics. The specific wall characteristics include eight categories: water and drainage, wall joints, wall facing, conditions at top of wall, foundation conditions and external stability, corrosion, impact and collision, and miscellaneous. Questions are answered as yes, no or unknown, while there is a choice of percentage of the wall exhibiting a characteristic. Inspection forms are provided in Appendix A.10.

Observations

- Drainage at top/bottom of the wall
- Blocked drains
- Permanent water flows and runoff
- Internal drainage (leakage through panel joints)
- Irrigation pipes
- Vegetation (evidence of drainage, can disrupt components of MSE wall)
- Irregular panel spacing and movement
- Popped panel corners
- Cracked panels
- Bowing in wall
- Tears in fabric
- Cracks in coping (indicative of wall movement)
- Cracks in parapets
- Leveling pad issues (exposure, cracking
- Corrosion/Erosion of panels
- Salt deposits

- Corrosion testing coupons
- Reverse batter
- Large deformations/Steep slopes at the wall base
- Presence or absence of bench at base of wall founded on a slope (reduces erosion)
- Presence of adjacent structures (can move along with the wall)
- Block wall issues (spacing, leakage, exposure of reinforcement, corrosion)

Walls are numbered with R-numbers (e.g. R-123) and tracked in a spreadsheet. A software Transportation Asset Management System (TAMS) with an open-source GIS-based interface between MapWindow and Microsoft Access was implemented to create an electronic database from field observations. The walls are identified by the symbol "1", "2" or "B" for one-stage, two-stage and modular block wall, respectively. A unique spatial identifier, usually a GPS point, is entered for each wall record.

Issues of concern identified by panel of experts

Short-term performance of MSE walls

- Wall drainage
- Wall design, details and specifications
- Retention of wall information

Long-term performance of MSE walls

- Corrosion of the retaining wall systems

A brief overview of some case studies and the mechanisms that had as a result the wall failure are provided below:

1. Soda Springs, Idaho

The wall was built in 1978 and was considered the first true MSE wall abutment in the United States. Failure occurred in 2002; six pre-cast concrete panels popped out.

<u>Cause of failure:</u> corrosion of the metallic soil reinforcing strips attached to the lower concrete facing panels. A chemically aggressive slag waste was used as backfill.

2. Susquehanna County, Pennsylvania

Built in 1985, failure in 1989. Cavity of 10 ft^2 opened up in the lower right quadrant of east abutment, loss of 70 yd^3 of backfill and pre-cast concrete panels toppled away from the wall.

Cause of failure: overstress of the reduced section in the critical bottom third of the wall.

3. Rockville, Maryland

Built in 1996, failure in 2003; geosynthetic reinforcement was used. Large gaps and separation in the wall facing blocks started in 2002. At failure, leaning and bulging of the wall face was observed and the top of wall moved 12 to 18 in. Portions of the wall face were wet even after periods of dry weather; indicative of water flow through backfill. Excavation revealed that the geogrid reinforcement was not horizontal. The compaction of the upper layer of fill was not sufficient (81% of γ_{dmax}).

Cause of failure: improper installation of the geogrid, inadequate internal drainage of the backfill soil and inadequate compaction of the reinforced soils.

4. Clearfield, Utah

Built in 2001, distress observed same month the bridge was open to traffic. Vertical separation between wall panels was reported along with undermining and displacement of MSE wall leveling pads, rotation of wall panels with accompanying spalling of several panel corners, outward rotation of the top MSE walls panels and overlying coping, cracking of the MSE wall coping, outward rotation/translation of barrier sections, cracking and displacement of the roadway pavement section near the southwest corner of the bridge, horizontal and vertical displacement of the sidewalk along the north side of the west approach embankment and development of voids beneath the sidewalk, and beneath the roadway slabs. Slope movement was in the order of 1.5 ft.

Cause of failure: the bench was not constructed with a full 4-ft width in all locations as per AASHTO specifications. There were changes in the embankment material and insufficient compaction. Erosion from runoff through cracks in the pavement or around the end of the barrier.

5. Salt Lake City, Utah

Built in 1997, failure in 2005. Buckling of MSE wall panels was observed. The panels were repaired but movement continued within the reinforced backfill zone.

<u>Cause of failure:</u> internal settlement of the wall backfill immediately next to the face of the wall and insufficient compaction of the soil.

6. Orem, Utah

Built in 2001, failure in 2003. Large void developed behind the back of the MSE wall and exposed the flat reinforced straps and their connection to the panels.

<u>Potential Cause of failure:</u> poor drainage and subsequent erosion or internal erosion and settlement behind the wall panel.

7. Northeastern Tennessee

Built in 1999, failure 9 months later. Geogrid reinforcement was used. Movement and deformations in spread footings and nearby electrical duct manholes. No global stability analysis was performed prior to construction of the wall, which would have revealed the necessity of more and elongated geogrid reinforcement.

<u>Cause of failure:</u> inadequate reinforcement and use of clayey backfill.

8. Southwestern Virginia

Built in 1999, failure 1 year later. Geogrid reinforcement with clayey backfill was used. The reinforced soil remained intact, while the geogrid reinforcement had pulled from between the masonry blocks. A car wash was located directly above the wall. Cracking in the ground surface behind and parallel to the wall. Compaction of reinforced soil was insufficient.

Cause of failure: poor drainage led to buildup of hydrostatic pressure behind the wall. Erratic compaction of fill soils, increased height of wall and use of clayey backfill within reinforced zone.

A team from Utah State University and another one from Brigham Young University inspected MSE walls in the State of Utah. The inspection form that was developed is separated into: 1) inspector and general information, 2) summary of key observations, 3) plan/drainage view, 4) cross-sections and 5) specific wall characteristics. The specific wall characteristics include eight categories: water and drainage, wall joints, wall facing, conditions at top of wall, foundation conditions and external stability, corrosion, impact and collision, and miscellaneous. Questions are answered as yes, no or unknown, while there is a choice of percentage of the wall exhibiting a characteristic. Inspection forms are provided in Appendix A.

Observations

- Drainage at top/bottom of the wall
- Blocked drains
- Permanent water flows and runoff
- Internal drainage (leakage through panel joints)
- Irrigation pipes
- Vegetation (evidence of drainage, can disrupt components of MSE wall)
- Irregular panel spacing and movement
- Popped panel corners
- Cracked panels
- Bowing in wall
- Tears in fabric
- Cracks in coping (indicative of wall movement)
- Cracks in parapets
- Leveling pad issues (exposure, cracking
- Corrosion/Erosion of panels
- Salt deposits
- Corrosion testing coupons

- Reverse batter
- Large deformations/Steep slopes at the wall base
- Presence or absence of bench at base of wall founded on a slope (reduces erosion)
- Presence of adjacent structures (can move along with the wall)
- Block wall issues (spacing, leakage, exposure of reinforcement, corrosion)

Walls are numbered with R-numbers (e.g. R-123) and tracked in a spreadsheet. A software Transportation Asset Management System (TAMS) with an open-source GIS-based interface between MapWindow and Microsoft Access was implemented to create an electronic database from field observations. The walls are identified by the symbol "1", "2" or "B" for one-stage, two-stage and modular block wall, respectively. A unique spatial identifier, usually a GPS point, is entered for each wall record.

Issues of concern identified by panel of experts

Short-term performance of MSE walls

- Wall drainage
- Wall design, details and specifications
- Retention of wall information

Long-term performance of MSE walls

- Corrosion of the retaining wall systems

1.5 Retaining Wall Monitoring and Health Assessment Technologies

There are several approaches to monitor and inspect retaining wall structures. Instrumentation and remote sensing methods are both used for data collection. Examples of instruments that are used for monitoring include strain gages, tiltmeters, extensometers, inductance coil pairs, fiber optic sensors, crack gauges, piezometers, pressure transducers and slope indicators. The two more common remote sensing techniques are the optical photogrammetry and 3D laser scanning. Table 1.23 presents different monitoring techniques and the measuring parameters.

Agencies follow different inspection schemes for data collection of retaining walls. The City of Seattle, for example, is using a digital protractor for wall tilt measurements, while measuring stations are permanently established on many walls (Molla 2014). The Pennsylvania Department of Transportation has implemented new technology as part of its data collection efforts in 2008 and 2009. LiDAR using a fixed-winged aircraft was used to assess the amount of creep that the Lewiston Narrows wall (the second-longest MSE wall in the world with a length of 2.5 miles). The goal of 0.10 ft proved difficult to confirm because of the low altitude required within the canyon. Use of a helicopter might be tried instead. Down-hole cameras in pipes and culverts are also used to inspect the drainage system (Pennsylvania DOT 2010). Arizona DOT used laser scanning and panoramic photography in “inaccessible terrain” (Priznar et al. 2010). British Columbia Ministry of Transportation and Infrastructure monitors walls with slope indicators, tell-tales, surface monitoring hubs, piezometers, tilt meters, etc. (British Columbia Ministry of Transportation and Infrastructure 2013). In a study conducted in Northern Ireland (Gridpoint Solutions Ltd. 2005) laser scanning was used at 6-month intervals to monitor movement in a 5 m high retaining wall along a railroad cut, to detect changes greater than 5 mm. It was found that this method was faster, cheaper and safer than conventional techniques. Table 1.24 shows some of the monitoring technologies and corresponding references.

Table 1.23. Monitoring techniques and measuring parameters for Earth Retaining Structures

Technique	Measurement
LiDAR	Wall identification and condition assessment
Photogrammetry	Condition assessment
Ground Penetrating Radar (GPR)	Object location in soil or concrete
Piezometers & Pressure Transducers	Measurement of stream water elevation
Thermal scanning	Identify water accumulation
Down-hole cameras	Inspection of drainage system
Slope indicators	Monitoring of lateral deformations
Crack Gauges	Monitoring cracks in walls
Surface monitoring hubs	Surface movement
Digital protractor	Lateral movement
Tilt meters	Lateral movement
Strain gages	Measurement of stress reinforcement
Extensometers	Horizontal and Vertical movement
Inductance coil pairs	Measurement of geosynthetic strain
Fiber optic sensors	Strain and temperature measurement
Half-cell potential (Ecorr)	Corrosion monitoring of steel reinforcement
Coupon testing	Corrosion monitoring of steel reinforcement
Linear Polarization Resistance (LPR)	Corrosion monitoring of steel reinforcement

Table 1.24. Monitoring technologies and references

Technique	References
LiDAR	Kemeny and Turner (2008), Kim et al. (2009), Oskouie et al. (2016), Priznar et al. (2010), Yen et al. (2011)
Photogrammetry	Cerminaro (2014), Wolf et al. (2016)
Ground Penetrating Radar (GPR)	Hugenschmidt and Kalogeropoulos (2009), Huston et al. (2001)
Destructive techniques for MSE walls	Elias et al. (2009), Fishman et al. (2009), Gladstone et al. 2006, Raeburn et al. (2008)
Nondestructive techniques for MSE walls	Elias et al. (2009), Fishman et al. (2009), Koerner and Koerner (2011), Lostumbo and Artieres (2011), Raeburn et al. (2008)
Digital protractor	Molla (2014)
Down-hole cameras	Pennsylvania DOT (2010)
Fiber Optics	Lostumbo and Artieres (2011)

1.5.1. LiDAR Mapping and Assessment

Light Detection and Ranging (LiDAR), also often referred to as "3D laser scanning", is an emerging three-dimensional mapping technology that employs a laser and a rotating mirror or housing to rapidly scan and image volumes and surficial areas such as rock slopes and outcrops, buildings, bridges and other natural and man-made objects. Ground-based or terrestrial LiDAR refers to tripod-based measurements, as opposed to airborne LiDAR measurements made from airplanes or helicopters (Kemeny and Turner 2008).

The output from ground-based LiDAR is a point cloud consisting of millions of laser distance measurements representing the three-dimensional scanned scene. The point clouds are then processed to extract geotechnical information, which includes discontinuity orientation, length, spacing, roughness, and block size. High-resolution digital images are also taken of the scanned scene, and these images can be "draped" onto the point cloud using texture-mapping techniques (Blythe 1999) to provide a 3D color Digital Terrain Model (DTM) of the scanned scene. Additional geological and geotechnical information can be extracted from the DTM that would be difficult to observe in the point cloud.

Distance values for millions of points on a reflected surface are generated. From the distance and the orientation of the laser pulse, the xyz coordinates associated with each reflected pulse can be determined. In addition, the intensity of the returned pulse is determined. In general, light colored objects and closer objects give a higher reflection compared with darker objects and objects farther away. Together, the xyz coordinates and associated intensity values for millions of data points outputted by the laser make up the "point cloud".

There are two primary types of 3D laser scanners: time-of-flight scanners and phase-shift scanners. The time-of-flight scanners are capable of a much larger range compared with the phase shift scanners. Thus, time-of-flight scanners would be preferred for large highway slopes and cliffs, while phase shift scanners would be preferred for small underground tunnels, for example. Also, the phase shift scanners have a much higher average data acquisition rate compared with the time-of-flight scanners. In terms of distance and position accuracies, the phase shift scanners have a slightly higher accuracy compared with the time-of-flight scanners.

In the case of the conditions assessment of retaining walls, surveying technology such a LiDAR can be deployed efficiently for providing a 3D data profile of the wall surface. While at present this approach can be effectively deployed on a project level, it is not far in the future when such data can be collected on a network level. Using the data collected over the years, an inventory can be developed for management of walls as a highway asset (Kim et al. 2009).

Figure 1.10 shows an example of LiDAR survey results of an MSE wall. Each pixel in the image represents a set of data points that is tied to x, y, and z coordinates. Linking the output of the LiDAR survey with the database of the walls coordinates can automate the process of condition assessment, and provides synoptic approach to asset management of walls. Survey year and survey results can be linked to the cross-section views and locations of the wall. The survey of wall facing with time can provide important information regarding the condition of the wall since perceptive deformation can be detected by comparing the consecutive scans. A wall inventory database clearly needs to include static data such as wall latitude, longitude, and implement such data within state coordinate system. In addition, foundation type, depth of embedment, and drainage measures should be included.

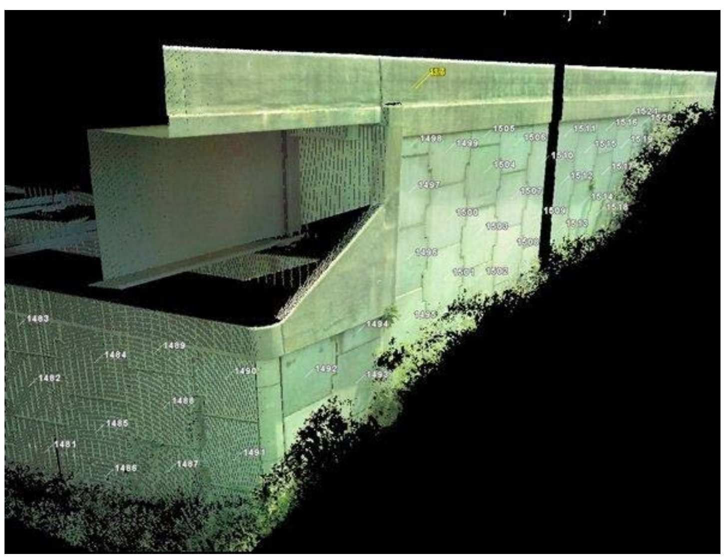


Figure 1.10. LiDAR mapping of MSE wall (from Kim et al. 2009)

Yen et al. (2011) evaluated the feasibility of using the mobile LiDAR technology to capture geospatial data of highways and use it for surveying, asset management, as-built documentation and maintenance operations. Mobile LiDAR systems collect field data of up to 150 miles a day, removing the need for lane closures while increasing productivity.

Based on discussions with service providers, a few state DOTs, such as Tennessee DOT, Hawaii DOT, Nevada DOT, and Texas DOT, have contracted with mobile LiDAR service providers for asset management. Caltrans has contracted with a mobile LiDAR survey firm to perform bridge clearance measurements and pavement surveys. Recently, Oregon DOT has purchased a mapping grade mobile LiDAR system. Survey service providers have been using survey grade mobile LiDAR systems to collect data for railroad and power transmission line management.

The pilot participants took about 2 hours with the vehicle speed mostly at 55 mph for data collection of the test section, a 5-mile divided 4-lane highway. This includes time that was taken to complete multiple passes, resulting in redundant test area data as well as capturing data of the two intersections. The multiple passes were valuable in examining system repeatability as well as filling in shadows created by large trucks blocking the LiDAR sensor’s Field-of-View. The short data collection time confirms high productivity of mobile LiDAR systems. In addition, the data collection personnel were safely protected inside the data collection vehicle.

Oskouie et al. (2016) used Terrestrial Laser Scanners (TLS) to measure retaining wall displacements. The horizontal joints between the wall panels were used as the benchmarks providing displacement data for all the panels on the wall through a fully automated framework; MSE walls were studied. First, an algorithm was introduced for extracting MSE wall facing panels' horizontal joints from a TLS generated point cloud. Next, the displacement of the wall was determined by comparing the extracted joint displacements. The method’s accuracy was evaluated using simulations and real-life data sets with an average accuracy of 94.72 %.

1.5.2. Photogrammetry for condition assessment of ERS

In photogrammetry, the 3D coordinates of a scene are determined from digital images taken of the same scene from different directions. In particular, information on the 3D coordinates is determined from the parallax, which is the change of angular position of two observations of a single object relative to each other. Today it is more common to use a standard digital camera and take multiple images of a scene from arbitrary directions and positions. The multiple camera positions are then determined using a technique called bundle adjustment that involves “feature matching" in overlapping areas of the images (Kemeny and Turner 2008). Digital photogrammetry and 3D modelling software are used to generate 3D models and inspect structures and structural elements.

Cerminaro (2014) investigated the use of photogrammetry to quantitatively assess the condition of retaining walls. 3D models of retaining walls were developed and offset displacements were measured to assess their condition. A case study from a site along M-10 highway in Detroit, MI (Figure 1.11) where several sections of retaining walls had experienced horizontal displacement towards the highway was presented and results were validated with field observations and measurements. A small-scale model was also built in the laboratory. The analysis showed that the accuracy of the offset displacement measurements is dependent on the distance between the retaining wall and the sensor, location of the reference points in 3D space, and the focal length of the lenses used by the camera.

The following steps were followed to obtain deflection measurements:

- Creating reference points on the retaining walls which were used to establish a scale and geo-referencing for the 3D models
- Collecting photographs from the retaining wall using an optical camera
- 3D models are created using 3D modelling software and the 2D photographs. The software uses the photographs and reference points to extract the location of each point on the surface of the wall in 3D space, it then uses this information to create a 3D model
- Comparing two 3D models from two points in time and analyzing the changes to obtain deflection measurements

The process involved taking photographs of the object of interest from at least two different locations. From each location there is a line of sight that runs from each point on the object to the perspective center of the camera. The images from two consecutive locations need to have a certain overlap and typically 60 percent overlap is used. In this study a Nikon D5100 was used for data collection. The method used in this study which is the most common method to acquire images for 3D modeling is the Pinhole Camera Model. This camera allows 16.2 megapixels pictures, and has digital single lens reflex (D-SLR), and AFS DX 18-55mm with vibration reduction (VR) lens. For the processing conducted in this study, Agisoft Photoscan Professional was used.

Results from the small scale model in the laboratory showed that the deflection measurements can be accurate when the data is captured within a distance of 40 ft. Three field datasets were taken in this study on the wall on M-10 highway. The distance between the surface of the wall and the camera was approximately 100 ft for each data set. The movement was measured in terms of offset relative to the adjacent walls at the expansion joints using a measuring tape and was confirmed by tilt-meter monitoring. The final results from the 3D model comparison from the case study, however, did not provide reliable deflection measurements. The unreliability of the results is due the actual deflection was not within the accuracy range of the models which were collected at a distance of 100 ft.

Figure 1.11. Retaining wall on M-10 (from Cerminaro 2014)

1.5.3. Inspection of retaining walls using Ground Penetrating Radar (GPR)

The technology of Ground Penetrating Radar (GPR) is used to determine the integrity of concrete bridge columns, retaining walls and roadways. GPR is a geophysical method that uses high frequency electromagnetic waves and detects the reflected signals from structural elements.

Hugenschmidt and Kalogeropoulos (2009) presented a study with the application of GPR for the inspection of retaining walls. The main objective was to locate anchor heads and to gain information on the general structure of the reinforced concrete wall. A semi-automated survey apparatus was developed, which consisted of a railing system, an antenna box, a ladder-like guiding system for the antenna box, an electric motor for moving the box up and down the face of the wall, a survey wheel for controlling the vertical position of the box and triggering the data acquisition and an electronic protractor for monitoring the angle between the guiding system and the vertical line thus controlling the lateral position of the antenna (Figure 1.12). Data was acquired along the face of the wall using three different antennas; up to 30 vertical lines were acquired per hour. This pilot study showed that data acquisition on large retaining walls can be carried out economically and with high precision.

Huston et al. (2001) developed a prototype handheld system in an attempt to use GPR technology on non-horizontal surfaces, such as columns and walls with higher frequencies than those used to examine roadways. The system performed moderately well in identifying rebars and concrete joints for reinforced concrete columns and walls. It was suggested that more development is needed before the system can be a practical tool for routine inspection of columns and walls.

Figure 1.12. Semi-automated survey apparatus (from Hugenschmidt and Kalogeropoulos 2009)

1.5.4. Condition Assessment of Mechanically Stabilized Earth (MSE) Walls

Elias et al. (2001) reported that the majority of the MSE walls for permanent applications are constructed to date with galvanized steel reinforcements. The galvanized steel, either in strip or grid configuration (95% of applications), is connected to a precast concrete facing. The advantages of galvanization steel reinforcement were listed by Gladstone et al. (2006) as: (1) minimizing the surface irregularities and their contributions to corrosion, (2) lowering consumption rate of zinc compared to steel, and (3) "passivation" of steel due to zinc oxides which lowers the rate of steel consumption compared to non-galvanized steel.

The Association for Metallically Stabilized Earth (AMSE) has compiled an inventory documenting details of 780 MSE walls constructed in the United States since 1972 (AMSE 2006). Approximately half of the walls in the AMSE inventory are located in the Western Region of the United States, within an arid climate where backfill sources are alkaline. Compared to steel grid type reinforcements, which are used predominantly within the Western Region, use of strip reinforcements is more uniformly distributed geographically. Approximately 40 percent of the walls constructed with strip reinforcements are located in the more temperate Southern climates, where soils are normally slightly acidic.

Corrosion of the tensile elements due to the chemical hardness of the soil-water is a major concern for the long term durability of MSE walls. The choice of backfill material and reinforcing material are two key issues to address in attempting to mitigate corrosion of MSE wall. Assessing the corrosion state of metal strips reinforcing highway retaining structures is one of the important asset management tasks for departments of transportation across the country.

Controlling factors of corrosion rates include (Raeburn et al. 2008):

- Water content - soil water contains the salts and constitutes the electrolyte necessary for corrosion
- Soil resistivity, when measured at saturation, gives a figure related to the total amount of salts present in the soil 153
- pH (potential of hydrogen), that governs the solubility of corrosion by-products and thus the buildup of protective layers around the buried metal
- Chloride content-chloride is the most common aggressive salt

- Sulfate content

Destructive and nondestructive techniques are available for corrosion detection. Measuring metal loss data from the exhumation of a wall is a common destructive technique for corrosion detection and measurement. Due to process of excavation while maintaining the integrity of the wall, this method is limited to reinforcement elements near the surface. Such a limitation may provide results that are not representative of the most corrosive area of the wall. Corrosion rates are established through weight loss and thickness measurements, and usually multiple measurements are made at different times to assess the effect of time on the rate of metal loss (Gladstone et al. 2006). The method is expensive since it is labor intensive, and requires caution in order to ensure that the stability of the wall will not be compromised during sampling.

Popular nondestructive methods for assessment of corrosion are polarization resistance measurements, linear polarization resistance (LPR) measurements, coupon testing and half-cell potential measurements of reinforcement (Ecorr). In polarization resistance measurements, composition and geometry of the surface of reinforcement should be known. The approach is based on converting the polarization resistance to a corrosion rate. For LPR, the potential is varied from "–5 to –20 mV" to "+5 to +20 mV" around the free corrosion potential while simultaneously measuring the applied current. Polarization resistance is determined from the slope current and potential. Since corrosion rates vary throughout the year, measurements should be taken during different seasons to attain an average corrosion rate for the structure (Gladstone et al. 2006). Coupon testing and half-cell potential measurements of reinforcements are installed at regular intervals during MSE wall construction. Zinc bars and steel plate coupons are installed, and reinforcements are wired for half-cell potential measurements at each monitoring station along the wall. Elias et al. (2009) advise that "given the advantages, utilization of remote electrochemical methods is highly recommended with at least some coupons buried for retrievals to confirm results." Their provided rule of thumb regarding installation is two locations spaced at least 200 ft (60 m) apart for MSE walls 800 ft (250 m) or less in length and three locations for longer walls. At each location, corrosion should be monitored at a minimum of two depths. Caltrans has developed a typical layout of 18 clustered coupons to be periodically extracted. With respect to frequency of assessing corrosion, Elias et al. (2009) recommend that potential and polarization resistance measurements (owing to their sensitive nature) be made monthly for the first three months, bi-monthly for the next nine months, and annually thereafter.

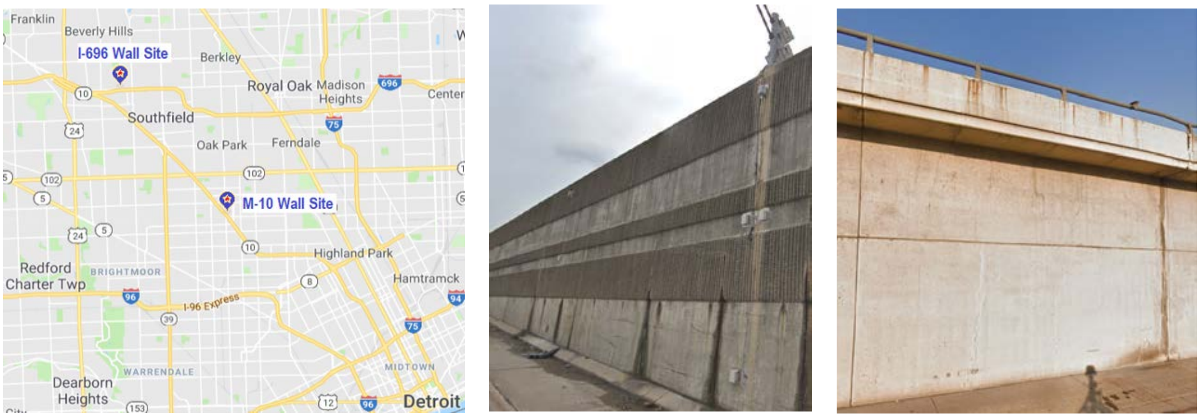
Koerner and Koerner (2011) presented instrumentation devices and strategies to monitor MSE walls with geosynthetic reinforcement during and soon after construction. The most common instruments are strain gages, fiber optic sensors, extensometers, piezometers, inductance coil pairs and slope indicators. It is recommended, that sampling and testing occur at five to seven-year intervals for a minimum of four retrievals, or one-third the expected life of the facility (Elias et al. 2009).

2. DESIGN AND DEPLOYMENT OF WIRELESS MONITORING SYSTEMS FOR THE I-696 AND M-10 RETAINING WALLS

2.1. Introduction

Sensors can be installed on retaining walls whenever an asset manager is seeking quantitative data related to how a wall is performing. Specifically, instrumentation provides managers with insight to the behavior of the structural and geotechnical subsystems of the overall wall system. To understand the behavior of retaining walls, performance parameters of interest include: horizontal and vertical wall movements, deterioration of wall elements, drainage behavior of the backfill, lateral earth pressures, vertical stress distributions at the wall base, corrosion state of steel reinforcement, pore pressures below the structure, and other environmental parameters that vary temporally (*e.g.* temperature, rainfall) (FHWA, 2009). Sensors can be used to measure some of these performance parameters. Instrumentation can be installed during wall construction, but the cost of instrumentation makes this a rare choice. Rather, instrumentation is typically installed after construction and only if there are some concerns about wall performance that warrant the cost and effort of instrumentation (Koerner and Koerner, 2011). When instrumentation is selected, many performance parameters are difficult to measure, especially those associated with the soil system including earth pressures on the back-wall surface.

In general, the most common measurement of retaining walls is wall movement including tilting and relative displacements between wall panels. While all walls exhibit some cyclic movement based on seasonal variations, progressive wall tilt is a serious issue and if left unmitigated, can lead to instability of the system. Measurements are commonly taken by tiltmeters (also termed inclinometers) which provide a measure of the rotation of the wall away from the system backfill (WSDOT, 2011). Tiltmeters can be installed permanently or they can be used intermittently. When used intermittently, mounting plates are installed on the wall with tiltmeters manually applied to these plates when measurements need to be taken (*e.g.* weekly, monthly). Linear variable displacement transformers (LVDT) can serve as another sensor-type useful for measuring the movement of wall panels relative to one another. LVDTs require the mounting of the two ends of the sensor to two adjacent wall panels to measure relative movement. The relatively low cost and small dimensions of LVDTs make them attractive options for relative displacement measurements between panels. Strain gages can also be used to measure the strain response of the wall over a defined gage length. Strain gages have been used widely on sensing



(a) (b) (c)

Figure 2.1. (a) Retaining wall site locations (Source: Google 2019); (b) I-696 Wall

strain in steel sheet pile walls; however, in some instances they have also been used on concrete walls. Strain can be highly valuable for measuring the deformable body response of the retaining wall under load (*e.g.* active earth pressure, thermal loads) including assessing the evolution of cracks that jeopardize the long-term durability of the wall. Strain gages are typically metal foil gages embedded in a thin polyimide carrier film, but alternative strain sensors such as BDI strain transducers have found use in walls in the past (BDI, 2006).

In this project, an instrumentation strategy is proposed for monitoring highway retaining wall systems. Emphasis is placed on a strategy suitable for rapid installation after wall construction to provide data on wall behavior. The project considers instrumentation that can be installed on exposed wall surfaces and that is easy to deploy. The instrumentation strategy adopts tiltmeters to measure wall tilt, long-gage strain gages to measure thermal and flexural strains, and thermistors to measure wall temperatures. These measurements offer insight to the wall response to its loading environment. The instrumentation is also intended to assess if a wall is behaving as designed aiding in an assessment of its capacity. To collect measurements from these sensors, a wireless monitoring system is adopted. The wireless sensor nodes are designed to use solar power for their operation and cellular modems for their communication, making them easy to install. The proposed wireless instrumentation strategy is validated using two retaining wall systems in southeast Michigan. The first retaining wall system is a reinforced concrete cantilever wall along I-696 while the second is a caisson-supported reinforced concrete wall along M-10. The M-10 wall system has a history of failures associated with corrosion-induced failure of the steel tendon anchoring the wall to the caisson (MDOT, 2013; AECOM, 2016).

2.2. Retaining Wall Systems

2.2.1. Overview of the I-696 and M-10 Retaining Wall Systems

In Michigan, common retaining wall systems along the state highways include: cantilever reinforced concrete (RC) walls, RC walls supported by caisson tiebacks, mechanically stabilized earth (MSE) walls, sheet pile walls and soldier pile with legging walls. The cantilever RC wall is the most common wall type in the southeast Michigan region. The I-696 corridor in the Detroit metropolitan area has a large number of RC cantilever walls. Two wall panels located near Central Park Boulevard supporting West Eleven Mile Road on the south side of I-696 in Southfield, MI are selected (Figure 2.1). These walls were constructed in the mid-1980's and are more than thirty years old. These retaining wall locations are selected due to observed relative displacement between adjacent wall panels and due to a high amount of drainage emanating from the lower portions of the wall surface. In addition to the I-696 wall, one wall panel of the M-10 retaining wall located near Schaefer Highway in Detroit, MI (Figure 2.1) is also selected for this project. The M-10 wall system is supported by RC caissons with the wall anchored to the caissons using post-tensioned tendons at an angle of 30 degrees from the vertical wall face. The M-10 wall is selected due to the history of corrosion failure of the post-tension anchor rod (MDOT, 2013; AECOM, 2013).

2.2.2. On-Site Visual Assessment

During on-site visual inspection in June 2017, the M-10 retaining wall system was found to be in very good condition overall. Due to the history of failing anchor rods, the on-site inspection specifically sought out visual signs of major wall deformations that might indicate distress. Even though the M-10 walls were in a good structural condition, evidence of minor distress was observed. At the top of the wall, pavement deformation of the supported service road indicated movement and compaction of the backfill system. Differential displacement (in plane and out of plane) between wall panels was also evident. In addition, mild leakage stains, small areas of concrete spalling, and vertical cracking were evident on the face of the wall. Photos from the on-site inspection are provided in Figure 2.2. Given the observations made, the wall was deemed to be an excellent candidate for monitoring. Specifically, monitoring could be used to assess if wall movement is the cause of the distressed pavement observed on the upper service road supported by the wall system.

The I-696 retaining wall system was also inspected in June 2017. While the wall system was found to be in very good condition, several concerns were raised. First, there appeared to be

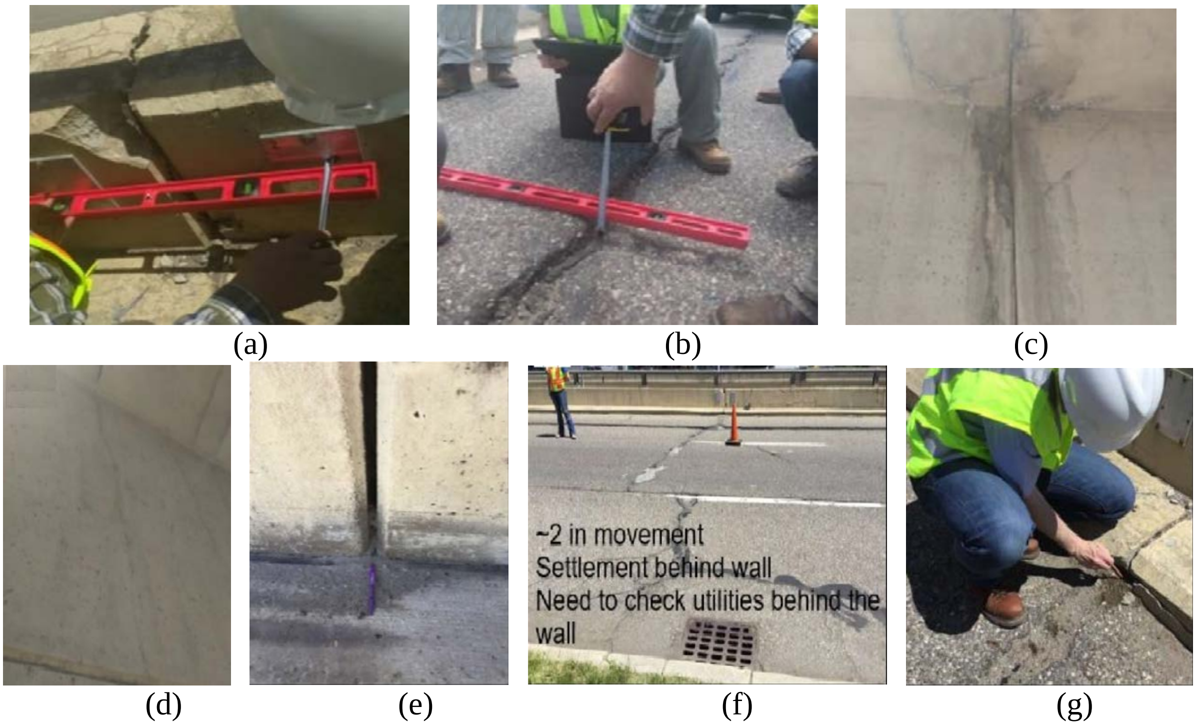
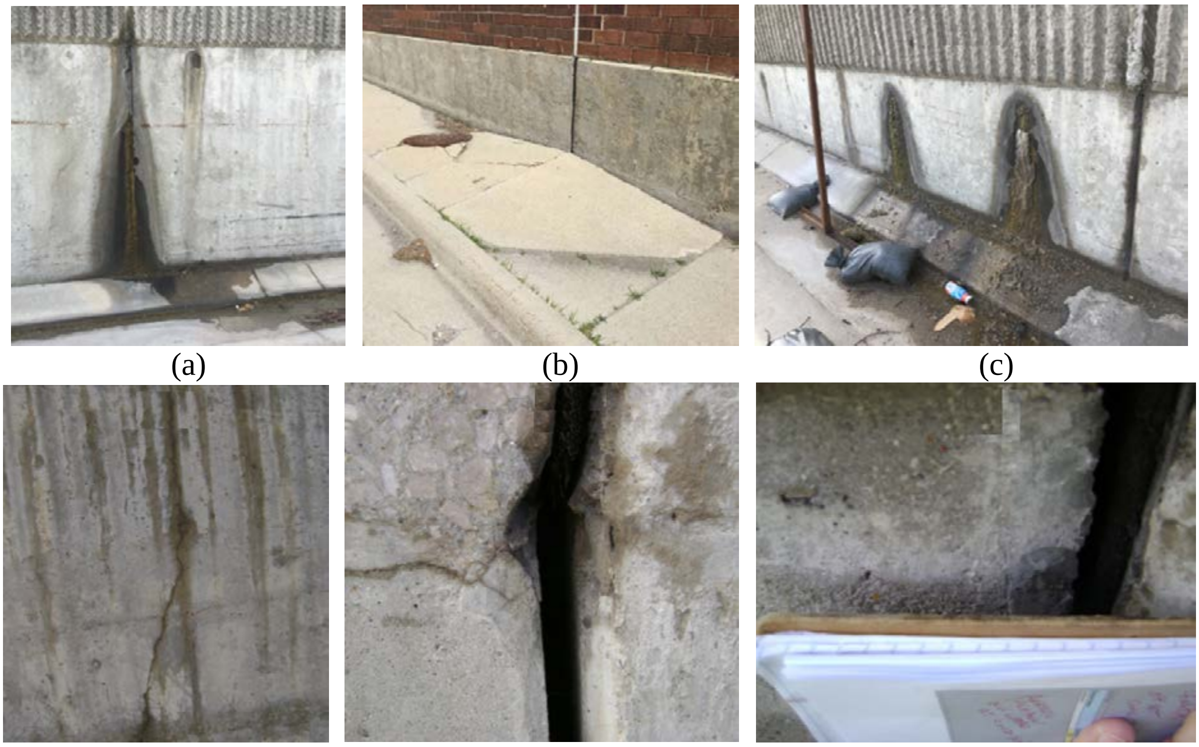


Figure 2.2. M-10 retaining wall system distress (June 2017): (a) wall tilting observed at the wall top; (b) severe lateral cracking of the service road pavement; (c) leakage stains on the wall face at the top of the wall; (d) vertical cracking of the wall face; (e) joint movement between wall panels; (f) distress of storm water pipe behind the wall; and (g) backfill soil evident at the wall joints.

excessive leakage of water through holes at the lower portions of the wall panels and at the vertical joints between panels (Figures 2.3a and 2.3b). The weather at the time of the site visit was dry and warm suggesting the weeping evident was associated with either a drainage system behind the wall in bad condition or due to a saturated backfill. The uniform nature of the weeping along the wall length suggested the later. The wall panels appeared to have minor levels of tilt and displacements between them. Given the observations in the field, the I-696 wall system also proved to be a good candidate for long-term monitoring in this project.

2.3. Long-Term Monitoring System Design and Installation

One panel of the M-10 retaining wall system and two panels of the I-696 retaining wall were selected for instrumentation. A permanent monitoring strategy that focused on instrumentation installed on the front face of the retaining walls was sought. The monitoring strategy considered for both walls included the measurement of tilt, strain and temperature.



(a) (b) (c)

(d) (e) (f)

Figure 2.3. Issues observed on I-696 wall panels (June 2017): (a) water leakage via the lower portion of the wall expansion joint; (b) walkway failure on the top of the wall back fill; (c) prolonged and severe weeping through drainage holes; (d) moderate levels of vertical cracking; (e) excessive wall expansion at panel joints; (f) differential tilt of adjacent panels.

A triaxial accelerometer well suited for the measurement of tilt was adopted to measure the pitch, roll and yaw of the wall. Strain gages bonded to an aluminum plate were used to provide a long-gage strain sensor for measuring thermal and flexural strain in the walls. Finally, thermistors were adopted to measure wall temperatures. The motivation for the selection of these sensors was that they are relatively low cost yet provide insightful measurement of the wall response to its loading environment.

2.3.1. Sensor Placement on the Wall Panels

Unlike bridges that require dozens of sensors on many of the main structural elements, retaining walls have expansion joints between wall panels that enable them to act with some degree of independence. A uniform instrumentation strategy was sought for measuring the panels in the M-10 and I-696 wall systems. For the M-10 wall system, the panel dimensions on the wall were measured during the on-site inspection to be 25’-0” wide and 22’-6” high from the front grade level, on average. The M-10 wall system is stabilized by a caisson with a tie rod anchoring the

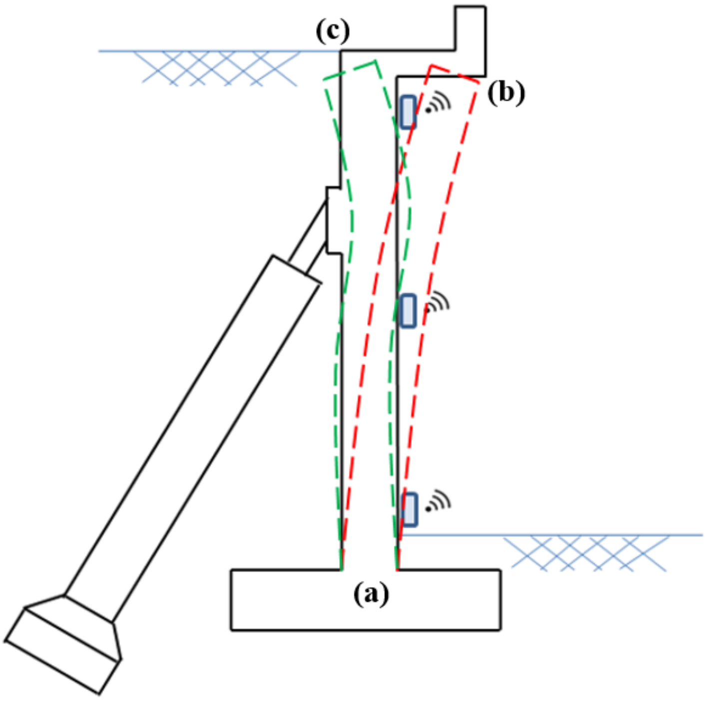
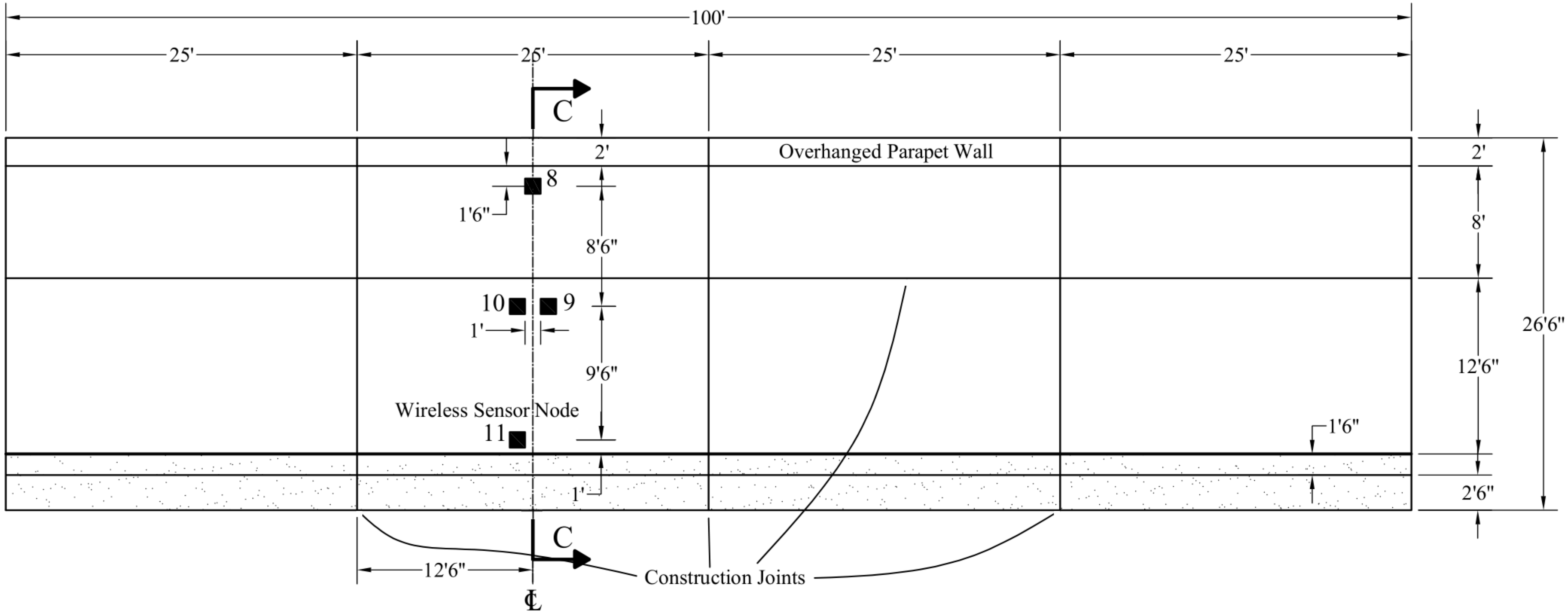


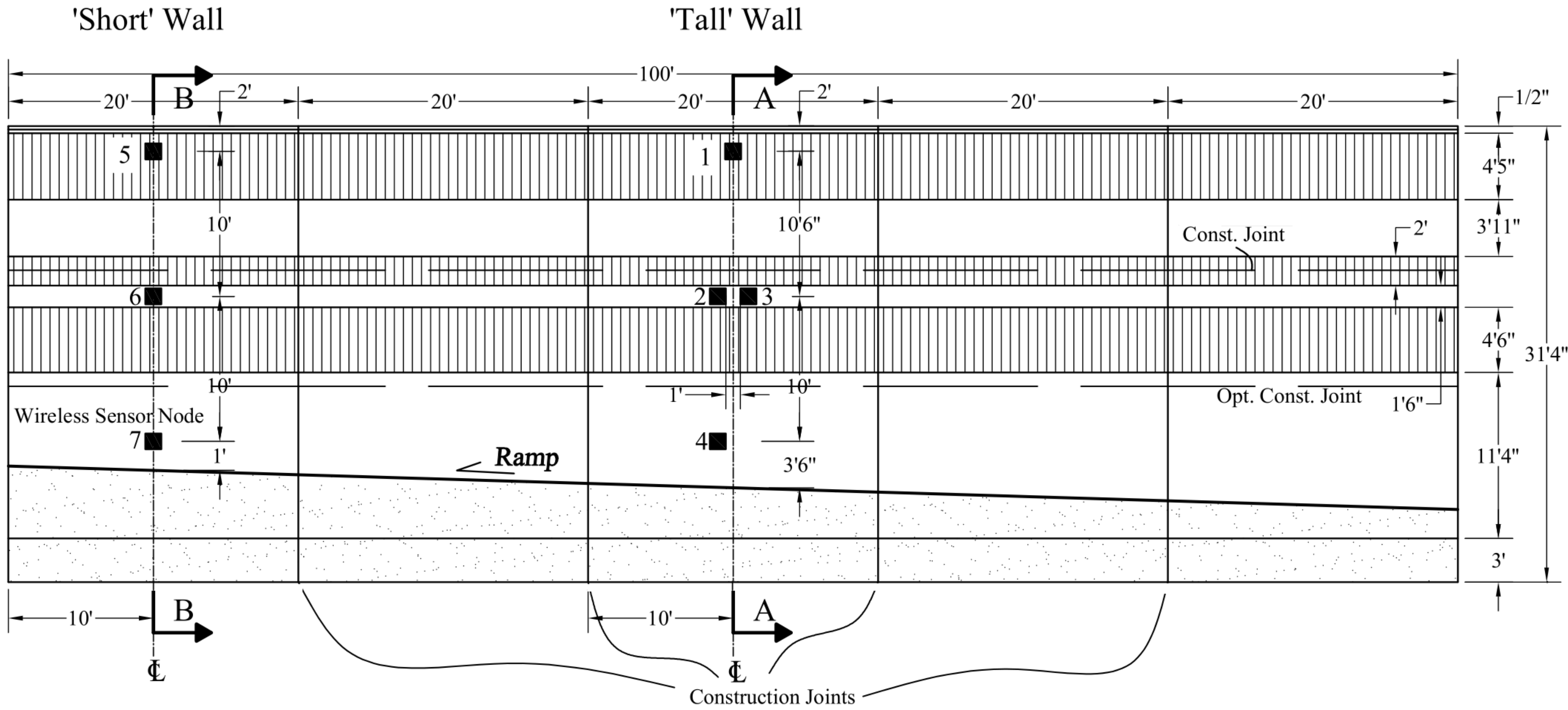
Figure 2.4. Possible vertical wall deformations of the M-10 wall

wall approximately 15’-9” from the front grade level. The history of tieback failure in the M-10 wall systems informed the instrumentation strategy. When the tieback is engaged, the wall deflection is restrained at the tieback with lateral earth pressures inducing a bulging deflected shape below the tieback point. Figure 2.4 shows the hypothesized deflected shape of the wall when the tieback is properly engaged as intended (*i.e.* the curve denoted as (a)-(c) in Figure 2.4). In this scenario, the maximum flexural moment in the wall would be below the tieback. If the tieback fails, the wall would then begin to respond like a cantilever wall with a deflected shape defined by the curve denoted as (a)-(b) in Figure 2.4; in this case, the maximum tilt would be measured at the top of the wall. The M-10 wall instrumentation places two tiltmeters on the same wall panel to assess the wall deflected shape: one at the top of the wall (19’-0” from grade) and another at mid-height (10’-6” from grade). Additionally, two long gage strain sensors were installed: one at the base (1’-0” from grade) and the other at mid-height (10’-6” from grade). Thermistors were also installed on the wall panel adjacent to each strain sensor to measure the wall temperature. All of the sensors were installed at the center of the panel along the same vertical line. Figure 2.5 summarizes the location of the sensors installed on the M-10 wall panel.



Node	Tilt Measurement	Strain Measurement	Temperature Measurement
8	√		
9		√	√
10	√		
11		√	√

Figure 2.5. M-10 instrumentation: two tilt-meters, two strain gages & two thermistors on a single panel.



Node	Tilt	Strain	Temperature	Remark	Node	Tilt	Strain	Temperature	Remark
1	√			'Tall' wall	5	√			'Short' wall
2	√			'Tall' wall	6	√			'Short' wall
3		√	√	'Tall' wall	7		√	√	'Short' wall
4		√	√	'Tall' wall					

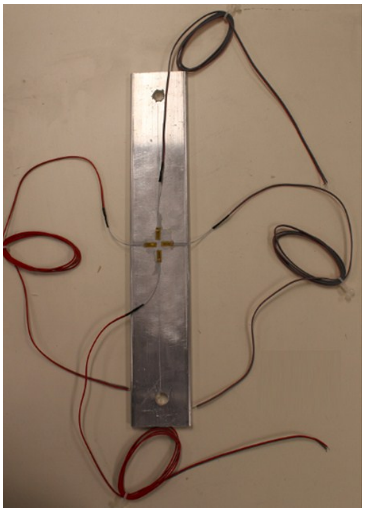
Figure 2.6. I-696 instrumentation on two separate panels 40 feet apart (so called "tall" and "short" walls)

For the I-696 wall system, two panels were selected as previously described. The panel at the 0 ft. reference vertical line (see Figure 2.6) is roughly 20’-0” wide and 26’-0” high above the front grade line while the panel at the -40 ft. vertical reference line is 20’-0” wide and 23’-0” high above the front grade line. The different heights are due to an inclined exit ramp for I-696 at the base of the wall system. The wall panels are hypothesized to respond with either flexural bending (with maximum tilt at the top of the wall) or through rigid body rotation. The instrumentation strategy was nearly identical to that of the M-10 wall panel with tiltmeters placed at the wall top and mid-height, and strain gages placed at the panel mid-height and base (Figure 2.6). The taller panel at the 0 ft. reference had tiltmeters installed at 13’-6” and 24’-0” above grade while the shorter panel at the -40 ft. reference had tiltmeters installed 11’-0” and 21’-0” above grade. The tall wall had two strain sensors installed: one at the base 3’-6” above grade and the other at mid-height at 13’-6” above grade. The shorter wall employed only one strain sensor at the wall base roughly 1’-0” above grade. Similar to the M-10 wall, thermistors were installed adjacent to each strain sensor to measure wall temperature.

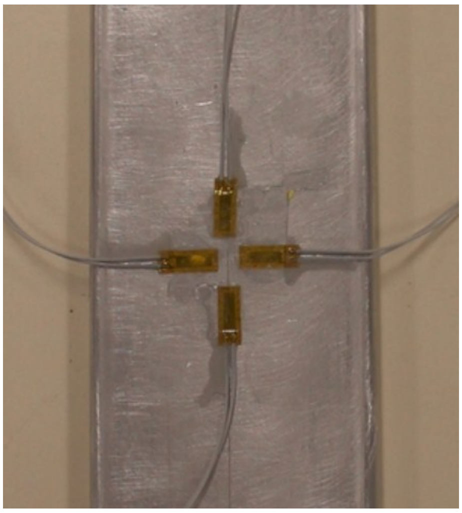
2.3.2. Sensing Transducers

Based on previous field measurements collected by MDOT on the M-10 wall system, the wall was measured to tilt +/- 0.05 degrees on a weekly basis. Based on this, a tilt-meter with a resolution of 0.01 degrees was sought. An orientation sensor with a triaxial accelerometer included was selected: Bosch BNO055 (Bosch, 2016). The BNO055 is a complete inertial measurement system including a triaxial accelerometer (14-bit resolution), triaxial gyroscope (16-bit resolution) and triaxial magnetometer. Only the internal accelerometer of the BNO055 sensor was used in this project to assess wall tilt. The BNO055 accelerometer has an acceleration measurement range of +/- 2g with a resolution of 1 mg. An additional feature of the sensor is that it outputs its measurements using a digital communication protocol (*e.g.* SPI, UART, I2C) allowing it to be easily interfaced to a microprocessor. Accelerations are used to estimate the rotation of the sensor; given the 1 mg acceleration resolution, this yields a tilt resolution lower than the desired 0.01 degrees sought. An additional feature of the BNO055 is that it includes temperature compensation providing thermally stable measurements between -40 ^{o}C (-40 ^{o}F) and 125 ^{o}C (257 ^{o}F).

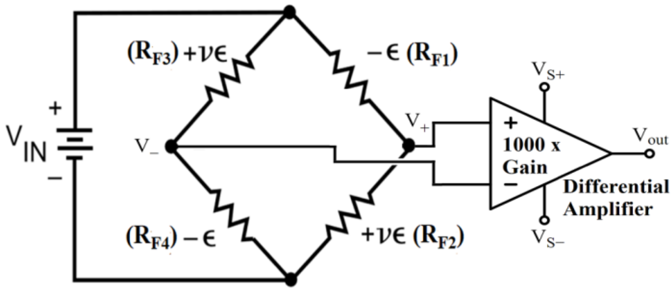
Strain sensors were needed to measure thermal strain and strain associated with the flexural response of the wall to lateral earth pressures. Accurate measurement of strain in concrete structures typically require a long gage length (in order for strain measurements to be immune to



(a)



(b)



(c)

Figure 2.7. Strain gage set-up: (a) long-gage aluminum plate with four active gages attached; (b) close-up of bonded gages; (c) full-bridge circuit.

localized cracking). A strain measurement system based on metal foil gages was custom designed for the M-10 and I-696 walls. The approach adopted an aluminum plate (2” wide, 1’ long and 0.25” thick) upon which four metal foil strain gages were attached (Figure 2.7b). The plate has two holes along its longitudinal axis for mounting to the wall panels with a gage length of 10” between the mounting holes. Small metal foil gages (Omega KFH-6-350-C1-11L1M2R) were bonded to one side of the aluminum plate using cyanoacrylate glue. The gages had 350 Ω nominal resistances with 2.05 gage factors and 2% transverse sensitivity (Omega, 2018). The four gages were configured in a full bridge circuit with two gages measuring axial strain and two measuring transverse strain. The full bridge configuration (Figure 2.7c) has the benefit of minimizing the thermal sensitivity of the strain set-up. The two longitudinally aligned gages were placed on opposite sides of the bridge and are denoted as R_{F1} and R_{F4} in Figure 2.7c; the transverse gages are used for thermal compensation and are denoted as R_{F2} and R_{F3}. The gages were powered using a 3.3V source (V_{in}) with the bridge output voltage (V_{out})

fed into a standard instrumentation amplifier with a 1000 times gain. This full bridge set-up allowed longitudinal strain, ε in the plate, to be calculated as:

$$\varepsilon = \frac{-2\left(\frac{V_{out}}{V_{in}}\right)}{GF\left((1+\nu)+\left(\frac{V_{out}}{V_{in}}\right)(1-\nu)\right)} \qquad (2.1)$$

where GF is the gage factor of the metal foil gages and ν is the Poisson ratio of aluminum. Prior to field installation, the thermal compensation functionality of the bridge was assessed in the lab. With the plate holding static load, the temperature of the plate was varied from 25 ^{o}C (77 ^{o}F) to 117 ^{o}C (243 ^{o}F). The thermal sensitivity of the full gage configuration on the aluminum plate was 0.13 με/°C. This thermal sensitivity is minimal due to the anticipated magnitude of expected strain (which is expected to be in the 10's of με). Prior to deployment of the plate to the M-10 and I-696 wall systems, a conformal polymeric coating was applied to the gages and lead wires to make them water tight and to protect them from the harsh operational environment.

Measurement of the temperature of the walls is critical to understanding their thermal expansion behavior. As a result, waterproof thermistors were selected for installation on the wall surfaces. The thermistor selected for this project was the TDK Group B57020M2 (TDK, 2018). It is contained in a watertight plastic case which ensured its durability when installed in the field.

2.3.3. Wireless Sensing Node

To collect data from the sensing transducers selected for the retaining wall systems, a wireless sensing node termed *Urbano* (Flanigan and Lynch, 2018) was adopted. *Urbano* (Figure 2.8) was designed at the University of Michigan and is an ultra-low power wireless sensor node that utilizes cellular communications to directly transmit its data to the Internet. This is a very attractive feature because it eliminates the need for an on-site base station that would otherwise be needed to collect data from a network of wireless sensors. Use of cellular telemetry has other advantages including precise time synchronization of the nodes. To transmit and receive data, *Urbano* utilizes a Nimbelink Skywire 4G cellular modem. The radio consumes 616 mA (referenced at 3.3V) when transmitting, 48 mA when idle, and 8.6 mA when in low-power mode; these seemingly high-power numbers are offset by the high data rates supported by the radio including a 5 Mbps upload rate. When the radio is needed, *Urbano* is designed to turn the radio on for bursting out data and then turning it back into sleep mode in order to minimize consumption of the battery energy.

Table 2.1. *Urbano* performance specifications

Characteristic	Specification
Computational Core	8-bit RISC Atmel 2561V µC at 16 MHz
Memory	256 kB Flash; 512 kB SRAM
Sensor Interface	10-bit ADC with 8 differential or 16 single-ended channels
Base Power without Cell	75 mW (Active); 21 uW (Sleep)
Cellular Communications	Verizon 4G Cellular Modem (2W power)

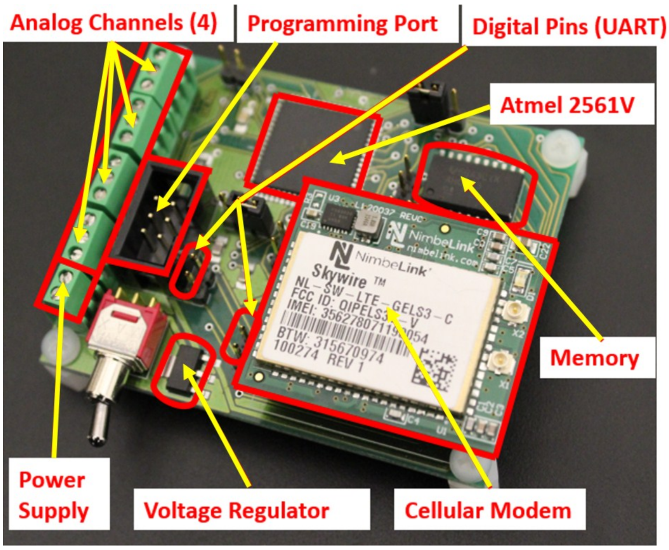


Figure 2.8. *Urbano* wireless sensor node for data collection

At the core of the *Urbano* node is an 8-bit microcontroller (Atmel Atmega2561V) clocked at 8 MHz. The microcontroller has 256 kB of flash memory for program storage and 8 kB of SRAM for data storage on-chip. Memory is expanded with an addition 512 kB of SRAM using an off-chip memory chip (Cypress CY62148EV30). The 8-bit microcontroller includes a multi-channel 10-bit analog-to-digital converter (ADC) capable of a maximum sample rate of 200 kHz. In this study, the on-chip ADC was used to measure temperature and strain. The strain gage and thermistor analog outputs were interfaced to the ADC through amplified bridge circuits as previously described. The microcontroller also has traditional serial communication ports (including UART and SPI) to which digital sensors can be attached. The tiltmeter (Bosch BNO055) was interfaced to *Urbano* using the UART serial communication port. The Atmega2561V is powered by a 3.3V source and draws 7.3 mA when active, but 4.5 µA when in power-save mode.

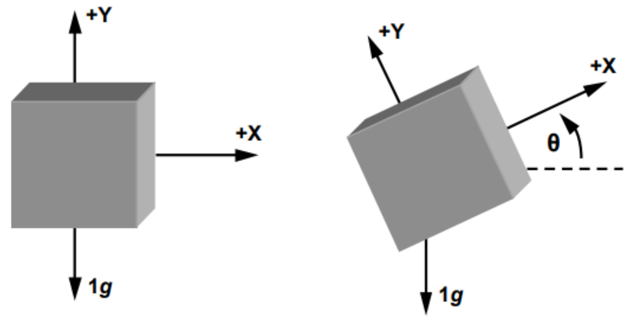


Figure 2.9. Two axes used for dual-axis tilt sensing

The BNO055 tilt-meter has its own microprocessor through which the device is operated by writing and reading on-chip registers. Acquiring acceleration data from BNO055 requires the *Urbano* microcontroller to write commands to registers on the BNO055 and then reading the measurement data from read registers. The Atmega2561V was configured to take 100 acceleration measurements on each of three axes of the BNO055; the accelerations were averaged on the *Urbano* microcontroller for each axis before pitch and roll tilt was calculated by the *Urbano* node.

2.3.4. Dual-Axis Tilt Calculation

The project selected the BNO055 accelerometer to serve as the basis for measuring wall tilts. The sensor was selected due to its performance attributes (namely, low noise floors) that allow tilts to be precisely calculated from the acceleration readings. The internal tri-axial accelerometer in the BNO055 is capable of measuring accelerations across a wide vibration range all the way down to static accelerations (*i.e.* can measure orientation relative to gravity). As a result, when the accelerometer is rotated in three-dimensional space and held stationary, the readings of acceleration on three axes can be transposed to measure tilt on three axes. In the case of the retaining wall systems monitored in this project, the out of plan tilt of the wall was sought. As shown in Figure 2.9, to measure out of plan tile, static acceleration relative to gravity (denoted as 1g axis) on two internal axes (x and y in Figure 2.9) are needed to estimate the angle, θ. For example, when the tilt is 0° as shown on the left of Figure 2.9, the x-axis acceleration would be 0 g and the y-axis acceleration would read 1 g. When rotated on the z-axis by the angle, θ, as shown on the right side of Figure 2.9, the x-axis acceleration will be a small number greater than 0 g while the y-axis will report an acceleration less than 1 g. While one axis is sufficient to estimate tilt (for example, reliance only on the y-axis acceleration measurement), there are three major benefits to including a second axis in determining the angle of inclination. First, the tilt measurement is less noisy with constant sensitivity. Second, it does not require alignment of the sensor package with a precise orientation of gravity before measurements can be taken. Finally, it can measure tilts in 360°. The constant sensor sensitivity is derived from reliance on two measurement axes. Whenever the incremental sensitivity of one axis is reduced (such as when the acceleration on that axis approaches +1 g or −1 g), the incremental sensitivity of the other axis increases. For a dual-axis tilt calculation (Figure 2.9), an easier and more efficient approach is to use the ratio of the two values, which results in the following calculation for tilt,

$$\theta = \tan^{-1}\left(\frac{A_{X,OUT}}{A_{Y,OUT}}\right) \tag{2.2}$$

where the inclination angle, θ, is in radians.

2.3.5. Packaging Wireless Sensor Nodes

The *Urbano* wireless sensor node was packaged in a water-tight NEMA-rated enclosure (8 ¾ x 5 ¾ x 3 in^3) prior to deployment on the M-10 and I-696 retaining wall systems. A picture of the wireless sensor enclosure is shown in Figure 2.10. The enclosure was selected to comply with the Michigan Department of Transportation restrictions on protrusions from the wall entering the roadway space to be less than 4" (this package extended only 3" into the roadway space).

Inside each enclosure was an *Urbano* node, signal conditioning circuits (*e.g.* amplified bridge circuit for the full-bridge strain set-up of Figure 2.7), and a 12V (2.9 A-hr) sealed lead acid battery (Powersonic PS-1229). Lead acid batteries are excellent battery solutions for recharging in extreme cold environments. To charge the battery while utilizing it to power the node, a charge controller was included in the enclosure. Each node was powered by a 12V (10 W) solar panel (Acopower HY010-12M) housed outside the enclosure. The tilt-meter nodes also included the Bosch BNO055 inside the enclosure bonded to the enclosure's bottom surface. The temperature and strain sensor nodes had both of these transducers installed outside of the enclosure for direct installation to the surface of the wall panels.

2.3.6. Field Installation on the Wall Systems

A total of 11 wireless sensor units were installed at the two wall sites (M-10 and I-696) in August and November 2018. Seven units were installed on the I-696 wall panels on August 25, 2018 during a warm and dry day. Four additional wireless sensors were installed on the M-10 wall panel on November 27, 2018 during a dry, but cold day. First, solar panels were mounted to light poles at the top of the walls (Figure 2.11a) with one panel used per wireless sensor node. To ease

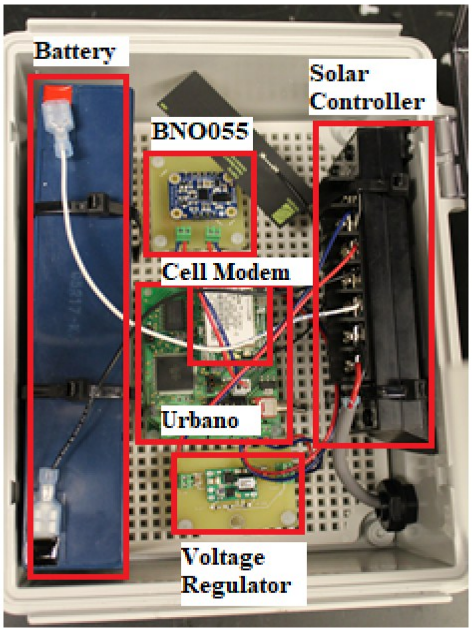


Figure 2.10. Inside the wireless sensor enclosure showing the Urbano node, solar charge controller, tilt sensor (Bosch BNO055), and lead acid rechargeable battery

their installation, the panels were pre-mounted to an aluminum frame system with a predefined angle optimized to maximize solar energy capture. Next, the wireless sensor enclosures were installed on the wall surfaces. To mount each enclosure, a 12-gage aluminum plate (14 by 14 in^2) was bolted to threaded rods pre-anchored into the wall by a crew from the Michigan Department of Transportation (Figure 2.11b). The aluminum plates had holes drilled in them to allow the wireless sensor enclosures to be mounted to the aluminum plates using threaded screws; the enclosures were installed after the plates had been attached to the wall surface. To reinforce the enclosure mounting, quick setting epoxy was also used between the back of the enclosure and the aluminum plate. The long-gage strain sensor was similarly installed by bolting the plate to threaded rods pre-anchored into the walls. Figure 2.11c shows tilt and strain enclosures mounted to the I-696 walls. Installation of the nodes took approximately one day per wall panel. Required for installation was a road/lane closure to ensure the safety of project personnel installing the nodes. MDOT provided a lift truck with a two-person crew to assist the team.

2.4. Data Acquisition Process

An automated data acquisition architecture (Figure 2.12) was created to collect data from the wireless sensors installed on the M-10 and I-696 wall systems. The system was designed to operate on a schedule with each sensor node programmed to collect data every one or two hours. The nodes on the I-696 wall panels collected data every hour while those on the M-10 wall were programmed to collect every two hours. The change in sampling frequency for the M-10 panel (which was installed in November 2018) was due to observing that the tilt and strain data on the I-696 panels (which were installed in August 2018) had less hourly variation than originally anticipated. When not sensing, the nodes remained in a sleep state to preserve battery energy. The tilt measuring nodes were scheduled to collect 100 acceleration samples (at 100 Hz) on each axis, average the samples, and report mean accelerations for each of the three axes. The strain and temperature units were scheduled to only take one sample at each hourly (or bi-hourly in the case of the M-10 panel) sampling cycle. After the data was sampled locally by each *Urbano* node, the nodes were programmed to communicate data to a cloud server using the cellular modem integrated with each node. The retaining wall monitoring systems used a commercial cloud data portal called Exosite for data management (Exosite, 2018). The project team selected a commercial data platform so that MDOT could continue to use the portal to collect wall data after the project officially ended.

Exosite hosted the monitoring data with a web portal used for data visualization. Strain and temperature were displayed in the portal as measured. The three axes of acceleration from each tiltmeter were processed on the Exosite server to measure tilt by using a real-time program coded in the high-level programming language called Lua. The Exosite web portal offered views of the measurement data in real-time using tabular and graphical displays (for example, see Figure 2.13). It also offered the ability for system end users to download the data for offline analysis.

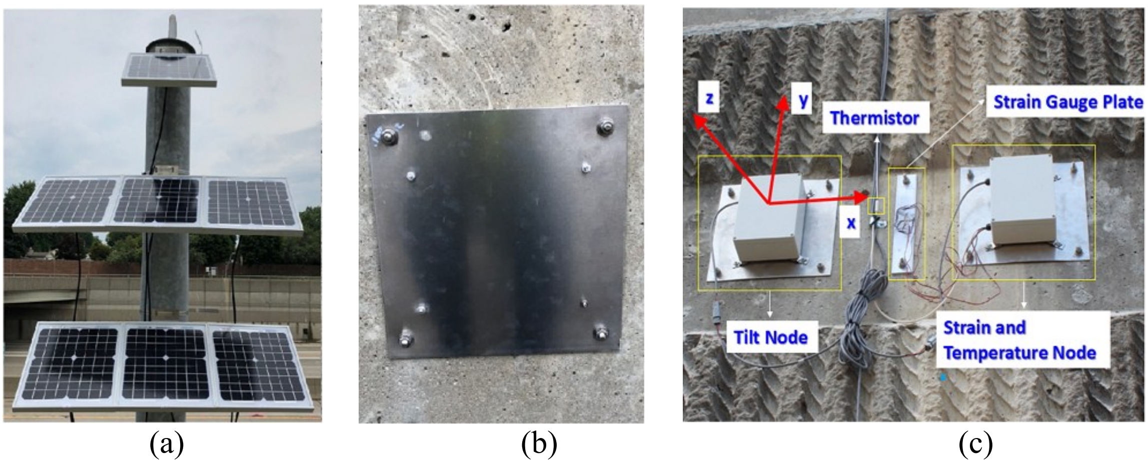


Figure 2.11. Installation of instrumentation on the I-696 wall: (a) seven solar panels to power seven wireless sensor nodes; (b) aluminum mounting plate bolted to the wall surface; (c) installed wireless sensor enclosures with strain sensor evident.

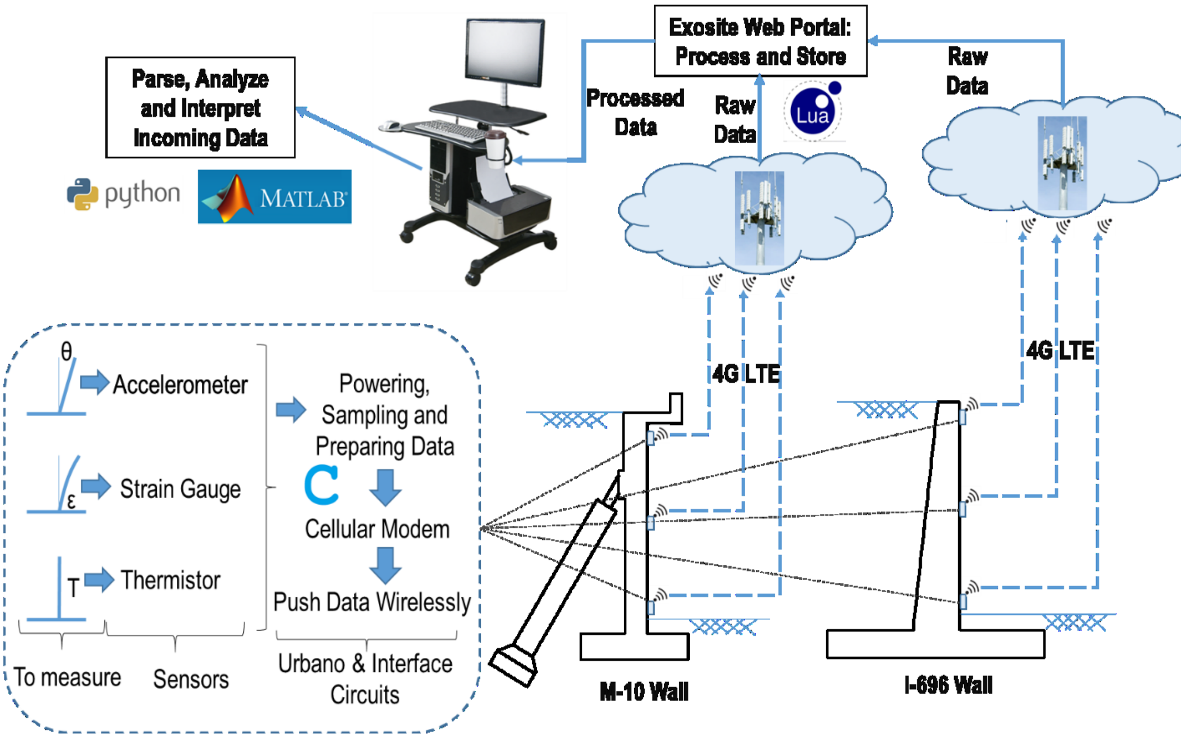


Figure 2.12. Data acquisition architecture for the I-696 and M-10 retaining wall monitoring systems (Admassu et al, 2019)

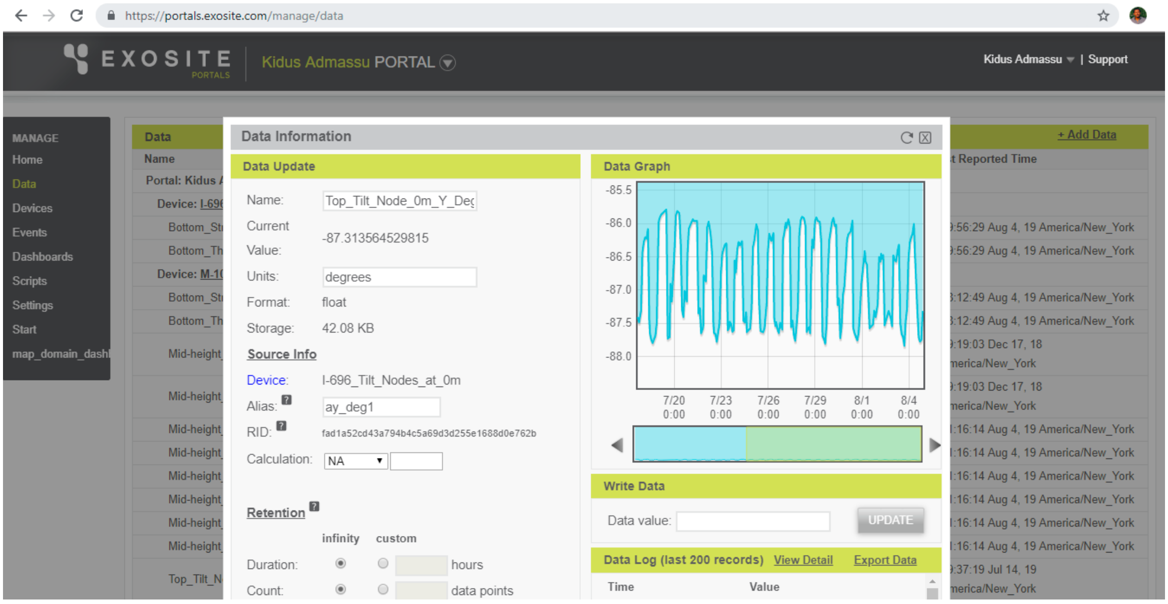


Figure 2.13. Screenshot of the online data management portal (Exosite)

3. RESPONSE DATA ANALYSIS OF THE I-696 AND M-10 RETAINING WALL SYSTEMS

3.1. Introduction

As previously described, this project deployed a permanent wireless monitoring system on three retaining wall panels in southeast Michigan to measure their response to operational and environmental load conditions. The data collected was intended to serve as the basis for assessing the performance of the walls within a risk management framework. In total, 11 wireless sensor nodes were installed on three separate retaining wall panels: two wall panels were located on the southside of the I-696 freeway in Southfield, Michigan near Central Park Boulevard and West Eleven Mile Road, while the third panel was located on the southside of M-10 freeway in Detroit, Michigan near the intersection of Schaefer Highway and James Couzens Highway. The wireless sensors deployed as part of the monitoring systems measured the tilt, strain and temperature of the wall panels. Data from the I-696 wall panels has been collected hourly since August 25, 2018 while data from the M-10 wall panel has been collected every two hours since November 27, 2018.

This chapter will provide a detailed overview of how the wireless monitoring systems performed over the one year monitoring period. Lessons learned from the installation of the monitoring systems will be presented. Using the data collected, a detailed analysis of the three retaining wall panels will be introduced by analyzing the different wall responses collected since August 2018. In addition, meteorological data (*i.e.* precipitation) was acquired from meteorological measurement stations located within 10 miles of the retaining wall sites. Time synchronized wall response and meteorological data was used to explore how the behavior of the wall panels change as a function of environmental conditions. The primary goal of the analysis was to correlate wall responses to environmental loads with the aim of identifying load conditions leading to maximum wall responses (*e.g.,* maximum tilt, maximum strain). Specifically, the analysis attempted to understand the thermal response of the wall panels under diurnal and seasonal variations in addition to changes associated with precipitation. The presentation of the response data collected from the three wall panels are presented in order: tall I-696 wall panel, short I-696 wall panel, and M-10 wall panel.

3.2. Performance of the Wireless Sensor Units

An objective of the project was to assess the performance of the wireless monitoring systems on the retaining wall systems. As previously described, three wall panels were monitored with 11 wireless sensor nodes that had been designed and assembled at the University of Michigan. A total of 16 channels of data were collected (6 channels on the M-10 wall panel, 4 channels on the I-696 short wall panel, and 6 channels on the I-696 tall wall channel). Figure 3.1 presents the performance of the 11 wireless sensor nodes over the course of the project. The green markers in the figure correspond to a valid measurement communicated to the cloud database server; the absence of a marker suggests the unit did not communicate data.

The wireless sensor nodes on the I-696 wall panels were installed on August 25, 2018. The nodes on both the tall and short wall panels worked properly from their initial installation. However, the sensors installed at the bottom of both wall panels had issues immediately after installation. The nodes collecting the bottom flexural strain from both wall panels and temperature on the tall wall

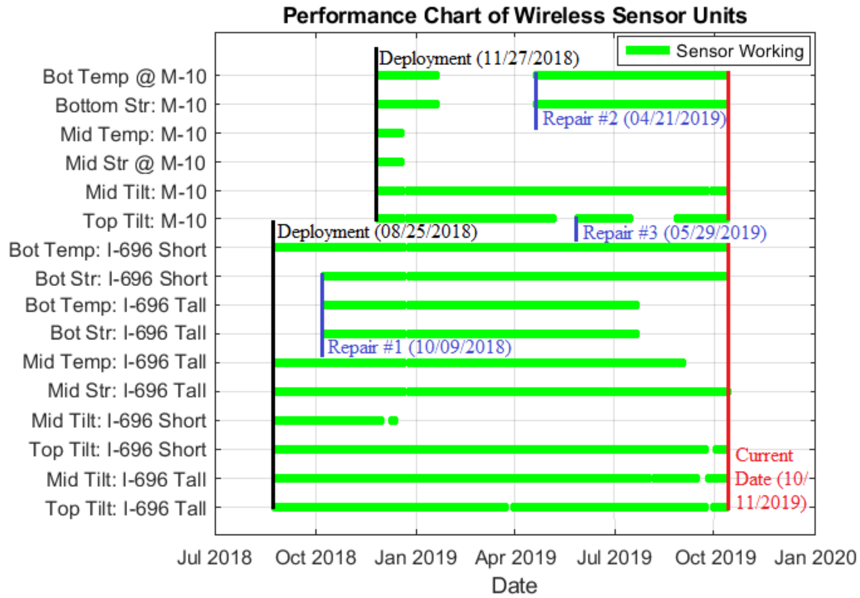


Figure 3.1. Performance of the wireless sensor nodes on the M-10 and I-696 panels.

panel did not operate after installation. On October 9, 2018, the team returned to the site and repaired the units after which they worked properly. During site visit, there was no apparent reason for the units not working. To avoid debugging the units at the site, the hardware was quickly replaced with new hardware after which the nodes properly collected data. The interface circuits for the strain sensors were also adjusted during the October 9, 2018 site visit to ensure all of the strain measurements would fall within the wireless node measurement range. The sensors operated well for the majority of the time thereafter on both wall panels until the winter season. By mid-winter a number of units struggle to remain in operation reporting their data. As shown in Figure 3.1, the following channels eventually stopped reporting data: bottom strain on the I-696 tall wall panel (stopped July 2019), mid-height tilt on the 1-696 short wall panel (stopped December 2019), mid-height temperature on the I-696 tall wall panel (stopped September 2019), and bottom temperature on the I-696 tall wall panel (stopped July 2019). The remaining channels on the I-696 panels continue to work and report data. The precise reason the sensor not working remains unclear and should be investigated further. Nonetheless, a sufficient level of data was collected by the wireless monitoring systems on the short and tall wall panels of the I-696 systems.

The wireless sensing nodes on the M-10 wall panel were installed on November 27, 2018 during inclement weather conditions. A total of 4 sensor nodes were deployed all of which worked properly upon installation. Shortly after installation, two of the nodes measuring strain and temperature at the mid-height and bottom of the wall stopped operating (the node measuring mid-height strain and temperature stopped in December 2018 and the node measuring bottom strain and temperature stopped in January 2019). It was not until after the harsh winter could the units be inspected and repaired. The units on the M-10 wall inspected on April 21, 2019 revealed the nodes had low nominal voltages, suggesting the batteries installed in November 2018 had been run down during the winter during cold temperatures and days with limited sun. The battery was replaced on the node measuring bottom wall strain and temperature; this unit has operated without incident since. During the site visit on April 21, 2019, the team did not have time to investigate the wireless node measuring mid-height strain and temperature. Later, these measurements were deemed not critical and the unit was never repaired.

In late May 2019, the wireless sensor node monitoring the top tilt of the M-10 wall panel went down. Given the critical nature of the tilt measurement, a site visit was performed on May 29, 2019 to repair the unit. During the repair, it was evident that the wire connecting the solar panel to the nodes had corroded due to moisture running down the solar panel wire and pooling at a connection where copper wires were exposed. This finding may explain why some of the I-696 sensors have gone down with time. In the future, extra care will need to be made to make the wire connection between the solar panels and the units is waterproof by selecting a more robust connector.

The performance issues encountered by the wireless sensors on the I-696 and M-10 wall panels provides insight to how the node designs could be improved for future deployments. A summary of the key findings are:

- The connection between the solar panel and the wireless sensor nodes is prone to corrosion; in the future, a more robust connection should be used less vulnerable to water and corrosion issues.
- The wires connecting the solar panels to the wireless sensor nodes provide a pathway for water to drip down to and pool at the connections; installation methods should avoid

installing the solar panel wires in a manner where gravity will naturally pull the water down to the connection.

- The wire between the solar panel and the node could be removed by mounting the solar panel directly to the enclosure; this was infeasible in this study because the units faced north and would not have direct exposure to the sun (and hence the need for separate solar panels installed on light poles above the walls).
- The winter season was harsher than anticipated resulting in wear down of the lead acid batteries. Larger batteries with a higher energy capacity should be considered. Also, the design of the wireless sensor node could be revised to lower its power requirements so as to alleviate the demands on the battery recharged by limited solar energy in the winter.

3.3. Tall I-696 Retaining Wall Panel

3.3.1. Description of the Wall System

The tall wall panel of the I-696 wall system is more than 30 years old and was designed as a classical reinforced concrete (RC) cantilever retaining wall system. The wall was measured during the site visit to be roughly 26’ above the grade line. However, the engineering drawings of the wall system reveal the wall sits on a 3’-0” thick RC footing system and has a height of 28’-5” above the top surface of the footing (Figure 3.2a). On the wall far side (F.S.), there exists a two layer backfill soil system that consists of a 13’deep medium compacted sandy soil stratum resting upon a 12’-7” deep medium compacted silty-sand soil stratum. On the wall near side (N.S.), the wall has three horizontal strips of 3” wide corrugated indentations. The strip vertical widths are (from top to bottom): 4’-7”, 2’-0” and 4’6”. The corrugated indentations have aesthetic value to the I-696 freeway corridor but play no real role in the structural behavior of the retaining wall system (MDOT, 1986). The construction of the wall panel occurred in multiple stages. First the footing was cast after which the primary retaining wall was cast in two stages to a height of 18’7”. The concrete retaining wall is tapered with a thickness of 3’-0” at the footing and 1’-10” at the top. The last stage of construction was the placement of a 9’-11” tall parapet wall 1’-5” thick. A cross section view of the wall system is shown in Figure 3.2b. At the street level, the F.S. surface of the parapet wall is later bricked to enhance the aesthetic of the wall.

Both horizontal and vertical steel reinforcement system is placed in the poured concrete wall as shown in Figure 3.2c. To accommodate the high tensile response of the F.S. of the wall, the vertical steel reinforcement is denser on the F.S. of the wall. Furthermore, the vertical steel reinforcement runs continuously through the vertical height of the wall and ensures full compatibility of the three wall segments. The wall reinforcement is further summarized in Table 3.1.

Understanding the structural design and geotechnical conditions of the tall wall panel is critical to interpreting the structural response of the wall. First, the soil conditions of the lower portion of the backfill soil at the bottom of the wall is less pervious than the top layer; this will strongly influence

Table 3.1. Reinforcement bars of the tall panel of the I-696 wall system.

Rebar Name	Size (or Diameter)	Length	Spacing	Rebar Shape
		Bottom		
A062100	#6 (or ¾”)	21’-0”	18” (F.S.)	Straight
B092006	#9 (or $1^1/_8$”)	20’-6”	18” (F.S.)	L-shaped
B091109	#9 (or $1^1/_8$”)	11’-9”	18” (F.S.)	L-shaped
		Mid		
EA062309	#6 (or ¾’’)	23’-9”	18” (N.S.)	Straight, Epoxy Coated
		Top		
EA060609	#6 (or ¾’’)	6’-9”	9” (F.S.)	Straight, Epoxy Coated
EA060900	#6 (or ¾’’)	9’-0”	18” (N.S.)	Straight, Epoxy Coated

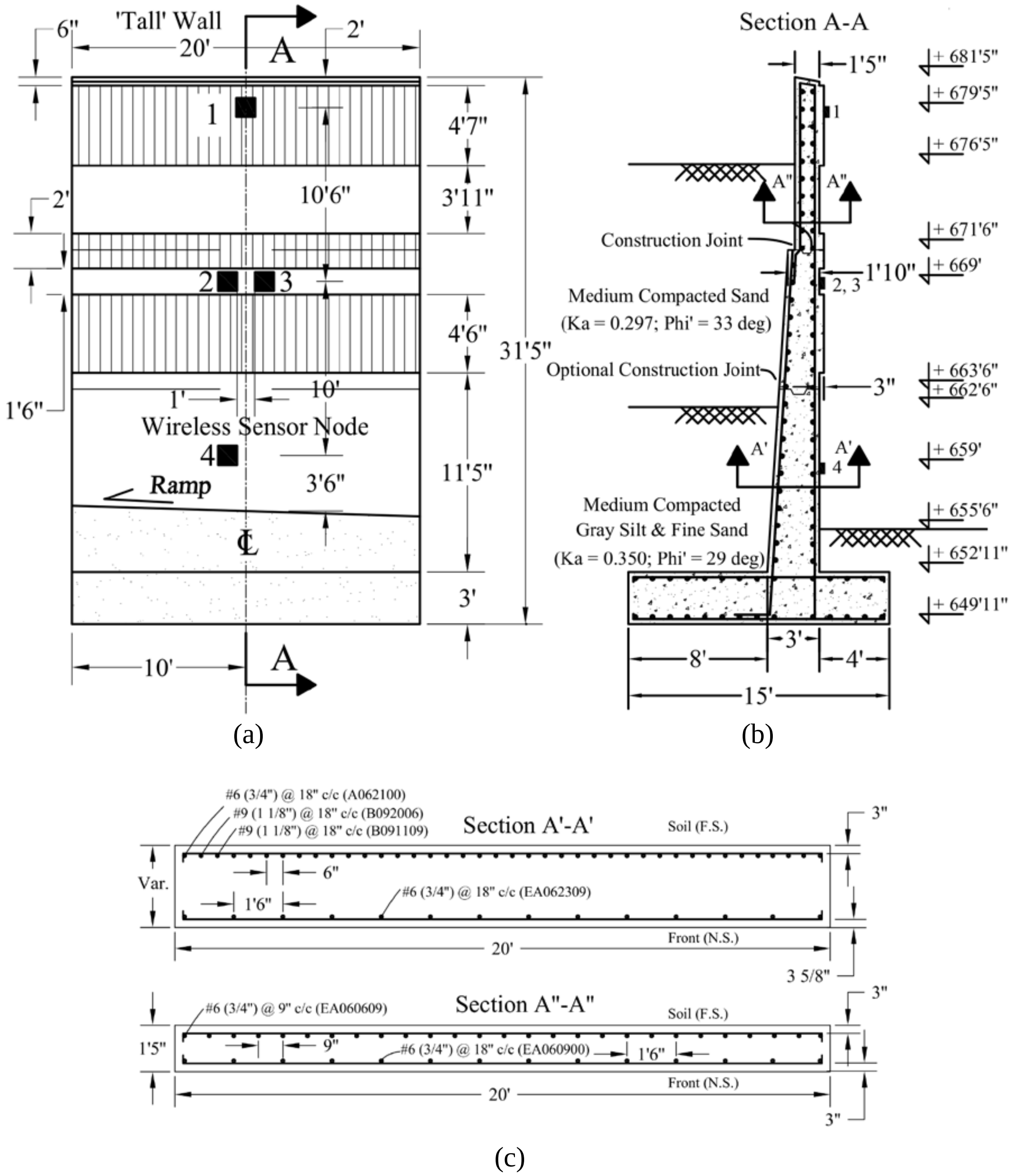


Figure 3.2. Dimensions and structural details of the 'tall' wall panel of the I-696 retaining wall site: (a) front side elevation showing sensor locations; (b) vertical sectional profile; (c) horizontal sectional plan.

the hydrostatic pressures on the wall back surface. Also, the lower portion of the wall has a much higher flexural rigidity than the upper portions to accommodate the higher flexural moments. In contrast, the top parapet wall is thinner and more lightly reinforced.

3.3.2. Daily Mean Responses

As previously discussed, the tall I-696 wall panel was monitored continuously from August 2018 to October 2019 with the wall tilt at its top and mid-height (collected by wireless sensor nodes 1 and 2, respectively, in Figure 3.2a), wall flexural strain at the bottom and mid-height (collected by wireless sensor nodes 3 and 4, respectively, in Figure 3.2a), and wall surface temperature at the bottom and mid-height (collected by wireless sensor nodes 3 and 4, respectively, in Figure 3.2a). The tilt response (using equal scales on tilt magnitude) is plotted in Figure 3.3, strain (on equal scales) in Figure 3.4, and wall temperature in Figure 3.3 and Figure 3.4. The daily means were calculated for each day by averaging the response data received over a 24 hour period from 12:00am to 11:59pm. To provide context to the data, the daily average precipitation was also extracted from an online weather database from a weather station in close proximity to the walls (Weather Underground, 2019). The daily total precipitation is plotted in Figure 3.3 and Figure 3.4. It should be noted that the strain measurements in Figure 3.4 are the raw strain readings from the strain sensors. With the residual strain in the wall at the start of data collection unknown, the strain was taken as zero at the start of data collection.

The tilt history of the top portion of the wall system demonstrated much greater variation in daily mean tilt as compared to the mid-height tilt. The top tilt varied from 0.5 to 3.5° while the mid-height tilt had a much smaller variation between 1.0 to 1.45°. The top-level tilt node was installed on the top of the thin parapet wall just 2’ below the wall top (Figure 3.2a). The wide variation in tilt of the parapet wall was attributed to both thermal variations (*e.g.*, thermal expansion of the soil backfill) and varying hydrostatic pressures associated with precipitation and other factors. Specifically with respect to precipitation, the wall appeared to be sensitive to repeated days of precipitation resulting in the build-up of hydraulic pressure in the top stratum of soil and corresponding higher tilts on the top of the wall. For example, continuous days of rain in late September 2018 into early October 2018 induced a noticeable upper tilt of the top portion of the wall (going from 1.0 to 2.5°); after rain ceased, the wall returned back to 1.0°. The daily mean tilt of the lower portion of the tall wall was less sensitive to precipitation with little variations in daily mean wall tilts during periods of rain. This may be attributed to the high flexural rigidity of the wall; it may also be explained by the lack of variation in the hydrostatic pressures in the lower soil stratum behind the wall.

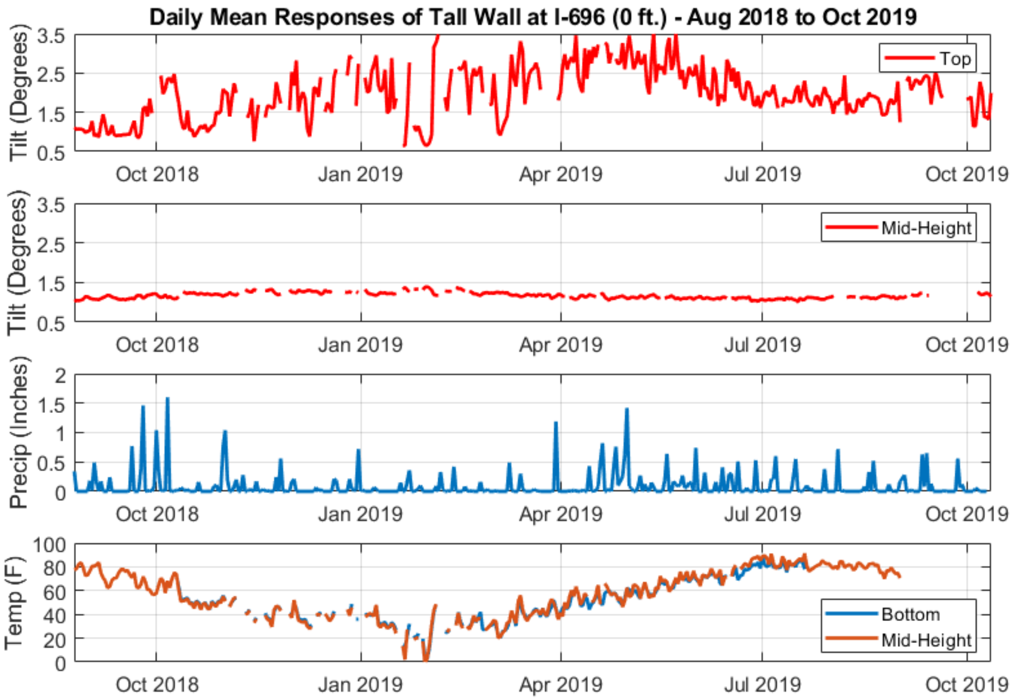


Figure 3.3. The daily mean response of the I-696 tall wall panel: top tilt, mid-height tilt, precipitation, and wall temperatures (August 2018-October 2019)

From late November 2018 to January 2019, the top tilt had a high level of day-to-day variation as the trendline mean of the tilt time history increased slowly. It is also noted that the wall daily mean top tilt dramatically varied in mid-January 2019 to mid-February 2019 when the wall temperature was near or below freezing (32 °F). In fact, the last few days of January 2019 saw the wall achieve a temperature of 0 °F after which a few days later the temperature was 42 °F; during this period the daily mean top wall tilt varied from 0.5 to 3.5°. By May 2019, the wall reached a maximum daily mean top tilt of 3.5°. After May 2019, the tilt at the top of the wall had less day-to-day variations and the mean trendline of the time history decreased to about 1.5° by July 2019. It was hypothesized that the daily mean top wall tilt trendline slowly increased from November to May due to lowering ambient temperatures and their effects on the backfill soil. Comparing the daily mean top tilt trendline with the wall temperature time history, the two appear to be correlated with a 30 to 45 day lag; this may be attributed to thermal inertia of the backfill.

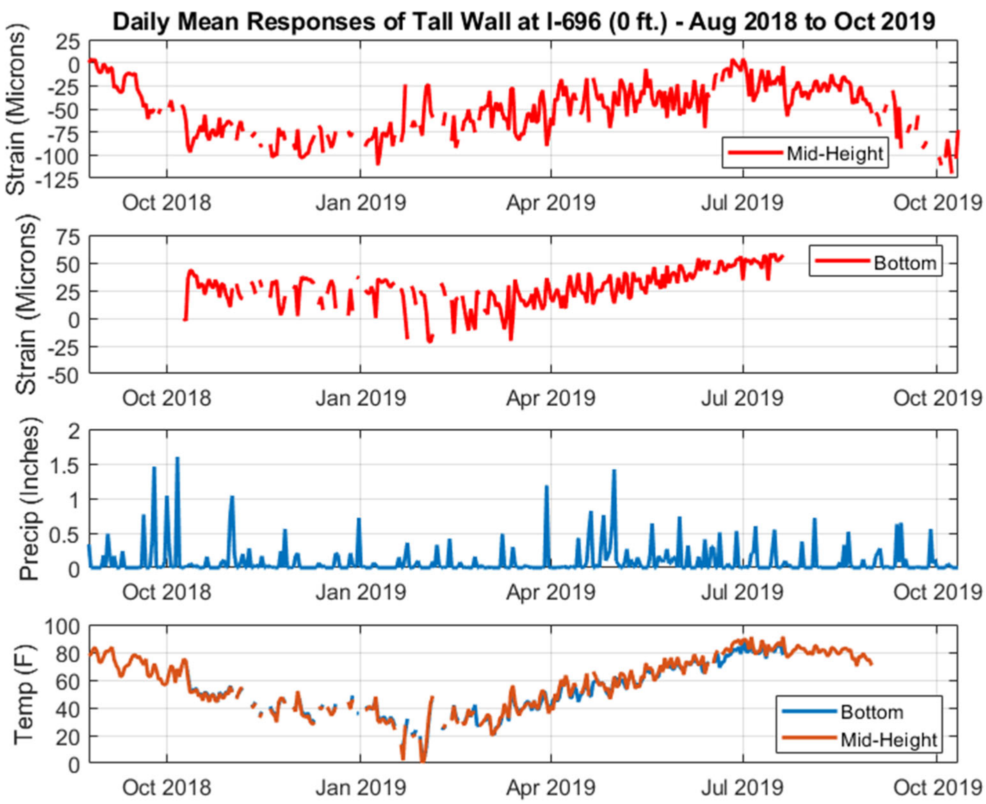


Figure 3.4. The daily mean response of the I-696 tall wall panel: mid-height strain, bottom strain, precipitation, and wall temperatures (August 2018-October 2019)

Overall, when the full 15 months of monitoring are considered, the parapet wall tilt exhibited sensitivity to precipitation in the late-Spring to mid-Fall season. During the Winter and early-Spring, the wall is less sensitive to precipitation and has a trend line correlated to wall temperature with a lag.

The daily mean strain responses at the wall mid-height and bottom captured changes in strain of the wall façade on the wall front side; the absolute state of strain was unknown. Taking compressive strain to be of negative magnitude and tensile strain to be of positive magnitude, the daily mean wall strain histories (Figure 3.4) exhibited a trend correlated to the wall temperature. The mid-height strain varied over the 15 month period a total of 125 με while the bottom strain varied only 75 με. Maximum compressive flexural strain (which would correspond to maximum tensile strain on the wall far side was during the winter).

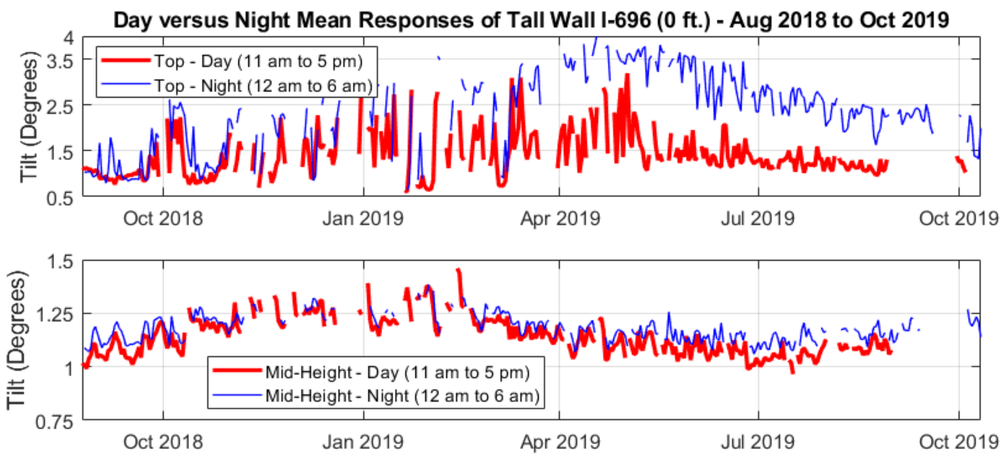


Figure 3.5. Night and day daily mean response of the I-696 tall wall panel: top tilt and mid-height tilt (August 2018-October 2019)

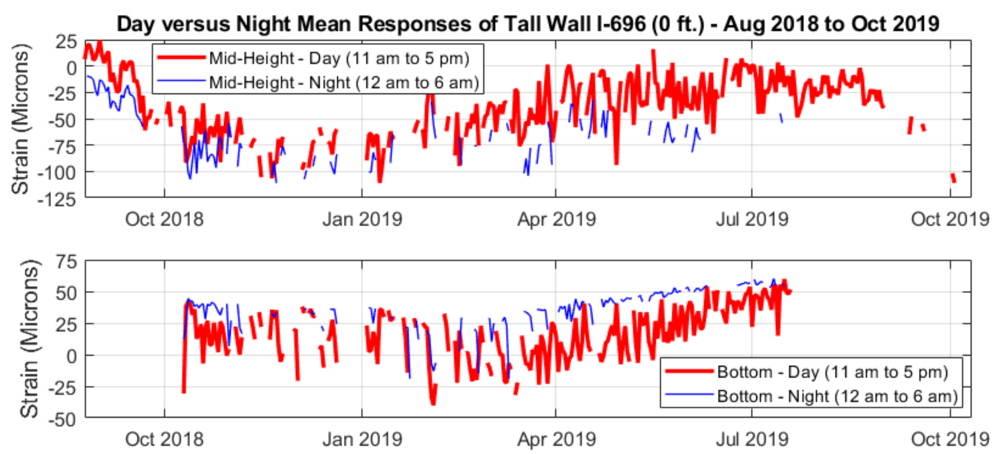


Figure 3.6. Night and day daily mean response of the I-696 tall wall panel: mid-height strain and bottom strain (August 2018-October 2019)

Figures 3.3 and 3.4 plotted the daily mean response of the tall wall panel. The daily variations were also investigated. It was observed that there was an interesting difference between the behavior of the wall during the night (11:59pm to 6:00am) and day (11:00am to 5:00pm). Figure 3.5 plots the top and mid-height average tilts during the night and day periods. Similarly, Figure 3.6 plots the mid-height and bottom average strains during night and day periods. As is evident from Figure 3.5, the evening tilt at the wall top and mid-height is noticeably higher than the average day tilt throughout the observation period. However, the difference in average night and day top tilt is especially pronounced from late March 2019 to October 2019. The strain measurements also had a noticeable difference between night and day with higher compressive strain in the night. The cause for this discrepancy is unknown. One hypothesis is that water is present in the night that is not there in the day adding temporary hydraulic pressure on the wall backside; the source of this water is unknown and could be from a failed water utility that is buried behind the wall.

3.3.3. Response Scatter Plots

In the previous section, the behavior of the tall I-696 wall was described over the 15 month monitoring period. In this section, the causality between environmental parameters and the wall behavior are studied using response scatter plots with linear regressed behavioral models fit. As previously described, the lower portion of the tall wall panel appeared to be sensitive to temperature. Plotted in Figure 3.7 is a scatter plot of lower wall responses (i.e., bottom strain, mid-height strain, and mid-height tilt) as a function of measured wall temperature. As shown, a strong linear relationship exists between these two measurands. Using linear regression to model the relationship, it is evident that the mid-height tilt of the lower portion of the wall varies roughly 0.004° per degree F of wall temperature. The greatest tilt is experienced during the colder months with maximum tilt observed at 1.4° when the wall temperature is 0 °F. Similarly, the wall strain at the bottom and mid-height was dependent on temperature. Based on linear regeression, the mid-height and bottom strain varied 0.92 με and 0.45 με per degree F, respectively.

The lower portion of the retaining wall was relatively insensitive to precipitation supporting the hypothesis that the lower portions of the wall backfill are saturated. Recall, this hypothesis was supported by visual observation of steady weeping in the wall panels in their lower sections. Shown in Figure 3.8, the mid-height tilt and bottom strain of the tall wall panel were plotted as a function of cumulative precipitation. Cumulative precipitation is taken as a weighted sum of prior precipitation that has been designed to model the time delay for rain to permeate in the soil and to develop hydrostatic pressure in the wall system. After periods of no precipitation, the cumulative precipitation model also assumes drying of the soil resulting in the alleviation of hydrostatic pressure. In this study, it is assumed the cumulative rain, C_{rain}, is:

$$C_{rain} = \sum_{j=0}^{i-1} \frac{j}{i} D(j) + \sum_{j=i}^{T} e^{\alpha(i-j)} D(j) \qquad (3.1)$$

where D is a daily time series of precipitation with j serving as an index that begins at 0 and marches backwards (*e.g.* 3 days prior is j=3), i is a constant that reflects the time it takes (in days)

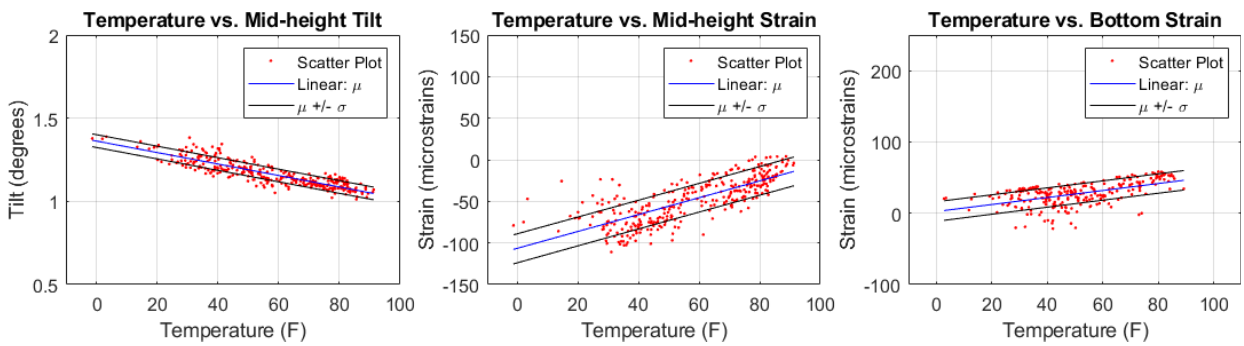


Figure 3.7. Relationships between I-696 tall wall mid-height tilt, mid-height strain, and bottom strain as a function of wall temperature (August 2018-October 2019)

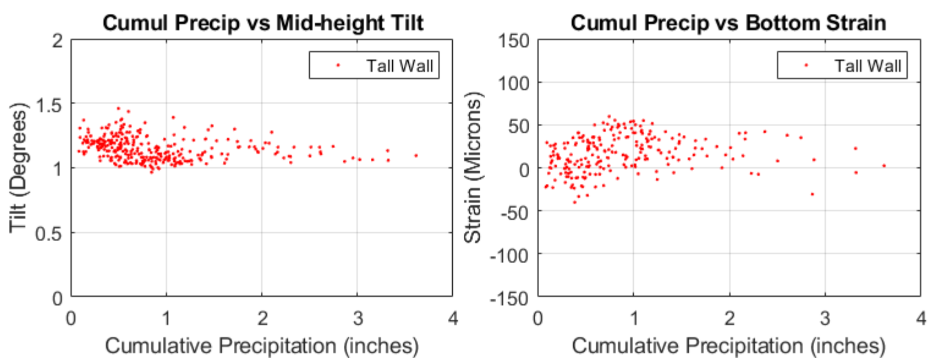


Figure 3.8. Relationships between I-696 tall wall mid-height tilt and bottom strain as a function of cumulative precipitation (August 2018-October 2019)

for soil to saturate the backfill, T is a constant that reflects the time it takes (in days) for the soil to dry after being saturated, and α is a time constant on the tail portion of the weighted sum. Using the wall top tilt and precipitation measurements collected during period of heavy precipitation (*e.g.* late September 2018 into early October 2018), the cumulative rain function is emperically determined with i=3 days, T=18 days and α=0.1. As shown in Figure 3.8, the mid-height tilt and bottom strain of the tall wall panel was insensitive to cumulative rain, reinforcing the hypothesis of a saturated back fill.

The behavior of the top portion of the tall wall panel, especially the parapet portion of the wall system, was observed to be sensitive to precipitation in the non-winter months while sensitive to temperature in the winter when there is less precipitation. Figure 3.9 plots the tall wall top tilt as a function of precipitation from August 25 to November 30, 2018 and April 1 to October 11, 2019

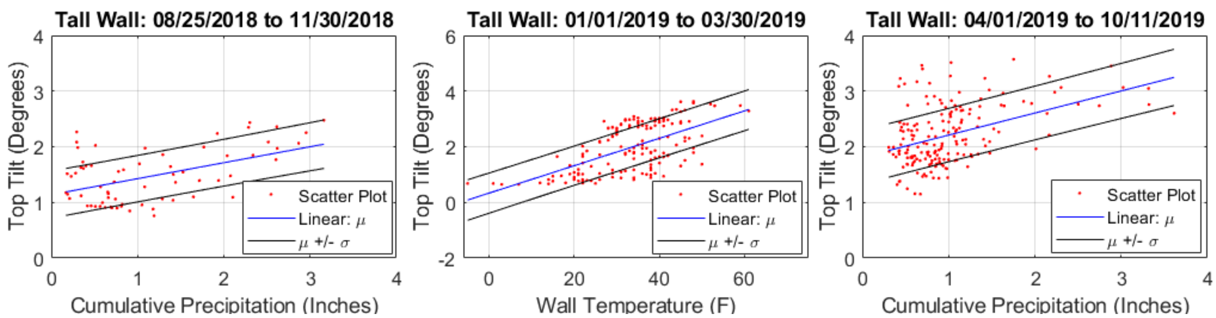


Figure 3.9. Relationships of the I-696 tall wall top tilt to cumulative precipitation (August 25 to November 30, 2018), temperature (January 1 to March 30, 2019) and cumulative precipitation (April 1 to October 11, 2019)

revealing a linear relationship between top tilt and cumulative precipitation during the non-winter observation period. The figure also plots the top wall tilt as a function of wall temperature in the winter (January 1 to March 30, 2019) revealing a fairly strong linear relationship of 0.05° per degree F.

3.3.4. Wall Deflection Curves

The prior sections explored analyses of the tall I-696 retaining wall panel responses. Both response time histories and response scatter plots were presented and discussed. This section considers an analysis of the wall deflections based on the top and mid-height daily mean tilt measurements. The deflected shape of the wall can be calculated from the top and mid-height tilt measurements under an assumed lateral earth pressure profile and structural properties. Structural properties including wall geometries, steel reinforcement locations, and material properties can be reasonably estimated based on the engineering drawings of the wall. The shape of the lateral earth pressures on the wall backside can also be estimated. In this analysis, three pressure profiles were assumed: lateral earth pressures from surcharge loads on the top surface (rectangular), backfill pressure (triangular), and hydrostatic pressure (triangular) as shown in Figure 3.10. Estimating the deflected shapes of the wall can aid in understanding the seasonal variations observed in the data, especially the wall responses to hydrostatic pressures associated with precipitation.

The lateral earth pressures from the backfill soil induce a flexural response of the wall. The top wall rotation, θ, due to the backfill earth pressures is static. However, the surcharge and hydrostatic lateral earth pressures vary depending on the surface gravity loads on the top of the backfill and saturation of the soil, respectively. Variations in these loads result in a variation in the top tilt, Δθ.

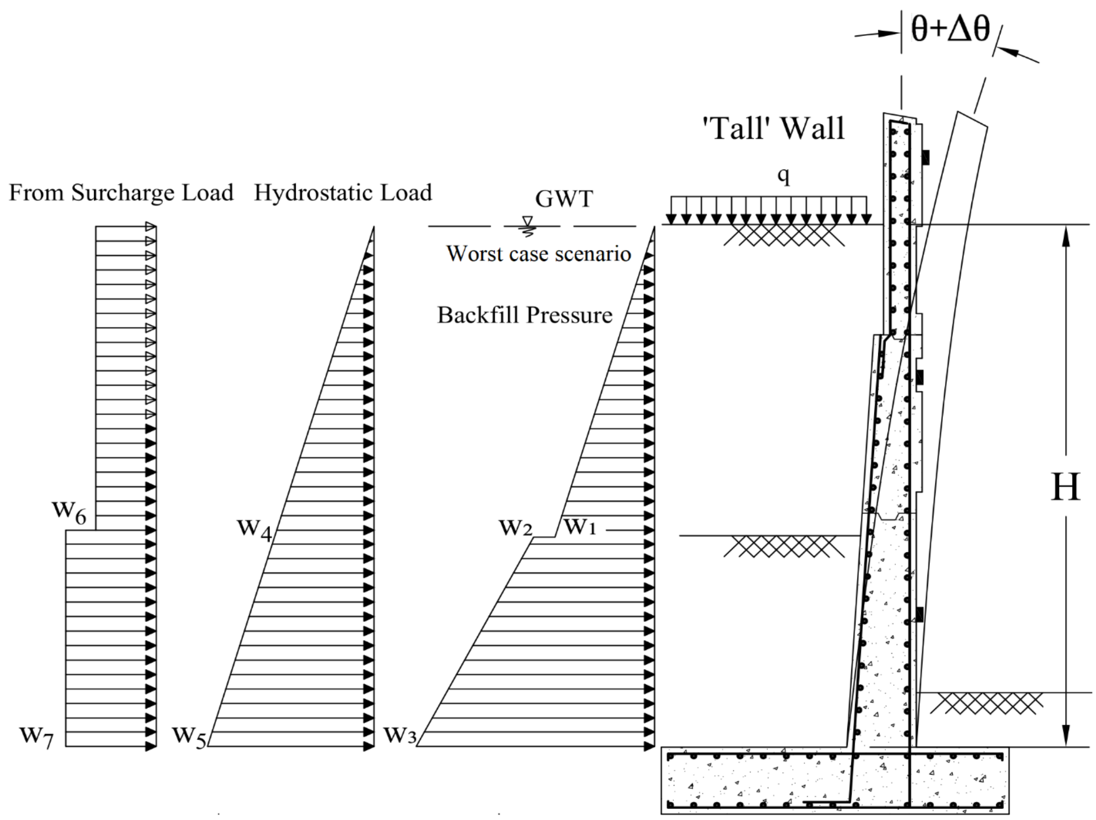


Figure 3.10. Cross-sectional view of the I-696 tall wall and its backfill lateral loads

In this section, the theoretical deflected shape of the wall panel are presented for each of the three lateral earth pressures: backfill pressure, hydrostatic pressure, and surcharge pressure.

Using the tilt measurements collected, the wall deflected shapes were estimated using the analytical relationship between rotation and deflection.

To compute, θ, the backfill information from soil boring elevation drawings was utilized. According to MDOT (1986), the backfill was a two-layer system with a 13'-11" thick medium compacted sand layered on top of a 9'-7" thick medium compacted gray silt and fine sand. The soil within each layer was assumed to have a uniform/homogeneous material distribution. The range of bulk and submerged densities of the two soil types are summarized in Table 3.2 (Yu et al, 1993). For analysis, the following properties are selected:

- Sand with medium compaction:
  - Bulk density = 0.069 lb/in^3 (submerged density = 0.038 lb/in^3)
- Sandy silt with medium compaction:
  - Bulk density = 0.073 lb/in^3 (submerged density = 0.042 lb/in^3)

Table 3.2. Typical bulk and submerged densities of selected soils (Based Coduto, 2001)

Soil Type	Bulk Density (lb/in^3)	Submerged Density (lb/in^3)
Firm silty sandy clay	0.058 to 0.085	0.022 to 0.049
Medium compacted sand	0.049 to 0.079	0.030 to 0.042
Medium compacted sandy silt	0.051 to 0.082	0.031 to 0.046

To estimate the backfill earth pressures, Coulomb or Rankin theory can be used. Due to the unknown frictional properties of the soil on the wall surface, Rankine theory was used. Rankine theory is also favored by state transportation agencies including AASHTO and FHWA. The Rankine active earth pressure coefficient, k_a, is given by (Das, 2011):

$$k_a = \frac{\cos(\beta - \theta)\sqrt{1 + \sin^2\emptyset - 2\sin\emptyset\cos\psi}}{\cos^2\theta\,(\cos\beta + \sqrt{\sin^2\emptyset - \sin^2\beta}} \tag{3.2}$$

$$\psi = \sin^{-1}\left(\frac{\sin\beta}{\sin\emptyset}\right) - \beta + 2\theta \tag{3.3}$$

where β is the slope of the top surface of backfill relative to the horizon (in this case β=0°), ϕ is the internal soil friction angle, and θ is the slope of the backwall incline (relative to vertical). Typical angles of internal soil friction were acquired from (Koloski, 1989):

- Sand with medium compaction: $\phi = 33^{o}$
- Sandy silt with medium compaction: $\phi = 29^{o}$

The angle of the back surface of the I-696 walls, θ, was computed as to be 3.6°. Based on Equation 3.2 and 3.3, the active earth pressure coefficients were computed as: k_{a1} =0.30 and k_{a2} =0.35 for the upper and lower soil layers, respectively. Using the active earth pressure coefficients, depths of the backfill layers (h_1 and h_2 referenced from the top surface of each layer), and bulk soil density, ρ, the backfill earth pressure profile (Figure 3.10) was calculated as shown in Table 3.3.

The calculations presented in Table 3.3 apply when the backfill soil is acting on the wall in an unsaturated state and with no acting surcharge load. When thebackfill has water to a specified saturation level, the active lateral pressure from the backfill soil will need to consider the submerged density of the soil in lieu of the bulk density for the portions of the backfill that are saturated (i.e., below the ground water table or GWT level) (Figure 3.11 and Table 3.4) .

Table 3.3. Static backfill earth pressures (no surcharge or hydrostatic pressure)

Equation	Calculation	Pressure Value
$w_1 = k_{a_1}\rho_{bulk_1}h_1$	$w_1 = 0.3 * 0.069\frac{lb}{in^3} * \left(13.95\, ft. * 12\frac{in}{ft.}\right)$	$\boldsymbol{w_1 = 3.47\, psi}$
$w_2 = \frac{k_{a_2}}{k_{a_1}} * w_1$	$w_2 = \left(\frac{0.35}{0.30}\right) * 3.47\, psi$	$\boldsymbol{w_2 = 4.04\, psi}$
$w_3 = w_2 + k_{a_2}\rho_{bulk_2}h_2$	$w_3 = w_2 + 0.35 * 0.073\frac{lb}{in^3} * \left(9.55\, ft. * 12\frac{in}{ft.}\right)$	$\boldsymbol{w_3 = 6.97\, psi}$

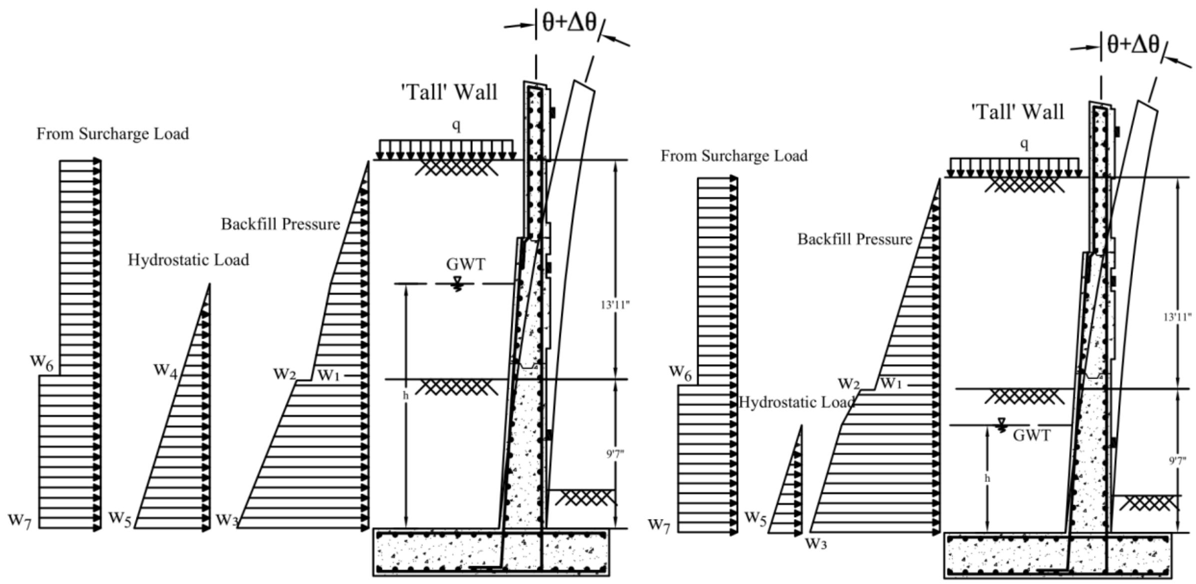
The flexural rigidity of the wall was next determined assuming the wall acts in flexural response as an ideal vertical cantilever. The horizontal flexure of the wall panels between their vertical joints was ignored to simplify the analysis. The vertical flexural rigidity of the wall is dependent on the wall moment of inertia, *I*, and the elastic modulus, *E*. Given the age of the I-696 retaining wall system, the material properties need to account for age, especially the modulus of elasticity for the concrete used in the wall construction. The effective modulus of the concrete was determined based on the documented 28-day compressive strength of the concrete (f_c'=4,000 psi) and consideration of creep and shrinkage (ACI 1997). The effective modulus, E_e, is based on the initial modulus, $E_i = 57{,}000\sqrt{f_c'}$ (in psi) and the creep coefficient, ϑ_t, with *t* specified in days:

$$E_e = \frac{E_{ci}}{1 + \vartheta_t} \tag{3.4}$$

$$\vartheta_t = 2.35 * \frac{t^{0.6}}{1 + t^{0.6}} \tag{3.5}$$

Given the age of the wall (33 years), the effective modulus, E_e, was determined to be 1.1x10^6 psi based on Equation 3.4.

The section moment of inertia, I_{cr}, was based on the assumption of a cracked section with the tensile response of the wall entirely taken by the steel reinforcement. This was a valid assumption given the age of the wall, the large loads present, and visual evidence of flexural cracking in previously excavated retaining walls (such as the M-10 wall system) in the vicinity of the I-696 wall (MDOT, 2013). Figure 3.12(a) highlights the assumption of the cracked section. To determine



(a) (b)

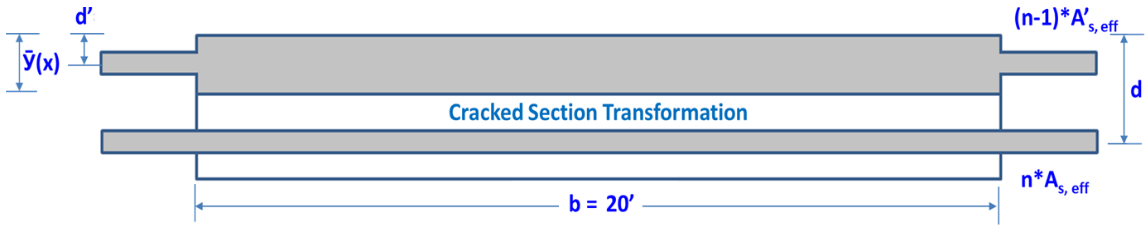
Figure 3.11. Static backfill earth pressures, surcharge and hydrostatic pressure: (a) higher versus (b) lower GWT

Table 3.4. Formulae to calculate backfill, surcharge and hydrostatic pressures

Equations (GWT in top layer)	Equations (GWT in bottom layer)
$w_1 = k_{a_1}\rho_{bulk_1} * (23'6" - h) + \rho_{sub_1} * (h - 9'7")$	$w_1 = k_{a_1}\rho_{bulk_1} * 13'11"$
$w_2 = \frac{k_{a_2}}{k_{a_1}} * w_1$	$w_2 = \frac{k_{a_2}}{k_{a_1}} * w_1$
$w_3 = w_2 + k_{a_2}\rho_{sub_2} * 9'7"$	$w_3 = w_2 + k_{a_2}\rho_{bulk_1} * (9'7" - h) + \rho_{sub_1} * h$
$w_4 = \rho_{water}(h - 9'7")$	$w_4 = 0$
$w_5 = \rho_{water}h$	$w_5 = \rho_{water}h$
$w_6 = k_{a_1} * q$	$w_6 = k_{a_1} * q$
$w_7 = \frac{k_{a_2}}{k_{a_1}} * w_6$	$w_7 = \frac{k_{a_2}}{k_{a_1}} * w_6$

the moment of inertia of the cracked section, I_{cr}, the location of the neutral axis, $\bar{y}$, must be calculated for the tapered section as a function of the wall height, x. Using the structural drawings to identify the wall geometries including reinforcement details, the cracked section was transformed based on the ratio of elastic modulus, *n*, between the steel ($E_s = 29\text{x}10^6$ psi) and concrete ($E_e = 1.1\text{x}10^6$ psi) (Figure 3.12(b)). The neutral axis, $\bar{y}$, was then parameterized as the following polynomial given the wall tapering (which affects the depth to the tensile

(a)



(b)

Figure 3.12. (a) Cracked section assumption with tensile load taken by vertical steel reinforcement and compressive load taken by concrete; (b) cracked section transformation.

reinforcement, $d(x)$) and the effective area of the steel in the tension zone, $A_{s,eff}$, and the compression zone, $A'_{s,\,eff}$:

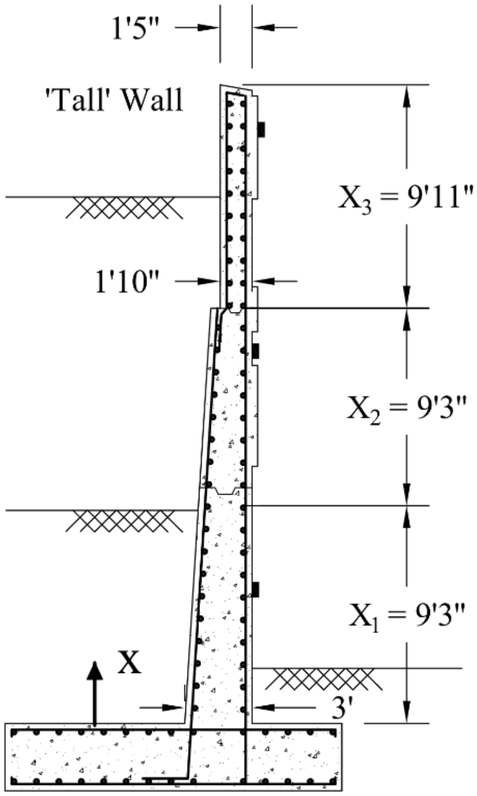
$$\frac{1}{2}b\bar{y}^2 + (n-1)A'_s(\bar{y} - d') - nA_s(d(x) - \bar{y}) = 0 \tag{3.6}$$

As shown in Figure 3.13, the tall I-696 wall panel has flexural reinforcement that varies over its height. As a result, the wall can be divided into three sections that will have separate formulas that offer the real positive root to Equation 3.6.

The neutral axis, $\bar{y}(x)$, was found as a function of height, x, by finding the real positive root of the polynomial of Equation 3.6. The cracked moment of inertia about the neutral axis, $\bar{y}(x)$, was found to be:

$$I_{cr}(x) = (n - 1)A'_{s,\,eff}(\bar{y}(x) - d')^2 + nA_{s,\,eff}\big(d - \bar{y}(x)\big)^2 + b\bar{y}(x)\left(\frac{\bar{y}(x)}{2}\right)^2 + \frac{b\bar{y}(x)^3}{12} \tag{3.7}$$

As before, Figure 3.13 summarizes the cracked section moment of inertia as a function of wall height, x.



Depth to Neutral Axis (NA) from front face of wall:

$$\bar{y}(x) = -0.0099x + 7.2455,\ in$$
$$(0 \le x \le 9'3")$$
$$\bar{y}(x) = -0.009x + 5.8718,\ in$$
$$(9'3'' \le x \le 18'6")$$
$$\bar{y}(x) = 3.064\ in$$
$$(18'6" \le x \le 28'5")$$

Cracked Moment of Inertia (I_{cr}):

$$I_{cr}\,(x) = 1.003\ x^2 - 688.52\ x + 123{,}048,\ in^4$$
$$(0 \le x \le 9'3")$$
$$I_{cr}\,(x) = 0.599\ x^2 - 403.13\ x + 70{,}091,\ in^4$$
$$(9'3'' \le x \le 18'6")$$
$$I_{cr}\,(x) = 4988.022,\ in^4$$
$$(18'6" \le x \le 28'5")$$

Figure 3.13. (a) Tapering of the I-696 cantilever RC retaining wall and the parapet wall; (b) Depth to Neutral Axis (NA) and Cracked Moment of Inertia (I_{Cr})

The I-696 tall wall was assumed to be in static equilibrium governed by the following moment balance:

$$E_e I_{cr}(x)\left(\frac{d^2 y(x)}{dx^2}\right) = E_e I_{cr}(x)\left(\frac{d\theta(x)}{dx}\right) = M(x) \tag{3.9}$$

where $M(x)$ is the flexural moment induced by the backfill, $y(x)$ is the displacement of the wall, and $\theta(x)$ is the wall tilt. Similarly, the wall responded to moments from hydrostatic pressure and top-grade surcharge, $\Delta M(x)$, which induced a time-varying displacement, $\Delta y(x)$, and tilt, $\Delta\theta(x)$:

$$E_e I_{cr}(x)\left(\frac{d^2 \Delta y(x)}{dx^2}\right) = E_e I_{cr}(x)\left(\frac{d\Delta\theta(x)}{dx}\right) = \Delta M(x) \tag{3.10}$$

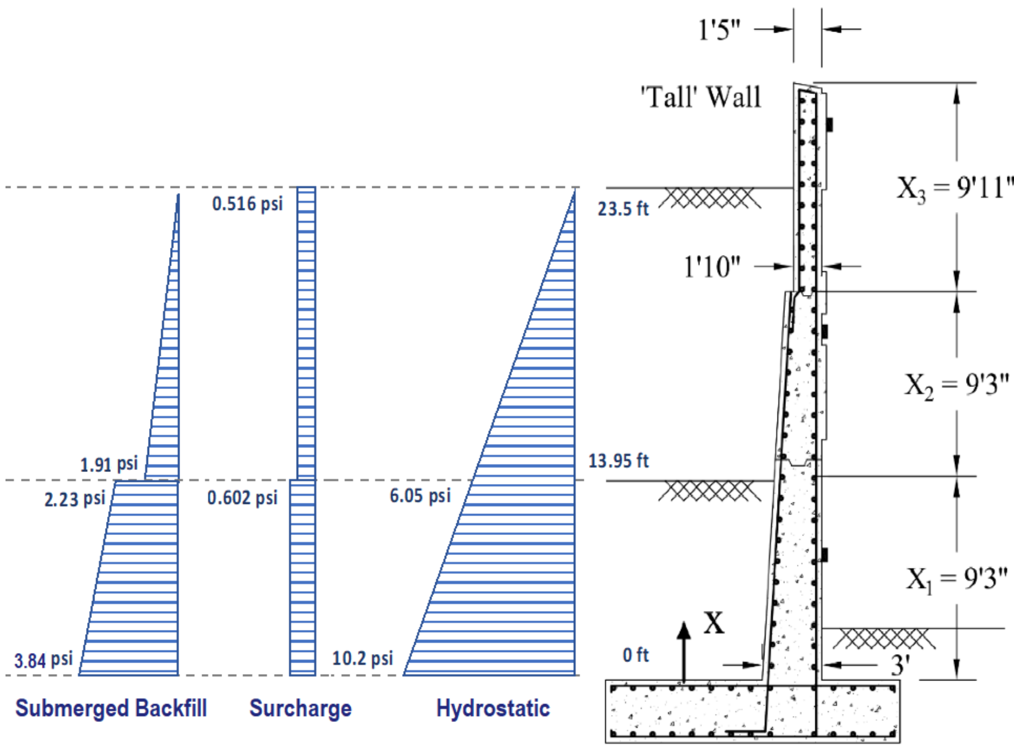


Figure 3.14. Lateral earth pressures on tall I-696 wall: backfill, surcharge, hydrostatic

Three load profiles were explored on the I-696 tall wall panel: backfill lateral earth, hydrostatic pressure, and pressure from surface surcharge. The maximum lateral load on the wall is when all the three loads act on the wall, simultaneously (Figure 3.14). With the rise of water in the backfill to the level close to the top surface, the bulk backfill pressures that were calculated in Table 3.3 need to be recalculated by utilizing the submerged unit weight of the soil layers (Table 3.2) and converted to a load diagram for the wall considering the width of the wall (20'). A surcharge pressure of q = 1.7 psi (shown in Figure 3.10) was considered on the top surface of the backfill resulting in a uniformly distributed lateral earth pressure on the wall ($w = k_a q$). This surface surcharge was conservatively obtained from the load assumptions made during the design of retaining walls (FHWA, 2009). Finally, hydrostatic pressure was also considered assuming a fully saturated backfill using the specific weight of water to be 62.43 lb/ft^3 (Figure 3.14).

Using the equilibrium condition of the wall, the wall deflection was theoretically predicted. Equation 3.9 was used to derive the wall deflection, $y(x)$, for four load cases to offer a range of feasible deflection scenarios: 1) backfill only; 2) backfill and surcharge; 3) backfill and hydrostatic (fully saturated); and, 4) backfill, surcharge and hydrostatic (fully saturated). Depending on the

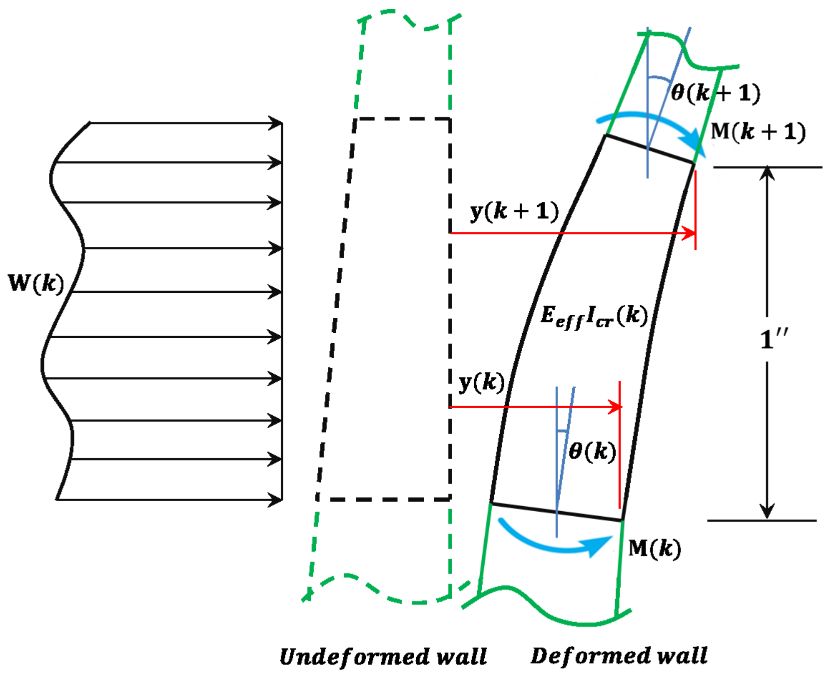


Figure 3.15. Discretization of the I-696 cantilever wall

level of the GWT delineated in Figure 3.11, there were different moment equations for the different sections of the tall I-696 wall system. Therefore, the analysis of the wall was simplified by discretizing the wall into 1" sections (δh) with equilibrium applied (Equation32.9) as shown in Figure 3.15. While the wall could be discretized more finely, the 1 inch discretization size was found to be sufficiently precise. The tilt and displacement of the wall section at the top of the discretized element, *k*, was:

$$\theta(k+1) = \sum_{i=1}^{k} \frac{M(i)}{E_{eff}I_{cr}(i)} = \theta(k) + \delta h \frac{M(k)}{E_{eff}I_{cr}(k)} \tag{3.11}$$

$$y(k+1) = \sum_{i=1}^{k} \theta(i)\delta h = y(k) + \theta(k)\delta h \tag{3.12}$$

The total bending moment acting on the reinforced concrete cantilever wall panel at a height of el

ement, *k*, is the superposition of the bending moments from the hydrostatic pressure, $M_{HS}(k)$, the surcharge, $M_q(k)$, and the backfill, $M_b(k)$ at that level. Therefore, the total bending moment, $M(k)$ on the tall I-696 wall was expressed as,

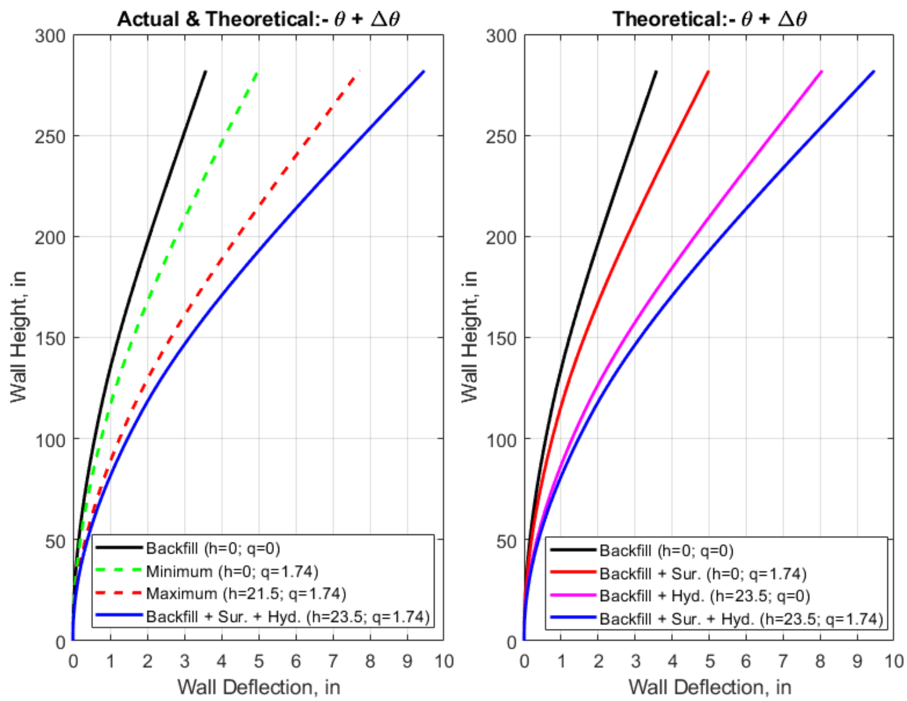


Figure 3.16. (a) Actual (left) and (b) theoretical (right) deflected shapes of the tall I-696 RC cantilever wall.

$$M(k) = M_{HS}(k) + M_q(k) + M_b(k) \tag{3.13}$$

To analyze the behavior of the wall, the finite difference method encapsulated in Equation 3.11 was applied for a given assumed surcharge, q, and height of saturated soil, h_{sat}. Given q and h_{sat}, the pressure on the wall was formulated by Table 3.4 and the moments determined by Equation 3.13. Equation 3.11 was analyzed using $E_c I_{cr}(k)$ for each discrete element working from the base to the top of the wall to determine tilt, $\theta(k)$. Finally, the displacement, $y(k)$, was calculated by Equation 3.12 using tilt.

The tall I-696 wall was monitored with two measures of tilt (*i.e.*, at the top and mid-height of the wall). These tilt measurements were used to assess the deflection curve of the wall based on the finite difference model developed. The two measurements of tilt were used to estimate two parameters of the lateral pressures on the wall: surcharge, q, and the height of the water saturation, h_{sat}. The two unknown parameters, q and h_{sat}, were determined by searching through a look-up table composed of the mid-height and top tilt for all variations of q and h_{sat} pre-calculated. For each tilt measurement pair, q and h_{sat} were identified. The deflected shape, $y(k)$, of the wall using these load parameters was determined. Figure 3.16a shows the actual deflection curve extracted from the measured tilts. The minimum and maximum curves are plotted. Figure 3.16b shows the theoretical deflected shapes of the retaining wall using the flexural rigidity and prescribed loading scenarios. The saturation of the soil is recognized to be a conservative load assumption (fully saturated backfill, $h_{sat} = 23.5'$ and q = 1.74 psi) and was considered as an upper bound on the wall response (Figure 3.16). For the actual deflection cases, it was discovered that the level of backfill soil saturation, h_{sat}, was dominant in increasing tilt significantly as compared to the presence of surcharge, q. The minimum deflection profile corresponded to $h_{sat} = 0'$ and q = 1.74 psi, while the maximum deflection corresponded to $h_{sat} = 21.5'$ and q = 1.74 psi.

3.4. Short I-696 Retaining Wall System

The second wall system instrumented was the "short" I-696 wall; this wall system is 40 feet to the east of the tall I-696 wall. The wall panel is structurally *identical* to the tall I-696 wall system (as described in Section 3.3) including wall dimensions, reinforcement details and backfill soil information. However, the exit ramp coming off of the I-696 freeway is inclined resulting in a higher soil profile on the front face of the wall. As a result, the front grade line of the short I-696 wall panel is higher by 2'-6" compared to the tall wall. The top of the short wall was measured during site visits to be 23'-6" above the grade line.

The tilt response (using equal scales on tilt magnitude) of the short I-696 wall panel is plotted in Figure 3.17, raw strain (on equal scales) in Figure 3.18, and wall temperature in Figure 3.17 and Figure 3.18. As was done before, the daily means were calculated by averaging the measurement data over a one day period from 12:00am to 11:59pm. The daily total precipitation is also plotted over the same period in Figure 3.17 and Figure 3.18 to provide insight to responses associated with precipitation. The raw strains plotted in Figure 3.18 were nulled to be zero at the start of data collection. Only one strain sensor was installed at the bottom of the short I-696 wall panel.

The top and mid-height tilts are plotted in Figure 3.17. As can be seen, the mid-height tilt sensor stopped operating in early December so only three months of data were collected. The top tilt exhibited greater variability as compared to the mid-height tilt sensor during that time, an observation consistent with the tall I-696 wall. However, the mid-height tilt on the short wall was

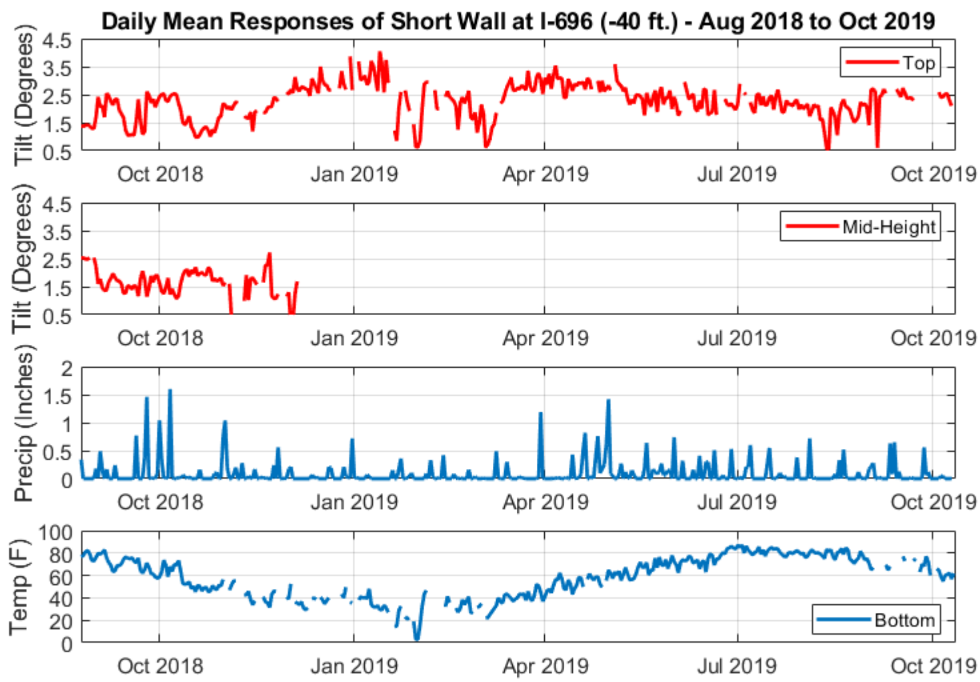


Figure 3.17. The daily mean response of the I-696 short wall panel: top tilt, mid-height tilt, precipitation, and wall temperature (August 2018-October 2019)

significantly greater than that on the tall wall, suggesting more movement in the short wall panel. Over the one year period, the top tilt varied from 0.3 to 4.1° while the mid-height tilt had a much smaller variation between 0.4 to 2.5° over the three months of measurements. Similar to the tall I-696 panel, the short I-696 wall panel appeared to be sensitive to repeated days of precipitation. Steady precipitation results in the build-up of hydraulic pressure in the top stratum of soil inducing larger tilts on the top of the wall. For example, continuous days of rain in late September 2018 into early October 2018 induced a noticeable upper tilt of the top portion of the wall from 1.5 to 2.5° with the wall returning back to 1.5° after rain stopped. From early November 2018 to January 2019, the top tilt had a high level of day-to-day variation as the trendline mean of the tilt time history steadily rose. In mid-January to mid-February during a time period of extreme cold temperatures (when the wall surface temperature is below freezing), the daily mean top tilt varied from 0.5 to 3.1°. By mid-March 2019, the top tilt of the short wall had less variation with a mean trendline up near 2.8°. Thereafter, the wall top tilt slowly reduced as the wall temperature steadily increased. By early August 2019, the top tilt has settled to about 1.5° with low day to day variation.

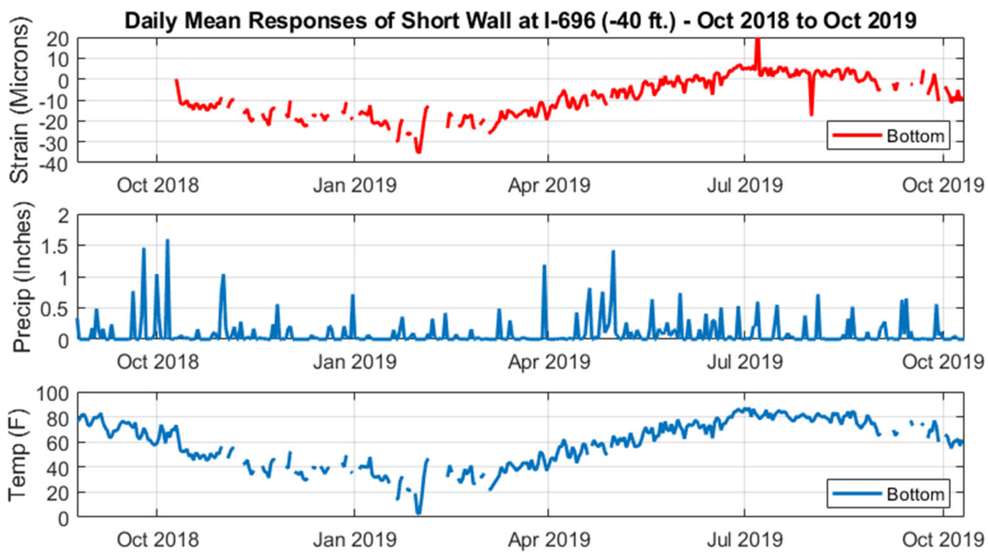


Figure 3.18. The daily mean response of the I-696 short wall panel: bottom strain, precipitation, and wall temperature (August 2018-October 2019)

For the remainder of the measurement period, the wall showed greater variation in top tilt. These observations in the tilt response were similar to those made for the tall I-696 wall panel. The daily mean strain response at the bottom of the short I-696 wall panel captured strain variations and do not represent an absolute state of strain. The daily mean strain (Figure 3.18) exhibited a trend correlated to the wall temperature. The bottom strain of the short wall panel varied only 60 με which was less than the bottom strain experienced in the tall wall panel (which was 75 με).

Due to the observations of difference in the response of the tall I-696 wall panel during night (11:59pm to 6:00am) and day (11:00am to 5:00pm), a similar analysis was performed on the short panel. Figure 3.19 plots the top and mid-height average tilts while Figure 3.20 plots bottom average strain during night and day. As is evident from Figure 3.19, the tilt of the short wall at average strain during night and day. As is evident from Figure 3.19, the tilt of the short wall at the top and mid-height was generally higher at night than during day. However, the top of the wall had higher tilt during the day from December 2018 to mid-January 2019 and from mid-March to May 2019, which is different than that observed in the tall wall panel.

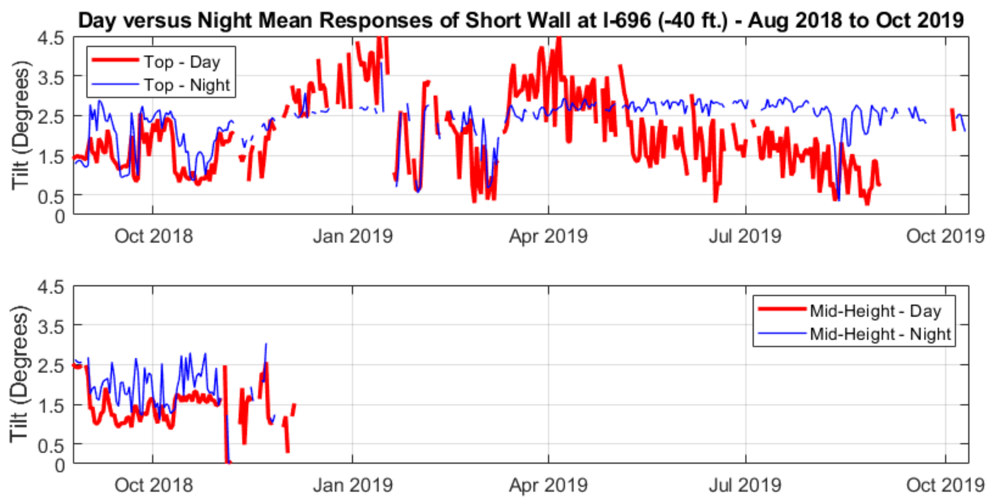


Figure 3.19. Night and day daily mean response of the I-696 short wall panel: top tilt and mid-height tilt (August 2018-October 2019)

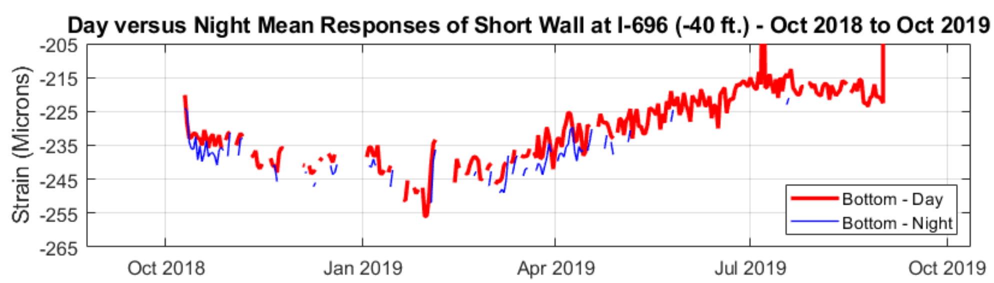


Figure 3.20. Night and day daily mean response of the I-696 short wall panel: mid-height strain and bottom strain (August 2018-October 2019)

The strain measurements also had a slight difference between night and day with higher compressive strain in the night likely due to lower night temperatures.

Scatter plots were studies to understand the causality between environmental parameters and wall behavior. Scatter plots similar to those constructed for the tall I-696 wall panel are done for the short I-696 wall panel. First, the daily mean bottom strain response of the short wall was plotted as a function of temperature. Figure 3.21 plots the bottom strain wall strain as a function of wall temperature. A strong linear relationship was evident with a sensitivity roughly 0.5 με to cumulative precipitation, C_{rain} (Equation 3.1). The scatter plot of strain versus C_{rain} in Figure 3.21 shows no dependencies.

Top tilt of the short I-696 wall was compared to top tilt of the tall I-696 wall. A strong correlation was evident between the two wall panels as shown in Figure 3.22. Also plotted is the scatter plot

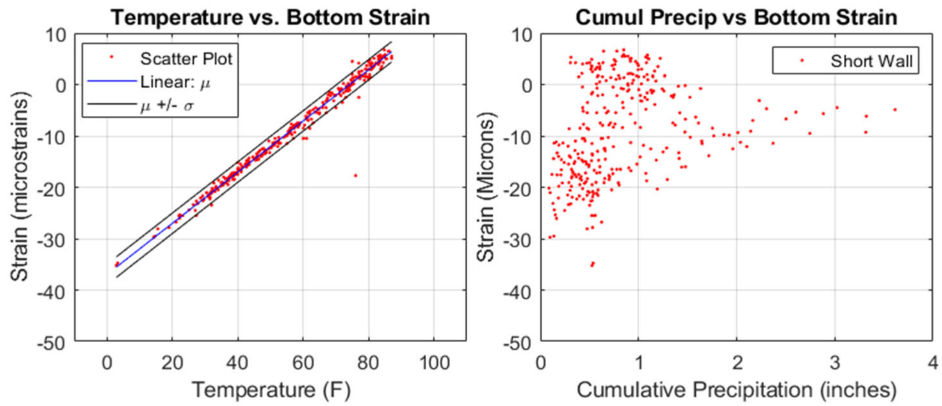


Figure 3.21. Relationships between I-696 short wall bottom strain as a function of temperature and cumulative precipitation (August 2018-October 2019)

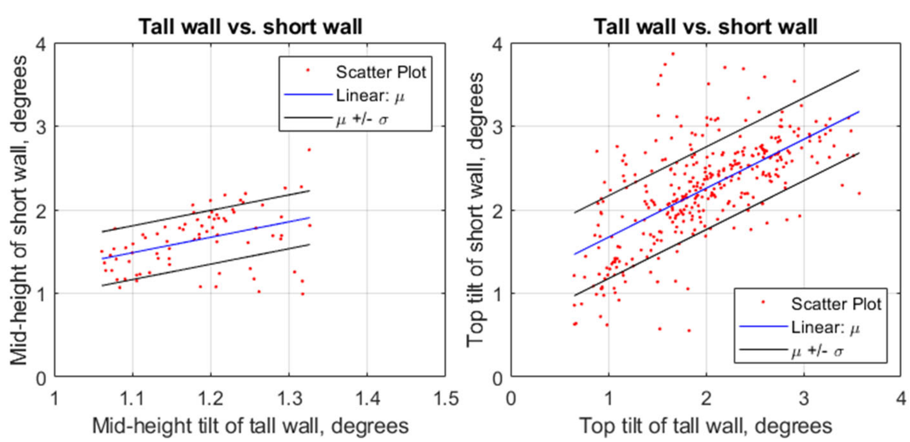


Figure 3.22. Relationships between I-696 short and tall wall panels: (a) mid-height tilt (August 2018-December 2018) and (b) top tilt (August 2018-October 2019)

of mid-height tilt of the short and tall wall over the period the short wall mid-height was measured. While less data was collected, there was a mild correlation between the two. These findings were not surprising given the close proximity of the two panels from one another.

In Figure 3.23, the theoretical and estimated by measurement deflection curves for the short I-696 wall are presented. The same procedure was followed to compute the actual deflections by looking at minimum and maximum deflection cases based on the top tilt measurements. For the actual deflection cases, same as the tall I-696 wall, it was discovered that the level of backfill soil saturation (h_{sat}) was dominant in increasing tilt significantly as compared to the presence of surcharge (q). The minimum deflection case corresponded to h_{sat} = 0' and q = 0.87 psi, while the maximum case corresponded with h_{sat} = 22.5' and q = 1.74 psi.

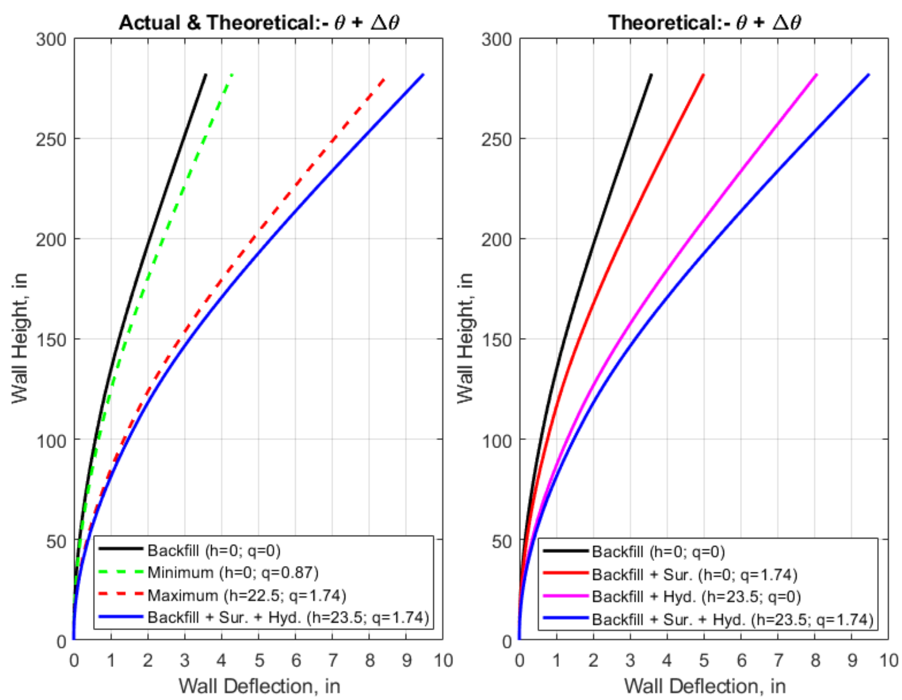


Figure 3.23. (a) Actual (left) and (b) theoretical (right) deflected shapes of the short I-696 RC cantilever wall.

3.5. M-10 Retaining Wall System

3.5.1. Description of the Wall System

The M-10 wall is more than 50 years old and is a reinforced concrete (RC) retaining wall system with panels 25' wide. Construction of the wall was in multiple stages. First, a 14' tall (above foundation pad) and 1'6'' thick reinforced concrete retaining wall was erected upon a 2'-6'' thick and 7’-9” wide foundation pad. Second, a 8’-0” tall wall with a horizontal beam at the bottom portion (which the tie-backs are attached to) was formed in the second cast along with a 2’-0” overhand barrier. The second pour of the wall was also 1’-6” thick except for the horizontal beam section which was 1’-10” wide. Details of the steel reinforcement is summarized in Table 3.5 while Figure 3.24 summarizes the structural details of the wall including its geometry and steel reinforcement. Each panel is stabilized with a post-tensioned (PT) battered caisson tie-backs (30^{o} from vertical). The tiebacks are spaced every 15’ to 18’ along the M-10 corridor. The instrumented

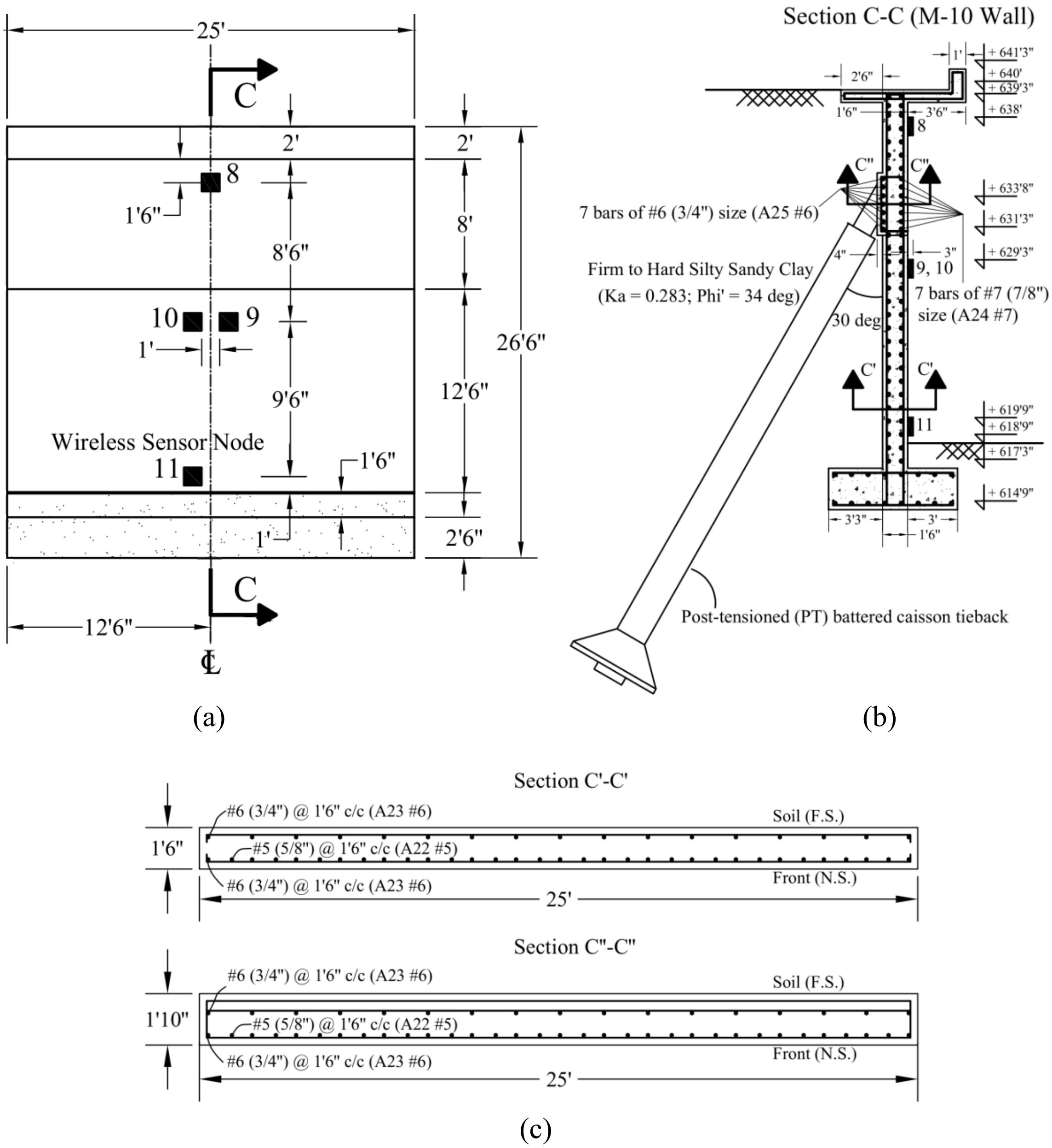


Figure 3.24. Structural details of the M-10 wall: (a) front elevation; (b) sectional profile; (c) cross-sectional profile detailing reinforcement.

panel shown in Figure 3.24a had two tie-backs stabilizing it; each tieback was 5’-0” from the vertical edge of the panel (15’-0” apart). The wall was measured during a site visit in June 2017 to be 22’-6” tall relative to grade on the front side of the wall. From the working drawings, the height of wall above the 2’6’’ thick foundation pad was 24’ (Figure 3.24a). On the wall back side (B.S.),

Table 3.5. Reinforcement bars of the wall panel of the M-10 wall system.

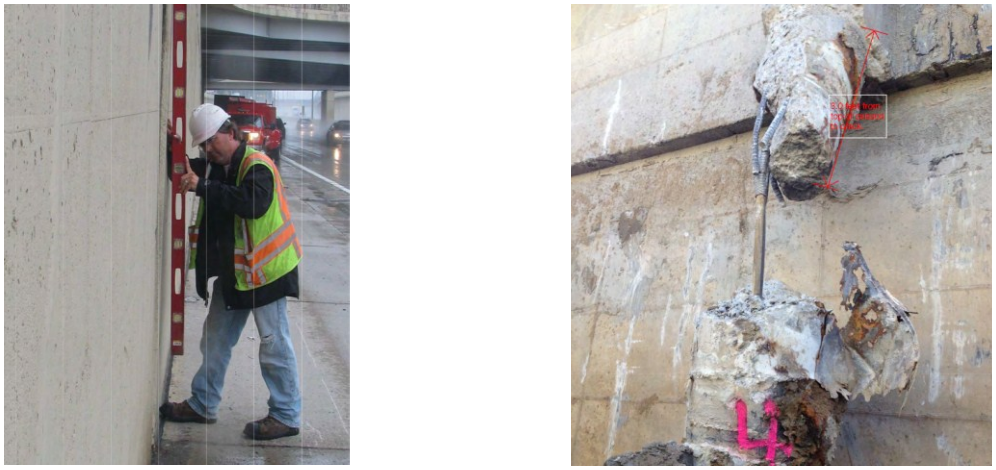
Rebar Name	Size or diameter	Length	c/c spacing	Rebar shape
Main Wall				
A22	#5 or $^5/_8$’’	23’	18’’ (N.S.)	Straight
A23	#6 or $^3/_4$’’	23’	18’’ (F.S. and N.S.)	Straight
Submerged Beam				
A24	#7 or $^7/_8$’’	21’	9’’ (N.S.)	Straight
A25	#6 or ¾’’	21’	9’’ (F.S.)	Straight

there exists a silty sandy clay backfill soil system. There were different levels of compaction (*i.e.,* firm to hard) throughout the height of the backfill but the backfill was analyzed as a single homogeneous layer considering the internal soil friction angle (34º) (MDOT, 1960).

The sensors were installed along the centerline of the panel centered between the two tiebacks. A summary of the sensors installed on the M-10 panel is shown in Figure 3.24a. There are two tilt units at the top and mid-height levels (*i.e*., wireless sensor units 8 and 9) of the wall. There are also two strain gage-thermistor units at the wall mid-height and bottom levels (*i.e.,* wireless sensor units 10 and 11). Data was collected from November 2018 to October 2019.

3.5.2. Preliminary Observations from 2012 and 2013

The M-10 wall was instrumented due to a past history of structural failures. In 2012, it was reported that wall panels on the northbound side of the M-10 corridor close to Schaefer Highway (roughly



(a) (b)

Figure 3.25. Preliminary investigation of the M-10 wall in 2012-2013: (a) tilt measurement during site visit; (b) failure of tie-back behind the wall (MDOT, 2013).

100’-0” north of Schaefer) had moved in mid-July. The initial thoughts as to the cause included the possibility of excessive hydrostatic pressure from an undrained backfill. MDOT performed an excavation of the wall backside and discovered the water main under the service road was leaking water into the backfill soil adding the hydraulic pressure. When the wall was measured, the wall had tilted 4” at its top (Figure 3.25a). Tilt monitoring was performed on the wall panels. Initially, the wall sections did not show significant variations but over a longer period from Fall 2012 to Summer 2013, significant changes in the wall tilt was observed. The monitoring showed a clear trend of movement suggesting to engineers that a progressive failure was underway. Upon excavation, the tieback was found to have been corroded to an extent that it was no longer engaged to the wall panel and restraining its motion (Figure 3.25b). The failed section of the M-10 wall was later replaced with a new wall section (MDOT, 2013).

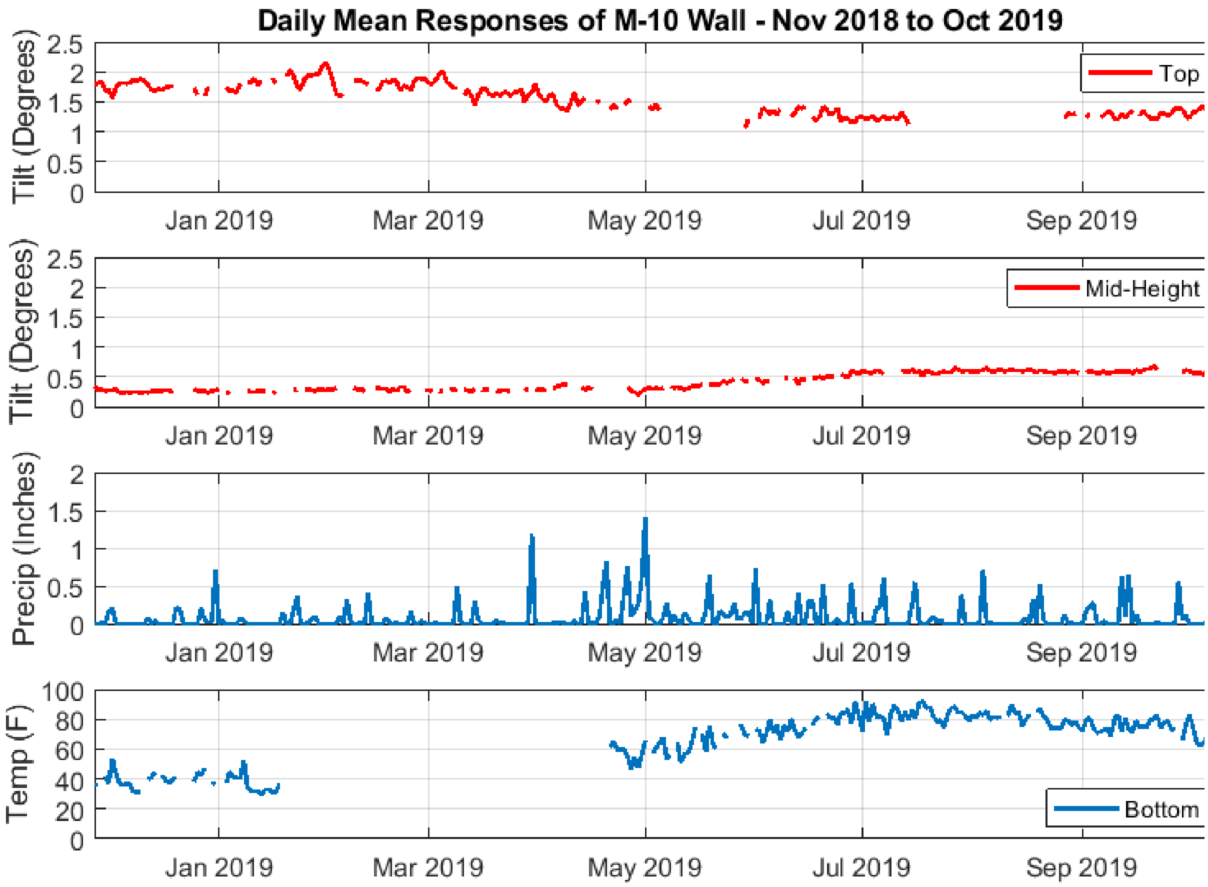


Figure 3.26. Wall response time histories of the M-10 wall: top-level tilt history; mid-height level tilt history; daily precipitation and wall temperature history at the mid-height level

3.5.3. Daily Mean Responses and Scatter Plots

The time histories of the daily mean wall responses of the M-10 wall panel at Thatcher Avenue near Schaefer Highway are presented in Figure 3.26. The daily mean tilt responses from the two wireless sensor units (i.e., wireless sensor nodes 8 and 9 in Figure 3.24a) at the top and mid-height locations are presented in Figure 3.26. Figure 3.26 also presents recording of the precipitation at the site based on data collected from an online weather database (Weather Underground, 2019) and the measured daily mean wall temperature at the mid-height location (i.e., wireless sensor node 10 in Figure 3.24a). Figure 3.27 plots the strain response of the M-10 wall panel along with precipitation and temperature.

The top tilt of the M-10 wall panel showed a high level of daily variation (similar to that observed for the I-696 walls) with tilt measuring from 1.1 to 2.0° with a mean trendline that appeared to be seasonally dependent (i.e., greater tilt in the winter and less tilt in the summer). The mid-height tilt was less variable measuring from 0.2 to 0.7° with a seasonal trend similar to the top tilt. However, the top and mid-height tilts of the wall were out of phase: when the top leaned out the mid-height pulled back in toward the backfill. It was hypothesized that the cold temperature contracts the tieback resulting in the tieback pulling the lower portion of the wall back toward the backfill. In such a scenario, the top which is not restrained would lean out as the tieback axial force pulled the panel back. Additionally, expansion of the top layer of the backfill due to freezing would push the top portion of the wall above the tieback out. As shown in Figure 3.28, the top and mid-height tilts exhibited a strong linear relationship with temperature. Strain also appeared to have a trendline with a strong season dependence as shown in Figure 3.27. In total, bottom strain of the M-10 wall varied a total of 70 με. When considering the strain response at the bottom of the wall relative to temperature, Figure 3.28 shows linear dependence but with a high level of variability due to some data points showing high compressive strain over a short period of a few days (as is evident in the time history plots of Figure 3.27).

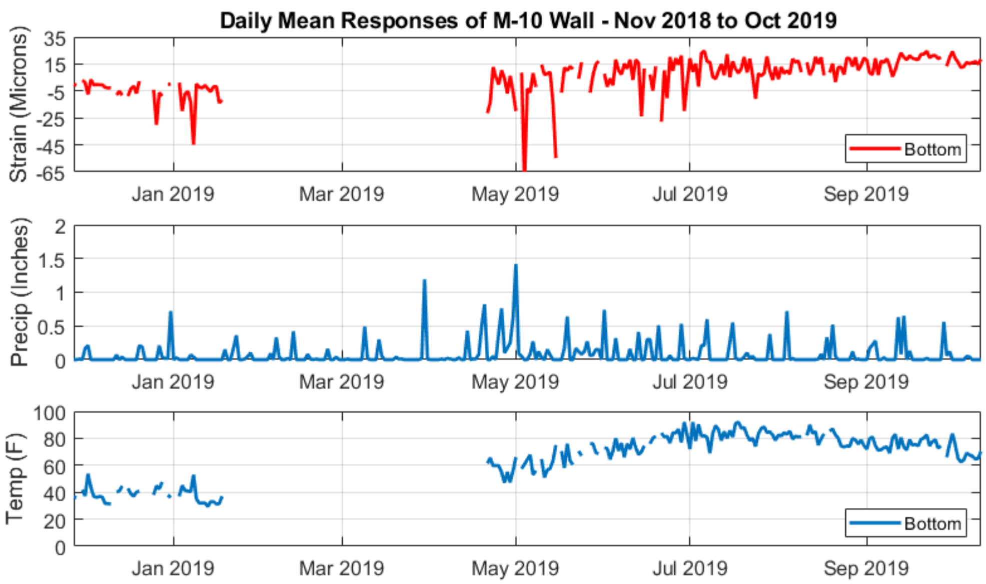


Figure 3.27. Wall response time histories of the M-10 wall: bottom-level strain history, daily precipitation and wall temperature at the bottom-level

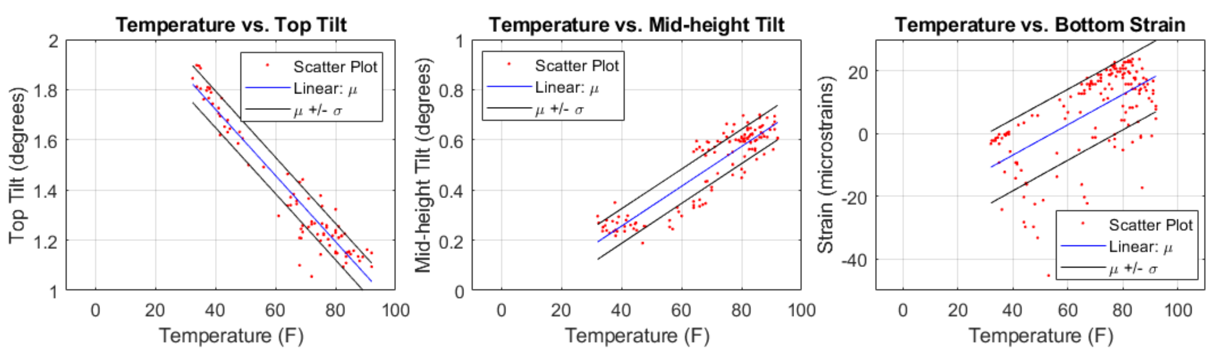


Figure 3.28. Scatter plots of M-10 wall panel response to temperature: top tilt, mid-height tilt and bottom strain

4. DEVELOPING THE MICHIGAN EARTH RETAINING STRUCTURE ELEMENT INSPECTION MANUAL

4.1. Introduction

Developing the Michigan Earth Retaining Structure Element Inspection Manual (MiERSEIM) required extensive research in the preliminary stage. Our team broke down this development into five objectives to manage the R&D progress. These steps are:

- Reviewing existing retaining wall management methods
- Conducting field reviews of 10 MDOT retaining wall systems
- Development of Earth Retaining Structure criteria
- Develop Structure and Appraisal (SI&A) Items for retaining walls
- Develop inspection procedure for retaining walls (MiERSEIM)

4.2. Reviewing Existing Wall Management Methods

Researching current organizational retaining wall inspection, monitoring, and reporting manuals was the first objective undertaken to minimize the "reinvent the wheel" aspect of this project. It was important to have an understanding of the process each government agency had when creating their policies and what they considered to be important aspects of the program. 13 agencies were researched based on manual availability and are listed below:

- National Parks Service (NPS)
- Oregon DOT
- Colorado DOT
- British Columbia
- The City of Cincinnati
- Penn DOT
- NYC DOT
- NY State DOT
- Kansas DOT
- California DOT
- Minnesota DOT
- Missouri DOT
- Maryland DOT

The information from the agencies policies and manuals were studied, compared, and analyzed to determine which methodologies would be desired for development of the MiERSEIM. Due to resource constraints, a few agencies have Inventory and inspection (I&I) programs specifically for

Mechanically Stabilized Earth (MSE) Walls only. For this project, inventory should include all walls regardless of ownership: any wall failure may impact a highway facility. From these 13 agencies, the manuals from the Colorado DOT and NPS were selected to have the ideals that align with this project.

4.3. Conducting Field Review of 10 MDOT Retaining Wall Systems

The information from the above manuals served as half of the process in developing the MiERSEIM. The second half involves field inspection to put the material to use. The Michigan Department of Transportation (MDOT) provided 74 different sites to investigate and from there, ten were chosen based on factors including type, size, condition, risk/consequence view, past monitoring information, and ease of access. The ten sites selected are:

- I-696 in Detroit
- US-10 in Midland
- I-75 at Brush Street in Detroit
- I-94 in Kalamazoo
- (222–MGrand St) in Allegan
- I–196 at Baldwin Connector
- I-75 Grand River Exit
- I-94 Water Street in Port Huron
- M-50 in Dundee
- US-31 along Bayfront Drive, near Petoskey

Once the sample data sets were determined, a team of personnel from the MDOT, University of Michigan, and the Mannik & Smith Group (MSG) visited each site to determine inspection criteria and methods through hands-on inspection. Every structural and non-structural component was examined to determine the feasibility of including the element in the inspection criteria. All defects were examined for their importance to failure rate, safety, and aesthetics. This data was then organized and placed into a spreadsheet to assist in creating an ERS SI&A Database. The spreadsheet grouped the wall according to the following data:

- Location
- Type
- Function
- Geometrics
- Condition of structure and components
- Nature of roadway traffic levels and surrounding development

- Risks associated with the structure's failure
- Restricted zone for permits
- Maintenance/Repair/Replacement work orders
- GPS coordinates
- Wall attachments, adjacent features, external stability conditions
- Date built/reconstructed
- Material, physical component types (foundation/wall/backfill/post/mount)
- Detailed dimensional data (begin/end stationing, offset, distance to road,
- slope, clearance)
- Historic eligibility, architectural forms
- Detour length, traffic class
- Photographs, letters, plans

4.4. Development of Earth Retaining Structure Criteria

Utilizing the data recorded from the inspection and the information provided by the above mentioned selected government agency manuals, the criteria to select ERS's in the inventory process was undertaken. The criteria developed for selecting ERS's are:

- Minimum height of wall (visible or total)
- Minimum length of wall
- Minimum height of retained fill
- Minimum face slope greater than 45 degrees
- Wall batter relative to roadway
- Walls within 30 to 100 feet of abutments

Minimum surface area and legal definition were not used as criterion.

4.5. Develop Structure and Appraisal (SI&A) Items for Retaining Walls

In order to create the MiERSEIM, a matrix was created utilizing the Colorado DOT and NPS Manuals related to Material and ERS Wall Types. These items were then combined to develop the starting point for the manual. These were expanded to include the following wall elements/characteristics assessments:

- Wall type
- Foundation
- Wall alignment
- Facing structure/treatments
- Surface coatings Attachments
- Guardrails/parapets
- Backfill material
- Backfill slope
- Drainage
- Erosion
- Vegetation
- Roadway
- Curb/Berm/SW/shoulder
- Adjacent features

Risks associates with ERS failures were also tabulated based on the failure potential, extent of the failure, threats to life/safety, link criticality/redundancy, average daily traffic impacts, and budget impacts.

These items were separated into primary and secondary element groupings and given an MDOT element number for reference. New elements were given numbers in the 900 range.

4.6. Develop Inspection Procedure for Retaining Walls (MiERSEIM)

After all the investigation and data layout was finalized, the MiERSEIM could be developed. The format for the manual mirrors the Michigan Bridge Element Inspection Manual (MiBEIM) for its familiarity. The manual begins with a Preface explaining the definition of the manual which is followed by an Introduction which explains the manuals purpose. A Detailed Element Description is included to define the information herein.

There are five main chapters to the Manual:

- Primary Elements – which describe the structural components of the ERS
- Secondary Elements – which describe the non-structural components of the ERS
- Scour Protection – which describes the scour protection devices for hydraulic ERS
- Appurtenances – which describe the attachments to the ERS
- Condition State Tables – which describe the deficiencies for each element type.

The finished manual will serve as a tool for ERS inspectors for the recommended 5-year interval inspections recommended by NCHRP. More frequent inspections may be triggered by: Walls performing poorly, environmental settings, age, consequence of failure, natural events, and condition.

5. RISK ASSESSMENT OF THE TALL I-696 RETAINING WALL SYSTEM

5.1 Introduction

The construction of highways in dense urban areas and in challenging terrain has increased the need for retaining walls. In the United States alone, more than 160 million square feet of new wall area is constructed every year within the national highway and road network (FHWA, 2008). This results in massive inventories of retaining wall structures requiring asset management including management of their risk of failure. The transportation asset management program is integral to the Moving Ahead for Progress in the 21st Century Act (MAP-21) which requires transportation agencies to adopt risk management strategies for all highway structures inclusive of retaining walls (FHWA, 2014). While risk management methods have been extensively studied for bridge structures, comparatively less research has focused on risk management methods for retaining walls. There has been recent interest in risk assessment of geotechnical assets in recent years. For example, a recently completed report by the National Cooperative Highway Research Program (NCHRP) describes the need for geotechnical asset management (GAM) (Vessely et al., 2019). The NCHRP report lays out frameworks for highway officials to begin planning for an implementation of GAM strategies inclusive of when to adopt monitoring; however, the report's aim was to offer a qualitative framework for GAM planning and not to provide details on how to execute specific GAM plans.

Visual inspection is the first step toward developing risk-based asset management methods for retaining wall systems. Visual inspection can provide a basis for assessing the physical condition of a retaining wall system. It can also provide insight to the movement and deformation of both the retaining wall structure and the geotechnical system it supports. While these qualitative observations can lead to a deeper understanding of how the system is behaving, a quantitative risk assessment is difficult to perform using visual observations. Hence, a fundamental question is how to go from visual inspection information (VII) to an assessment of the risk of failure of a retaining wall system (Figure 5.1a). Structural monitoring can serve as a powerful augmentation to visual inspections offering *quantitative* data on the performance to the retaining wall system (Figure

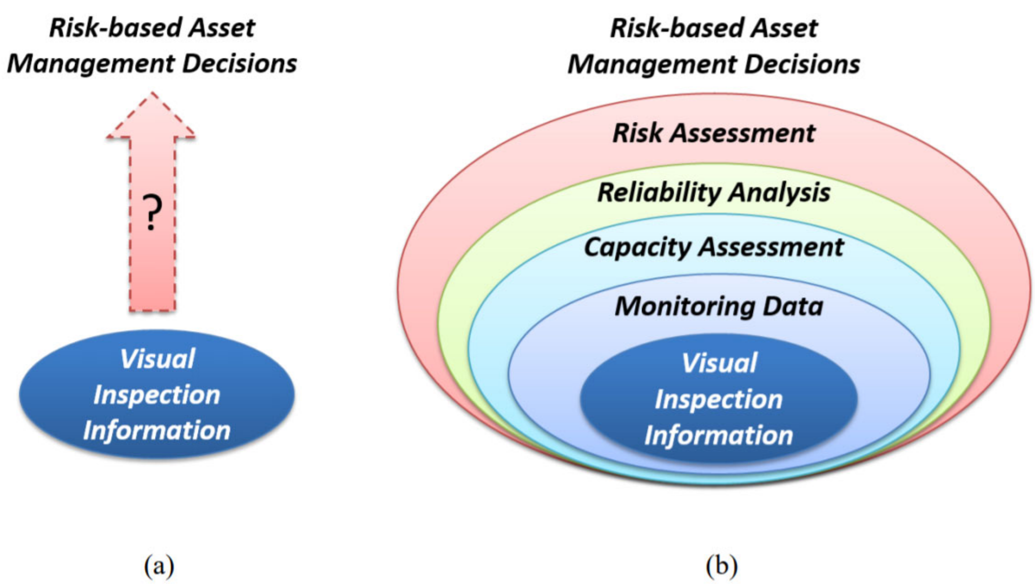


Figure 5.1. Illustrations of how to go from visual inspection to risk-based asset management: (a) current state of practice; (b) proposed approach of using monitoring data to inform quantitative reliability and risk assessments (Source: O'Conner, 2015).

5.1b). Specifically, structural monitoring systems can be installed to assess retaining wall response to loads including lateral earth pressures from permanent, temporary and cyclic loads and temperature loads. Sensors can also be installed in a retaining wall backfill to measure pressures, moisture and other factors critical to the load imposed on a retaining wall system. Monitoring data combined with visual inspection information allow load demands on the wall to be quantitatively assessed. Evidence of the performance of in-service retaining walls from monitoring data can also help identify changes in design assumptions and boundary conditions that affect the structural capacity of the system (Admassu et al., 2019). Estimates of the load demand and structural capacity derived from monitoring data and visual inspection information can then be used to calculate the reliability of the retaining wall (*i.e.,* the probability of the retaining wall system exceeding a defined performance limit state). Finally, risk is simply the product of the probability and consequences of exceeding the defined limit state.

In this chapter, a data-driven risk assessment methodology based on long-term monitoring data and visual inspection information is described. The risk assessment method developed complements the GAM risk planning framework proposed in Vessely et al. (2019) but is significantly more quantitative due to its reliance on structural monitoring data. The risk assessment method relies on measured wall responses to estimate the loads imposed (*e.g.*, backfill earth pressures, thermal). The loads estimated from the instrumented wall response data are then applied to a structural model to assess the load effect on the wall behavior. Visual inspection information is also used to inform assumptions necessary to assess the structural capacity of the instrumented wall. Assuming normally distributed load and capacity parameters, the first order reliability method (FORM) is adopted to assess the probability of the wall response exceeding a defined limit state in the form of a reliability index, β. Combined with a qualitative (*e.g.,* high, medium, low) or quantitative (*e.g.,* cost of damage and repair) definition of the consequences of exceeding the limit state (*e.g.,* wall failure), the risk of a wall system can be ascertained. In this chapter of the project report, the data-driven risk assessment method is developed specifically for the tall I-696 wall system using the long-term monitoring data previously presented. While the method is presented specific to one wall system, it can be generalized and easily applied to almost any other GAM application. The chapter concludes with a summary of key study findings and a description of the future work needed to advance the risk assessment framework for retaining wall systems.

5.2 Risk Assessment Framework

The risk assessment framework proposed herein is summarized in Figure 5.2. It relies on three primary sources of information: structural drawings/design documents, visual inspection information, and measurement data. Structural drawings are essential for detailing the structural design of the retaining wall system, construction sequencing, and backfill soil properties. This information is essential for building a mechanics-based model (*e.g.*, finite element method model) of a retaining wall and identifying the appropriate limit states of the structural materials (*e.g.*, yield strengths). Visual inspections carried out by inspectors guided by the Michigan Earth

Retaining Structure Element Inspection Manual offer detailed information on structural conditions including the physical condition of primary and secondary structural elements. Visual observations and inspector assigned condition states (or condition ratings) offer insight to the health of the structure and inform an understanding of the capacity of the wall. For example, visually identified section loss, structural corrosion, and the weakening of boundary conditions may imply a reduced system

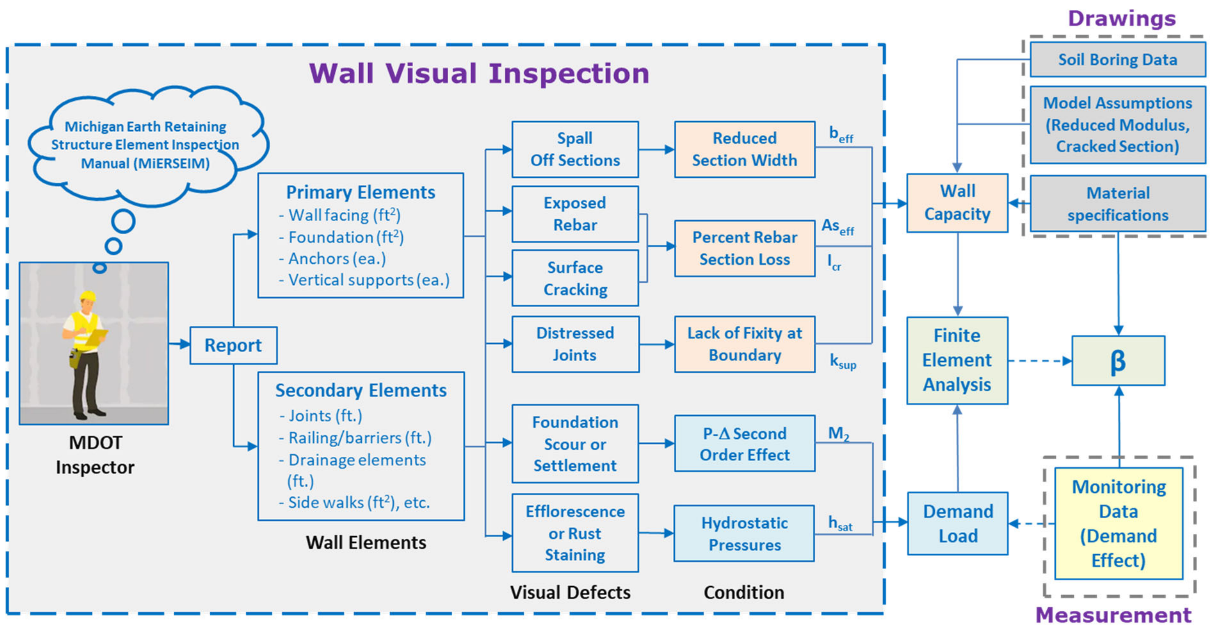


Figure 5.2. Proposed risk assessment framework for retaining wall structures.

capacity. Visual inspection can also uncover load demands not accounted for in design (*e.g.*, excessive tilts leading to second order P-Δ effects). Different from visual inspection, monitoring systems offer data associated with wall responses to loads. This data can be used to estimate the various loads imposed on the retaining wall and be vital to modeling changes in system capacity.

The risk-based method proposed in this section is based on quantitative calculation of the reliability of the retaining wall structure. The limit state established in the reliability analysis is the design limit state such as the yield stress of reinforcement bars or crack widths in the concrete wall. Reliability is a measurement of the probability of exceeding the defined limit state function, $G(\mathbf{X})$, where $\mathbf{X}$ is a vector of random variables that are the inputs to limit state. Given the load demand (D) and structural capacity (C) of the wall system, the limit state function is the difference between capacity and demand:

$$G(\mathbf{X}) = C - D \tag{5.1}$$

Failure is equivalent to $G(\mathbf{X}) < 0$ and can be defined more precisely as

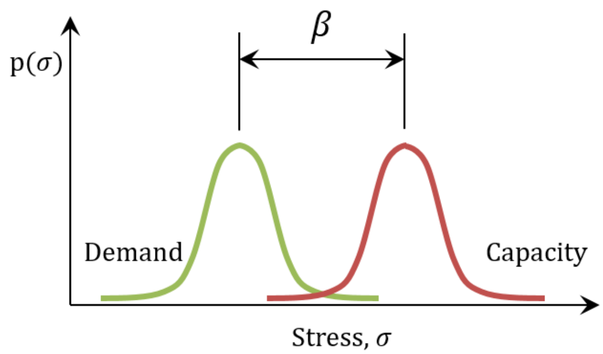


Figure 5.3. Illustration of demand and capacity distributions in relationship to the reliability index, β.

$$P_f = \int_{G(\mathbf{X})<0} f(\mathbf{X})dX \tag{5.2}$$

where $f(\mathbf{X})$ is the joint probability density function of **X**. The reliability index, β, is a scalar value defined as the input to the cumulative density function, Φ, to equate it to the probability of failure:

$$P_f = \Phi(-\beta) \tag{5.3}$$

The reliability index is a widely used parameter that defines the margins of safety in design codes. For example, load resistance factor design (LRFD) codes such as those adopted by AASHTO are designed to attain a reliability index of 3 or greater in most structural components.

When the random variables defining the load effect and capacity are assumed to be normally distributed, the first order reliability method (FORM) can be conveniently adopted to calculate the reliability index via a closed form solution,

$$\beta = \frac{\mu_C - \mu_D}{\sqrt{\sigma_c^2 + \sigma_D^2}} \tag{5.4}$$

where μ_C is the mean capacity, $\mu_D$is the mean demand (load effect), and σ_c and σ_D are the standard deviations on the capacity and demand distributions. Figure 5.3 provides a graphical interpretation of the reliability index where β is a measure of how far apart the demand and capacity means are normalized by the square root sum of their variances.

Often, the system capacity and demand are stated as stress values in critical components of the structure with capacity described by the yield limit state of the materials used. As a result, the demand side of the reliability analysis is based on estimation of the stress response (or load effect) of the critical component. In design, the load effect on the structure is based on assumed statistical models of the worst case loading that the structure may experience over its complete life cycle. In risk assessments of the structure, the load effect is what is actually measured over the life cycle of the structure. In many instances, the load effect cannot be directly measured. In these cases, analytical models describing the structure are used to convert measured responses to a distribution of the stresses pertinent to the reliability analysis. Long-term monitoring data collected from retaining walls can be used to estimate the loads imposed on the structure. Load estimates can then be used to derive a statistical model of the load effect in a defined critical structural element or structural detail.

After the reliability of the structure is established, a risk assessment can be performed. The reliability analysis offers the probability of exceeding a defined limit state such as the point where materials begin to yield. This probability of failure, P_f, can be combined with the consequence of failure, $C_\$$, to estimate the risk, R:

$$R = P_f * C_\$ \tag{5.5}$$

The consequences can be described in the form of monetary costs such as the cost of system repair or the cost of damage to other physical assets. Also included in the cost can be opportunity cost (such as the cost of road closures) and that of human life (based on an equivalent cost per each life lost). The risk assessment can consider a total number of events, n_E, of exceeding a limit state, $P_{f,E}$:

$$R = \sum_{i=1}^{n_E} R_{E_i} = \sum_{i=1}^{n_E} P_{f,E_i} C_{\$,i} \tag{5.6}$$

5.3 Reliability of the I-696 Tall Wall

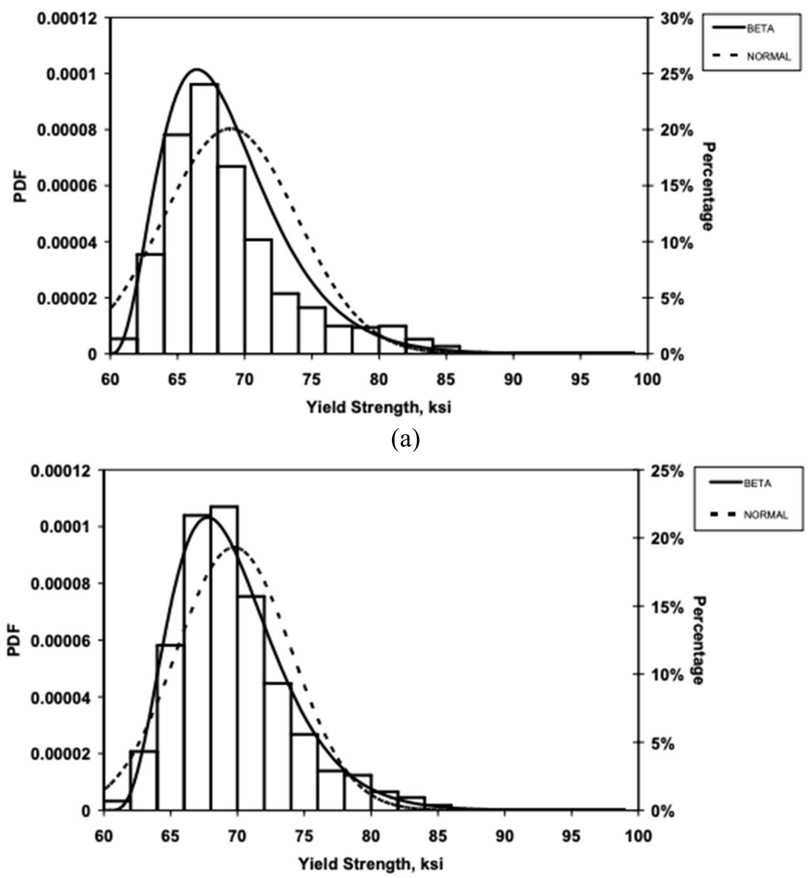
To highlight the general process of the risk management approach proposed, the tall I-696 retaining wall system was considered in this project. The tall I-696 wall was designed as a cantilever wall. The wall was inspected by the project team in 2017 to assess its general structural condition. Based on that field investigation, the wall was considered to be in very good structural condition with some surface cracking evident on the front side of the wall. Specifically, vertical cracking was observed at the horizontal midpoint of the wall panel, especially at the wall base. Some distress was observed at the panel joints with relative displacement evident between the tall I-696 wall panel and adjacent panels. Especially noticeable was water drainage from the bottom of the wall with water coming from the joints between adjacent panels as well as from holes in the wall associated with the form work used during construction. Water drainage was evident year round, even during relatively dry summer periods. In addition to the drainage at the base of the wall, the backside of the wall also illustrated distress with significant distortion of the sidewalk at the top of the wall backside. Specifically, the team observed sidewalk panels sinking down 3” to 6” near the tall wall panel. Due to the presence of a manhole cover associated with a buried water pipeline system behind the wall, it was hypothesized that the pipeline system might be failed allowing backfill to enter the system resulting in the loss of backfill volume over time.

Continuous drainage at the wall base suggested the wall backfill is saturated with water. With the cantilever wall experiencing tension on the wall backside, flexural cracks on the wall backside may expose the steel reinforcement to water. The steel reinforcement on the wall backside is standard steel (*i.e.*, not epoxy coated) and has a 3" cover (see Figure 3.2). The steel reinforcement was suspected of having some form of corrosion and possible section loss, thereby reducing the flexural capacity of the wall. In this study, the base of the cantilever wall at its connection to the wall system footing was considered as the critical wall section experiencing maximum flexural load (*i.e.*, maximum moment). The limit state was considered to be the yield strength of the vertical steel reinforcement on the wall backside.

As previously described, the wall was instrumented in August 2018 with tilt sensors installed at the wall mid-height and top. In addition, long-gage strain sensors were installed at the mid-height and bottom of the wall (along with temperature sensors at each strain sensor locations). The wall was monitored from the end of August 2018 to the end of October 2019 offering over a year's worth of response data for the data-driven risk assessment method. The stress in the steel reinforcement was not monitored but the tilt and strain measurements from the wall front side were used to estimate the stress in the tensile steel reinforcement under assumed states of reduced capacity due to corrosion of the steel reinforcement.

5.3.1. *Steel Reinforcement Capacity*

The vertical steel reinforcement on the backside of the retaining wall was considered to be the critical structural element that would control the wall overall reliability. As a result, the steel reinforcement yield stress was defined as the limit state of primary interest; exceeding the yield stress would constitute "failure" of the wall system. The steel reinforcement yield strength was not specified in the structural drawings; however, structural design codes in use at the time of the wall design would prescribe Grade 60 structural steel for the buried reinforcement. While Grade 60 steel has a nominal yield strength of $f_y = 60\, ksi$, it must be defined probabilistically to account for variations in material properties. Bournonville et al. (2004) has probabilistically modeled the properties of Grade 60 structural reinforcement steel based on extensive experimental testing. While ASTM A615 Grade 60 reinforcement steel best follows a beta distribution, a normal distribution is deemed to be a fair representation. Grade 60 steel reinforcement is manufactured to have a minimum yield stress of 60 ksi but in reality it will have a higher mean yield stress. For example, #6 and #9 reinforcement steel bar sizes have mean yield strengths of approximately 69 ksi (Bournonville et al. 2004). The standard deviation was estimated to be approximately between 4.3 and 5.0 ksi. Figure 5.4 presents the histograms and probability density functions (beta and normal) for ASTM A615 Grade 60 reinforcement for bar sizes #6 and #9. In this study, the yield strength of the tensile steel reinforcement was assumed to be a normal distribution with a mean at 69 ksi and standard deviation of 5 ksi.



(a)

(b)

Figure 5.4. PDF of Yield Strength of ASTM A615 Grade 60 Steel Reinforcement Bars: (a) Size #6; (b) Size #9 (Bournonville et al. 2004).

5.3.2. *Effect of Corrosion*

Failure of retaining walls due to the corrosion of steel components has been observed in the past. For example, panels of the M-10 retaining wall system in Detroit failed due to corrosion of tieback rods linking a section of the wall system to their caisson elements (MDOT 2013). Inspection of the failed wall panels found moisture ingression through the horizontal cracks that developed at the interface between the bottom of the wall and the footing. The moisture originated from a leaky water pipeline in the backfill. The water also led to the tieback cross section being so corroded that it failed. Evidence of continuous drainage at the base of the tall I-696 wall suggested a potentially corrosive environment that has the potential to reduce the size of the steel reinforcement. It was hypothesized that the loss of steel cross section reduces the capacity (as the subsequent study revealed).

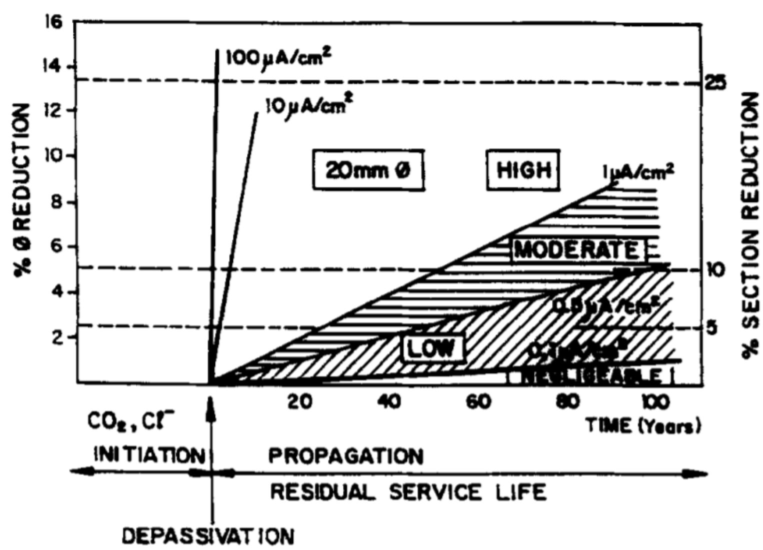


Figure 5.5. Percent section/diameter reduction for different corrosion activity ratings (Source: Andrade and Alonso, 1996)

The challenge with retaining walls is that is near impossible to assess if corrosion is occurring in buried steel on the backside of the wall without excavating the backfill. Should the backfill be excavated, a number of approaches are available for measuring the degree of corrosion in buried reinforcement including half-cell potential measurements (Elsener et al. 2003). These invasive methods (due to the need to connect to a reinforcement bar to serve as a working electrode) provide a measure of the potential of the concrete reported in voltage per copper sulphate electrode (CSE). Measured potentials can provide a guide for probability of corrosion activity in buried reinforcement. More recently, electroimpedance spectroscopy techniques have also been developed to assess the polarization resistance, R_p, of buried reinforcement based on four probes at the surface of the reinforced concrete structural element. The polarization resistance of the reinforcement bar, R_p, can be related to the corrosion rate, I_{cor}, of the steel reinforcement through Stern's law ($I_{cor} = B/R_p$) where B is Stern's constant (which is experimentally derived). Corrosion rate is most closely tied to corrosion activity and corresponding weight loss due to corrosion (with higher corrosion rates over time leading to greater weight loss of steel). Andrade and Alonso (1996) report on the loss of steel reinforcement bar section due to corrosion rate, I_{cor}, and time. Figure 5.5 presents a figure from Andrade and Alonso (1996) that graphically tabulates the percent section loss of buried steel reinforcement as a function of time since carbon dioxide and chloride ingress into the concrete and corrosion rate.

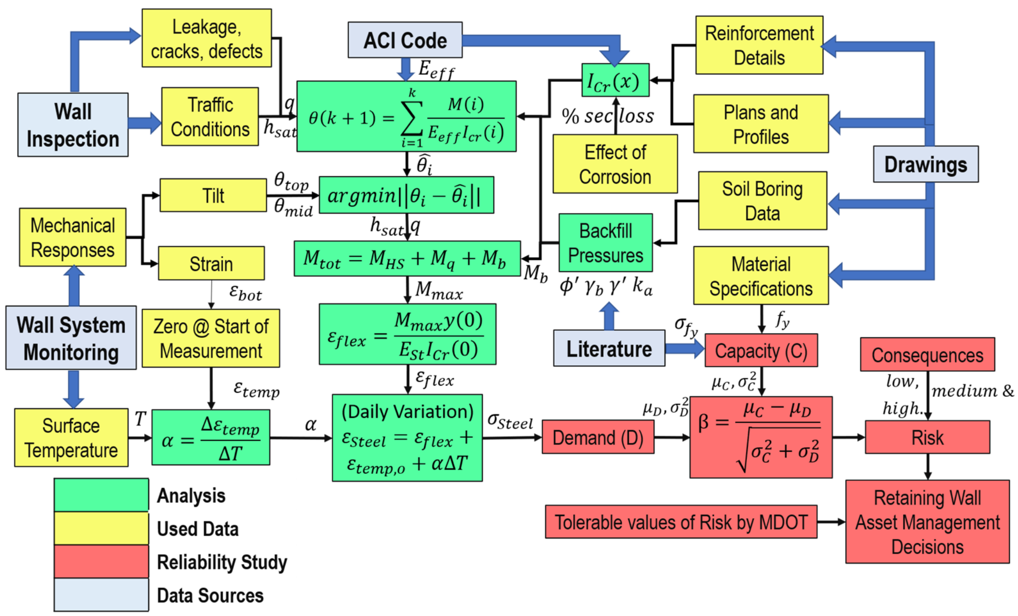


Figure 5.6. Overview of the reliability and risk assessment framework for the I-696 retaining wall system using tilt and strain measurements from wall front side.

Based on Figure 5.5, the age (33 years) of the I-696 wall panels suggested very little section loss under the assumption of low to moderate corrosion rates in the wall. If it is conservatively assumed that carbonation and chloride ingress occurred on the first day of construction and a moderate corrosion rate (*e.g.*, 0.5 $\mu A/cm^2$) exists, a section loss of 3% in the buried steel reinforcement was estimated using Figure 5.5. In this study, three states of buried vertical steel reinforcement were assumed given the uncertainty associated with the degree of corrosivity of the operational environment: 0, 10 and 20% section loss of the vertical steel reinforcement. The reliability of the tall I-696 wall panel was calculated for these three corrosion states.

5.3.3. *Strain Response Analysis*

The previous chapter described the data collected from the I-696 tall wall panel and the development of a discrete-element model that can be used to estimate the lateral earth pressures on the wall and to calculate deflection curves of the wall system. To perform a reliability analysis, the model previously developed (inclusive of material properties) was adopted for the tall I-696 wall panel. Material properties including the bulk and submerged weight of soil, friction angle, concrete effective elastic modulus, and steel elastic modulus are assumed to be deterministic in the

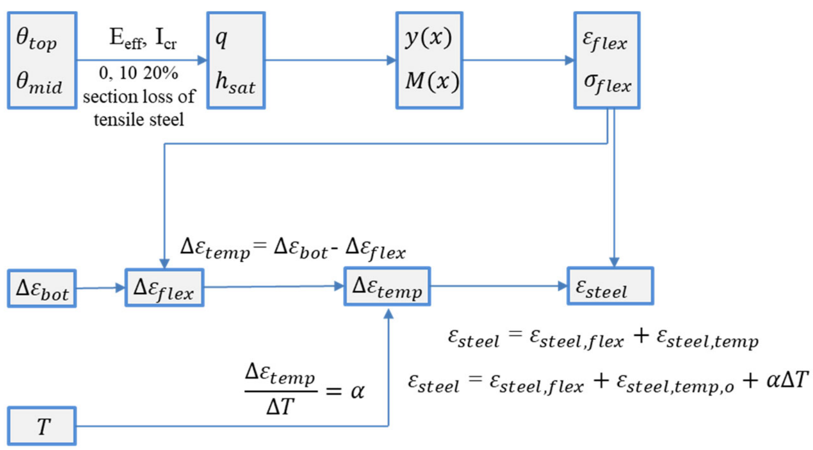


Figure 5.7. Load effect estimation from tilt responses

model. Future analyses could be made more sophisticated by treating all model parameters probabilistically. The reliability analysis framework adopted in this project for the tall I-696 wall system is summarized in Figure 5.6. More specifically, how the strain data will be processed from the front of the wall to estimate stress in the vertical steel reinforcement in the back of the wall is presented in Figure 5.7.

The wall system monitoring system provided tilt (θ), strain (ε) and surface temperature (T) measurements for more than a year of monitoring. The daily mean measurement of these wall responses were used to assess the loads imposed on the retaining wall system using the discrete element model previously described. Two specific loads were considered in the analysis: lateral earth pressures (resulting from a surface surcharge and saturation of the soil) and thermal loads associated with the temperature of the wall. Tilt measurements are not influenced by axial expansion of the wall due to thermal loads; this allows tilt measurements to be used to isolate the flexural behavior of the wall including the flexural strain in the steel reinforcement, $\varepsilon_{steel,flex}$, in the critical zone at the base of the wall.

The surcharge and hydrostatic pressures were defined based on the surcharge load, q, and the height of backfill soil saturation, h_{sat}. As previously described, the wall tilt can be used to estimate these load parameters by minimizing the error between the measured wall tilt and that estimated by the discrete element model:

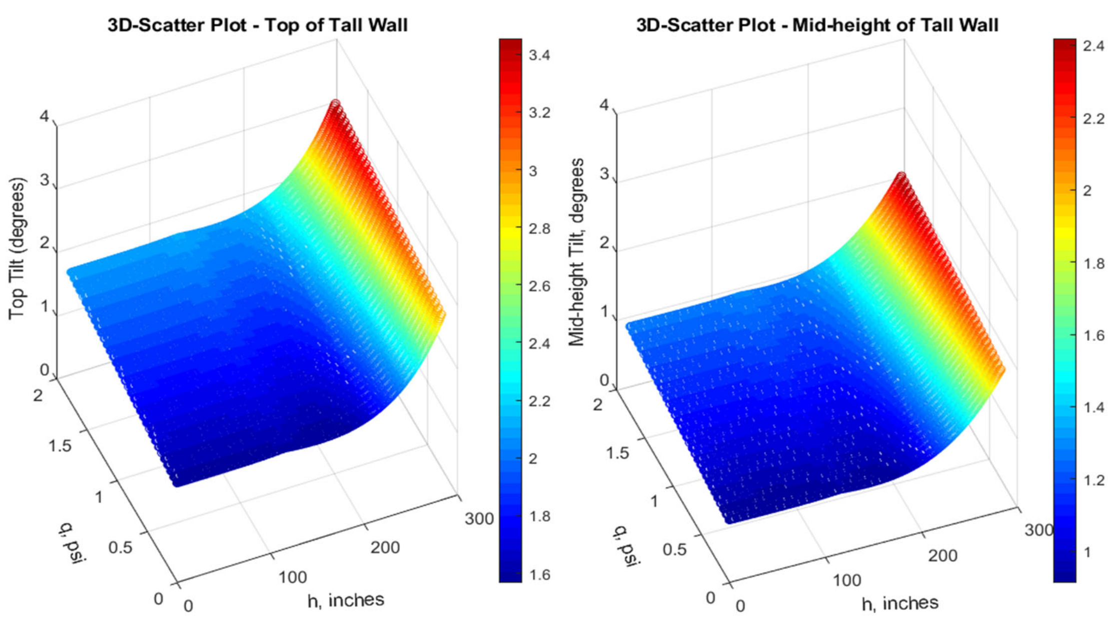


Figure 5.8. Top and mid-height tilt for tall I-696 wall panel assuming no corrosion for variations in surcharge load, q, and water saturation level, h_{sat}.

$$\underset{q,h_{sat}}{argmin}\|\theta_{meas}-\theta_{model}\| \tag{5.7}$$

Equation 5.7 was solved by use of a look-up table of pre-calculated top and mid-height tilts for a range of surcharge pressures ($q \in \{0,1.74\}\,psi$) and water saturation levels ($h_{sat} \in \{0,282\}\,in$).

Figure 5.8 shows how tilt (θ_{top} and θ_{mid}) changes under different load parameters (q and h_{sat}) for the case of no rebar corrosion. Hydrostatic pressure clearly dominates the tilt response of the wall as compared to top surface surcharge; moreover, tilt angles rise exponentially at higher levels of saturation in the backfill soil.

Provided the optimal surcharge load, q, and height of backfill saturation, h_{sat}, estimated for each daily set of tilt measurements, the flexural moment applied to the cantilever wall, $M(x)$, was calculated using the methodology shown in Figure 5.7. The total bending moment acting on the cantilever wall at a height of element k, $M(k)$, was the superposition of bending moments from hydrostatic, $M_{HS}(k)$, surcharge, $M_q(k)$, and backfill, $M_b(k)$, pressures:

$$M(k) = M_{HS}(k) + M_q(k) + M_b(k) \tag{5.8}$$

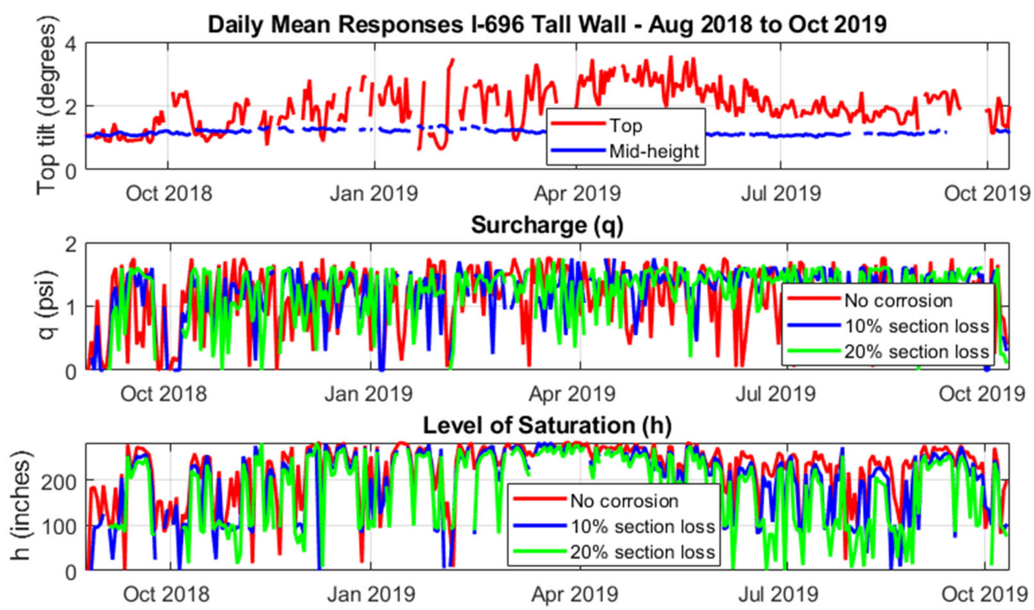


Figure 5.9. Daily mean response of tilt and estimation of surcharge load, q, and water saturation level, h_{sat}, based on tall wall tilt measurements over one year of monitoring. Three states of steel section loss of the tensile reinforcement considered: 0, 10 and 20%.

Using the discrete-element model, the flexural moment on the wall allowed the flexural strain to be estimated everywhere in the wall system. For example, it was used to estimate the flexural strain in the front face of the wall where strain is actually measured: ε_{flex}. It was also used to estimate strain in the vertical steel reinforcement on the backside of the wall at the controlling section (namely, at the wall-footing interface zone): $\varepsilon_{steel,flex}$. This was the load effect on the steel reinforcement bars experiencing axial tension due to the backfill earth pressures. Using the steel elastic modulus ($E_{st} = 29x10^6\ psi$), stress in the steel reinforcement due to flexural response can be calculated:

$$\sigma_{steel,flex} = E_{st}\varepsilon_{steel,flex} \quad (5.9)$$

It should be noted that this approach to inverse modeling to estimate the lateral earth pressure loads (q and h_{sat}) was reliant on the discrete element model and its material and geometric assumptions.

Figure 5.9 shows the estimated time series of surcharge and water saturation levels obtained using the tilt measurements at the top and mid-height of the tall wall system. The analysis was performed for the three assumed corrosion states: 0, 10 and 20% section loss in the

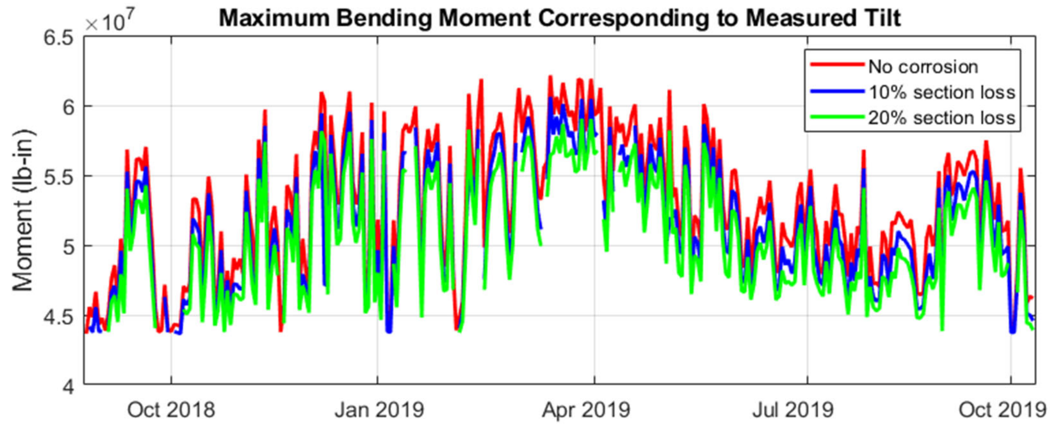


Figure 5.10. Daily maximum bending moment variation at the base of the wall for three states of assumed corrosion in the tensile steel reinforcement.

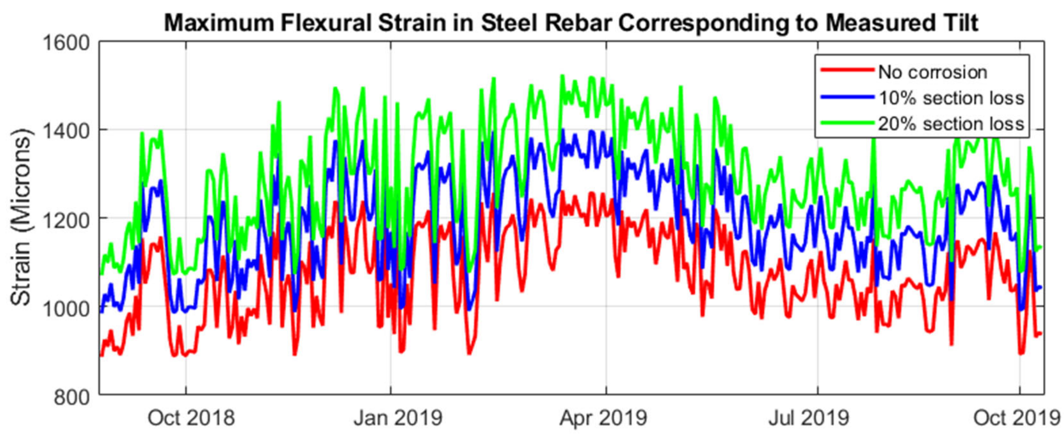


Figure 5.11. Vertical steel reinforcement strain at the base of the wall backside due to flexural moment.

steel reinforcement on the backside of the wall. The analysis was performed for each corrosion state because changes in the area of steel reinforcement in the wall cross section altered the location of the section neutral axis resulting in three different models for estimating the lateral earth pressures behind the wall. Figure 5.10 shows the calculated total bending moment at the wall base for the three corrosion states. Figure 5.11 shows the calculated flexural strain, $\varepsilon_{steel,flex}$, in the backside steel reinforcement due to the estimated moment for the three corrosion states.

The strain measurements collected from the front face of the tall wall were influenced by both flexural moment (*i.e.*, strain associated with flexural bending) and temperature (*i.e.*, axial strain). An illustration of this is shown in Figure 5.12. During the summer when the wall is warm, the wall experiences expansion which is axial tension; during the winter it contracts creating axial compression. With estimated flexural strains estimated by the model, the strain response of the wall due to the thermal load environment can be obtained. Unlike tilt which is an absolute measurement, the strain measurements at the bottom of the wall represent change in strain since the start of measurement: $\Delta\varepsilon_{bot}$. Given the estimates of ε_{flex}at the point of the strain measurement, the change in strain due to flexure, $\Delta\varepsilon_{flex}$, since the start of the measurement of strain was calculated. Hence, the change in strain associated with temperature, $\Delta\varepsilon_{temp}$, can be found by subtracting the estimate of $\Delta\varepsilon_{flex}$ at the bottom of the wall (at the point of strain measurement) from the measurement itself, $\Delta\varepsilon_{bot}$:

$$\Delta\varepsilon_{temp} = \Delta\varepsilon_{bot} - \Delta\varepsilon_{flex} \quad (5.10)$$

The change in strain due to temperature was plotted as a function of wall surface temperature shown in Figure 5.13. The plot is for changes between sequential daily measurements. The thermal expansion coefficient, α, obtained was 1.89 με/°F which was close coefficients documented in the literature for reinforced concrete (which are 3 to 6 με/°F) (Berwanger and Sarkar 1976).

Axial strain in the wall due to temperature was assumed uniform across the wall section. Hence, the $\Delta\varepsilon_{temp}$ at the front of the wall was considered as the same as the thermal induced strain in the steel reinforcement in the wall backside. The strain in the steel reinforcement on the wall backside was equal to the residual strain at the start of measurement, $\varepsilon_{steel,temp,o}$, plus the change in strain due to temperature change, ΔT, relative to the first day of measurement (when T =80°F). This was used to calculated thermal stress in the reinforcement:

$$\sigma_{steel,temp} = E_{st}\varepsilon_{steel,temp} = E_{st}\left(\varepsilon_{steel,temp,o} + \alpha\Delta T\right) \quad (5.11)$$

The residual strain in the reinforcement due to thermal behavior in the past (*i.e.,* prior to monitoring) is unknown. The temperature of the concrete at the time of casting was assumed to be approximately 50 °F; compared to the start of monitoring when the wall temperature was 80 °F, the thermal coefficient estimated for the tall I-696 wall system was used to calculate the thermal residual strain $\varepsilon_{steel,temp,o}$ which was 56 με in tension.

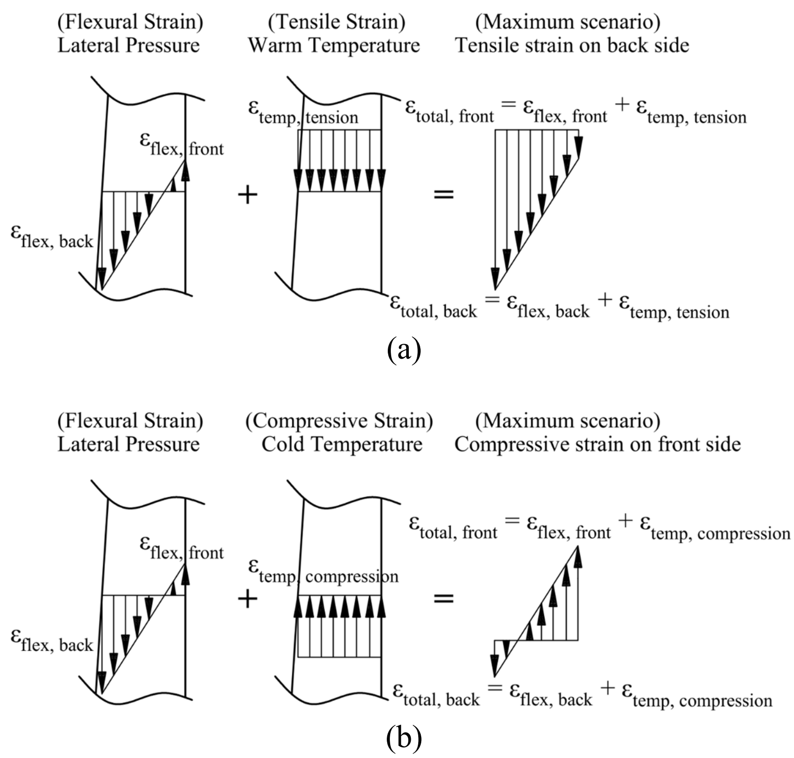


Figure 5.12. Strain profiles on the I-696 tall and short walls at different seasons of the year: (a) During Spring and Summer seasons where the temperature gets warmer; (b) During Fall and Winter seasons where the temperature gets colder.

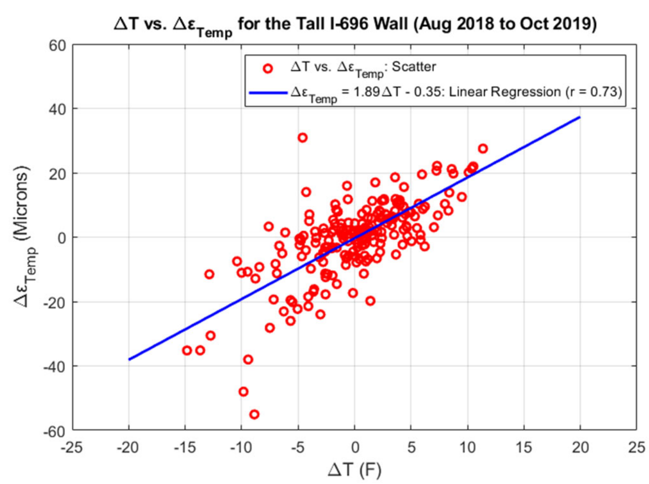


Figure 5.13. Scatter plot showing wall strain response to thermal load versus change in temperature is linear.

5.3.4. *Reliability Analysis*

Using the methodology previously described, the daily mean wall response was used to estimate the flexural and thermal strain in the vertical steel reinforcement bars on the backside of the tall I-

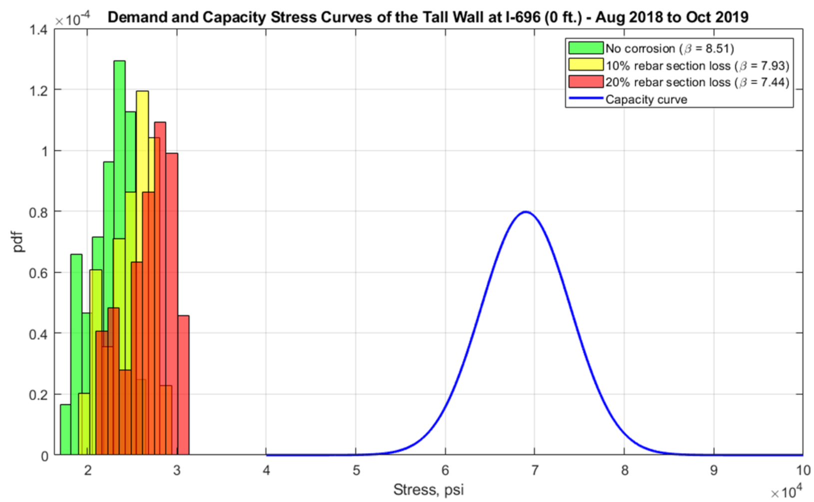


Figure 5.14. Histograms of estimated vertical reinforcement steel tensile stress compared to probabilistic model of steel reinforcement yield stress.

696 wall. The total strain was then used to estimate the total tensile stress in the reinforcement. The analysis was performed for each day of measurement using the daily mean tilt and strain responses. The total stress time series for the three corrosion states were used to create histograms of the stress in the vertical steel reinforcement at the wall base on the backside of the wall. The histograms for the three corrosion states are plotted along with the probabilistic model of the steel reinforcement yield strength as shown in Figure 5.14.

The histograms of the total steel stress were far below that of the probabilistic model of the steel yield stress. The histograms of the estimated steel stress for the three corrosion states were treated as if they were normally distributed with their mean and standard deviations calculated. The closed form expression for the reliability index (Equation 5.4) was then used to estimate the reliability of the wall system. The mean and standard deviations of estimated stress in the steel reinforcement at the base of the wall along with the mean and standard deviation of the yield strength of the steel were used to estimate the reliability index, β. Assuming no loss of rebar section due to corrosion, the reliability index was calculated to be 8.5; assuming 10% and 20% section loss, the reliability index reduced to 7.9 and 7.4, respectively. These reliability index values provide a robust margin of safety for the wall, suggesting the wall has a low probability of failure. It should also be noted the reliability indices obtained from monitoring data are far above those intended during the design process ($\beta \approx 3$).

Table 5.1. Updated FHWA condition ratings to include the reliability index (β_i) thresholds that bound corresponding condition rating codes.

(1) Code	(2) Condition Description	(3) % Section Loss	(4) Condition	(5) Qualitative Note	(6) Cost
9	Excellent	0 %	$\beta \geq \beta_9$	No problems noted	C_9
8	Very Good	+	$\beta_9 > \beta \geq \beta_8$	No problems noted	C_8
7	Good	Superficial	$\beta_8 > \beta \geq \beta_7$	Some minor problems	C_7
6	Satisfactory	Damage	$\beta_7 > \beta \geq \beta_6$	Some minor deteriorations	C_6
5	Fair	(0%, 5%]	$\beta_6 > \beta \geq \beta_5$	Minor sec. loss, cracking, scour	C_5
4	Poor	(5%, 10%]	$\beta_5 > \beta \geq \beta_4$	Advanced sec. loss, deterioration	C_4
3	Serious	(10%, 20%]	$\beta_4 > \beta \geq \beta_3$	Loss of sec., seriously affected elements	C_3
2	Critical	(20%, 50%]	$\beta_3 > \beta \geq \beta_2$	Adv. deterioration/s of elements	C_2
1	"Imminent" Failure	(50%, 70%]	$\beta_2 > \beta \geq \beta_1$	Major deterioration/s that need closing of road	C_1
0	Failed	(70%, 100%]	$\beta_1 \geq \beta$	Out of service	C_0

5.4 Risk Assessment

Risk assessment considers the reliability index (providing the probability of exceeding a defined limit state) and the consequences associated with exceeding the limit state with risk is simply the probability times the consequence of exceeding the limit state. Prior work by Flanigan et al. (2019) has established the concept of "lower" limit states that can be defined below the probability of failure and that correspond one-to-one to condition ratings. In other words, there is an equivalency between condition rating (given by an inspector) and the reliability index estimated from monitoring data. The work of Flanigan et al. (2019) has revealed the key for corrosion-based deterioration is attributing the percent section loss to reliability index thresholds as shown in Table 5.1. Table 5.1 utilizes the 9-point condition rating scale with its associated condition description (column 2) and qualitative note (column 5) (FHWA, 1995). However, added is a qualification of the percent section loss (column 3) tolerable under each condition rating. Section loss of structural elements is already considered by visual inspectors when performing condition ratings for bridge elements. Table 5.1 provides a proposed set of percentage section loss of steel reinforcement for the tall I-696 wall that is consistent with existing qualitative description of section loss tolerated

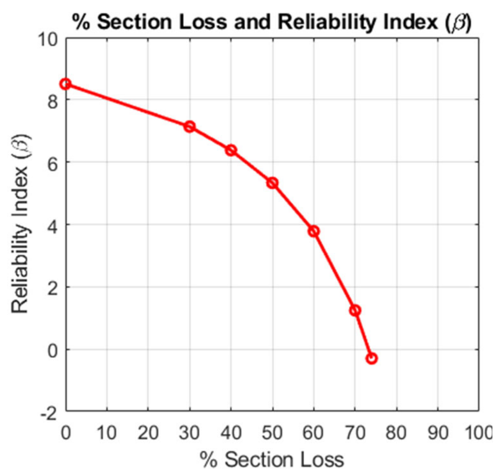


Figure 5.15. Reliability index values for varying levels of section loss in the tall I-696 retaining wall panel backside vertical steel reinforcement.

in existing condition ratings. With some qualitative description of section loss, the reliability index thresholds can be considered (column 4). For example, if a condition rating if 6 corresponds to uncorroded steel reinforcement, under assumption of a fully saturated back fill with the AASHTO code specified surface surcharge (1.74 psi), β_6 would then be 8.51 for the tall I-696 wall panel. For condition rating 3, assuming 20% section loss of the reinforcement, this would establish a reliability threshold of β_3 of 7.2. Figure 5.15 provides the reduction in reliability index for each percent section loss of vertical steel reinforcement. This can be useful for rationally establishing the beta thresholds and the tolerable degree of section loss that can be considered. Once a condition rating is assigned, the retaining wall manager must make a decision on what to do; namely, to repair or not. There are costs to the actions taken triggered by the condition rating (or estimate reliability index, β). These costs can be used along with the reliability indices (which now provide a probability of exceeding a condition rating reliability index threshold) to calculate risks associated with post-inspection decision making.

An alternative approach in the short term, is to simply bin the reliability index into three reliability categories: high, medium, low with low meaning low reliability or a higher probability of failure and high meaning high reliability or a low probability of failure. For example, two thresholds can be established by the asset manager for a given retaining wall type: β_{low} and β_{high}. For example, β_{low} could be selected to link to condition rating 1 and 0 while β_{high} could be selected to link to condition rating 6 and higher.

Table 5.2. Red-yellow-green (R-Y-G) risk categories mapping reliability index (β) values with consequence of failure event

Reliability Index	Consequences		
	Low	**Medium**	**High**
$\beta > 3$			
$2 < \beta < 3$			
$\beta < 2$			

Table 5.3. Consequence Categories for Highway Retaining Wall Structures (Theme of Table Adopted from: (M. Imam et al, 2012))

Consequence Categories	Consequence Examples
Human	○ Fatalities and injuries ○ Psychological damage ○ Inconvenience (affected utility lines, road closures, stranded state, etc.)
Economic	○ Replacement/repair costs and loss of functionality/downtime ○ Traffic delay, traffic re-routing and traffic management costs ○ Clean up costs (backfill soil falling on ramp or freeway lanes, etc.) ○ Regional economic effects and loss of production/ business ○ Investigations/compensations and infrastructure interdependency costs
Environmental	○ CO_2 emissions and energy use ○ Pollutant releases (from sewerage lines)
Social	○ Loss of reputation (of the transportation agency in jurisdiction) ○ Erosion of public confidence ○ Undue changes in professional practice

Similarly, consequences can be defined as high, medium and low allowing Table 5.2 to guide asset management decisions. In this approach, the reliability index is purely quantitative but the consequences would be described more qualitatively. These consequences would be associated with the cost of failure of the retaining wall asset. High levels of judgement would need to be given to define specific costs, especially for some of the less tangible consequences such as social consequences (*e.g.*, inconvenience, loss of reputation, erosion of public confidence, psychological damage) and loss of human life which is invaluable. Table 5.3 provides an overview of the different consequence types one can consider. All of these consequences could be weighed when assigning for each asset being managed to a low, medium and high consequence category. In the case of the tall I-696 wall monitored in this study, its structural function of supporting a two-lane highway (Eleven Mile) above an eight lane freeway (I-696) in a high volume traffic region (i.e., metropolitan Detroit), this wall would mean high consequences if it failed including closure of Eleven Mile, closure of the I-696 ramp, and potential partial or full closure of eastbound I-696. Given the high reliability ($\beta > 7$) but high consequences, Table 5.2 would classify this asset as "yellow" indicating more vigilant observation by visual inspection.

6. CONCLUSIONS – RECOMMENDATIONS

6.1 Conclusions

The implementation of a long-term, wireless and unattended monitoring solution for cantilever and caisson supported RC retaining walls (located in the Detroit metro region) was presented. The monitoring solution comprised of tilt-sensors, strain sensors and thermistors to measure wall panel tilt, compressive strains and wall temperatures, respectively. To detect very small responses in the walls, the sensors were selected to have extremely low noise floors offering high measurement resolutions (0.01° in tilt angle; 2με in strain and 1 °F in temperature). The monitoring systems installed on the I-696 and M-10 panels performed well over a one-year monitoring period.

11 wireless sensor units were installed on the retaining wall systems along the I-696 (two wall panels) and M-10 (one wall panel) freeway corridors that collected a total of 16 measurements from the three wall panels. The tilt, strain and temperature of the wall panels were all collected to observe both the wall panel responses but also their thermal state. Data was collected for over one year allowing seasonal variations in the wall behavior to be observed. The long-term nature of the monitoring system deployments allowed the robustness of the sensors to be studied. The sensors installed on the tall I-696 and M-10 wall panels performed relatively well surviving the duration of the monitoring period; the long-term performance of the wireless sensors on the short I-696 wall panel were less robust. Issues observed during periods when the sensor nodes were serviced revealed issues associated with moisture penetration to the node enclosures and some power issues. None the less, the data collected from the tall I-696 panel and the M-10 panel were sufficient to perform a quantitative risk assessment of the walls.

The performance of the instrumented retaining wall systems was assessed using the data collected. Specifically, the wall panels exhibited strong dependence on environmental parameters, most notably temperature. In general, the cantilever wall system along I-696 exhibited higher drifts on its top sections as compared to the mid-height. The tall I-696 wall panel tilted as much as 3.5° while the mid-height maximum tilt was 1.45°. The top of the I-696 wall system was a parapet wall whose flexural rigidity was less than the lower wall portions and exhibited sensitivity to moisture in the form of precipitation. The lower portion of the wall system was less variable day-to-day and had a behavior much better correlated to temperature, most especially mid-height tilt and bottom strain. The wall experiences maximum flexural response during the cold winter with maximum mid-height tilt (1.4°) and compressive strain. The differences in behavior at the top and the bottom portions of the cantilever wall are significant because they inform a monitoring strategy for future wall studies. Specifically, should tilt be measured on an irregular basis (for example, manually) or regularly over a short period (say a few weeks or months), the maximum wall response may not be observed. The short-term variations of the wall tilt can be significant (such as the top of the I-696 wall); a more accurate view of wall behavior require at least one year of monitoring to see the full range of seasonal variations.

The short I-696 wall panel behaved in a manner comparable to the tall I-696 wall panel but exhibited more variation in tilt at its mid-height. This also goes to show the variations wall panels can exhibit under nearly identical environmental and backfill soil conditions. Hence, behavior at one panel may not necessarily serve as a fully representative sample of the adjacent panels along a highway corridor. Instrumentation of retaining wall panels will always be sparse given current cost of purchasing and installing instrumentation.

The M-10 wall system has a history of failing tie-backs on the north side of Schaefer Highway. In this study, a representative wall panel on the south side of the Schaefer Highway was instrumented. The wall panel had mild variation in its tilt measurements with top tilt varying from 1.1 to 2.0° and mid-height tilt varying from 0.2 to 0.7°. The tilt was correlated to temperature with cold temperatures pulling the lower portion of the wall towards the backfill and the upper portion thrusted outward away from the backfill. It was hypothesize this was a result of contraction in the soil pulling the tie-back caisson back and the lower portion of the wall with it. The active earth pressures above the tie-back would then push the unrestrained upper portion outward. This suggests the tie-rod is engaged and working as expected. Similar to the cantilever wall panels of I-696, the maximum flexural demand on the lower portion of the wall and maximum tension in the tie-rod is during the cold winter.

After all the investigation and data layout was finalized, the MiERSEIM could be developed. The format for the manual mirrors the Michigan Bridge Element Inspection Manual (MiBEIM) for it s familiarity. The manual begins with a Preface explaining the definition of the manual which is followed by an Introduction which explains the manuals purpose. A Detailed Element Description is included to define the information herein.

There are five main chapters to the Manual:

- Primary Elements – which describe the structural components of the ERS
- Secondary Elements – which describe the non-structural components of the ERS
- Scour Protection – which describes the scour protection devices for hydraulic ERS
- Appurtenances – which describe the attachments to the ERS
- Condition State Tables – which describe the deficiencies for each element type.

The finished manual will serve as a tool for ERS inspectors for the recommended 5-year interval inspections recommended by NCHRP. More frequent inspections may be triggered by: Walls performing poorly, environmental settings, age, consequence of failure, natural events, and condition.

Risk assessment methods have been widely studied for bridges, but comparatively less research has been focused on developing risk assessment tools for retaining walls. Most recently, some novel work has been completed in proposing risk assessment frameworks for geotechnical assets (*i.e.,* geotechnical asset management (GAM) planning). As Vessely et al. (2019) has concluded, GAM planning must include prescription of structural monitoring where appropriate. An aim of this project was the development of a risk assessment framework that utilized structural monitoring data to define the reliability of the retaining wall system. Combined with the consequence of exceed the limit state obtained from the reliability analysis, the risk of the asset can be determined. Quantifying risk in this way established for the first time, a clear pathway of using monitoring data within a broader GAM strategy. An especially valuable feature of the proposed risk assessment procedures was the explicit inclusion of visual inspection information to define structural conditions critical to the evaluation of structural capacity.

The risk assessment method was applied to the tall I-696 wall panel to illustrate its use. The long-term monitoring data from the wall panel, coupled with the discrete element model previously developed, were used to estimate wall loads. The thermal load was measured but the backfill earth pressure needed to be estimated by finding an optimal surcharge load, q, and level of soil saturation, h_{sat}, that predicted tilt measurements close to those measured. Provided the visually observed drainage from the lower portions of the wall, it was hypothesized that the uncoated vertical steel reinforcement bars may have experienced corrosion. Without a direct measure of corrosion state, three corrosion states were considered for the wall: 0%, 10%, and 20% section loss of the steel reinforcement. Tilt measurements provided a direct means of estimating the strain in the wall due to flexural bending. The strain measured on the front face of the wall was then used to isolate the thermal strain in the wall associated with the measured wall temperature. The thermal axial loading and flexural moment from the backfill were then used to estimate the load effect in the vertical steel reinforcement on the wall backside. Assuming normal distributions, FORM was used to estimate the probability of the wall exceeding the yield strength of the steel reinforcement under the different corrosion states (0%, 10% and 20% steel reinforcement section loss). Assuming no corrosion to the rebar, the reliability index was calculated as 8.5. Assuming 10% and 20% section loss, the reliability index reduced to 7.9 and 7.4, respectively. These reliability indices indicated an extremely low probability of exceeding the steel reinforcement yield strength. From a risk assessment perspective, the consequences of failure would be extremely high due to the fact that the I-696 wall system supports a very active two lane service road (Eleven Mile) at its top; in addition, failure of the wall would likely require closure of the eastbound I-696 Exit 11 (Evergreen Road). None the less, the low probability of failure implies the wall is a low risk asset.

6.2 Recommendations for Future Work

The research team collected images using a camera and then developed a 3D point cloud model through the Structure from Motion technique for one of the instrumented sections. This was outside the original scope of this project, however this example help demonstrates the possibilities for incorporating this type of data collection to the inspection procedure. Images can be collected using vehicle mounted cameras.

Another opportunity for future work, is to incorporate the data collected from monitored and/or instrumented retaining wall sections with other type of data, such as land use, local geology, lifelines, population density using a GIS based platform.

This study was intended to conceptually define a risk assessment framework for asset management of retaining walls using monitoring data. It could and should be further refined prior to adoption by transportation officials. Specifically, a more robust probabilistic assessment should be performed using the structural model including statistical modeling of all system properties (not just the yield strength of steel). For example, soil properties (e.g., dry and submerged weights, internal friction angles), concrete effective elastic modulus, and residual strain in the reinforcement require statistical models to define within the FORM analysis. Also, other critical limit states should be considered including crack width on the wall backside and overall deflections (to account for second order effects). Finally, future work should provide a more rational mapping between the condition rating and the loss of section that then would define the lower limit states (β_1 through β_9).

7. RECOMMENDED IMPLEMENTATION PLAN

7.1 List of products expected from research

The products of this research include a final report summarizing the research results from all the research tasks and presenting the development of a sensing strategy that can be used by structural inspectors to assess the coupled performance of the wall structure and the geotechnical system it supports, as well as a reliability framework using first-order reliability methods (FORM) to assess the reliability factor (β) for wall components. A new inspection manual was developed to reflect the instrumentation strategies and risk analyses. Training materials will also be provided for the training session targeting MDOT engineers, but also consultants working with MDOT. The final inspection manual has been provided in Appendix C and described in Chapter 4.

7.2 Audience for research results

The main audience for the research results includes MDOT's bridge designers, structural and geotechnical engineers and MDOT consultants. The extended audience can be other state DOTs and other government agencies involved in inspection and asset management for retaining walls. The deliverables from this project will significantly improve the ability to quantitatively, and within a risk-based framework, assess the performance and condition of retaining walls and reduce costs associated with the "worst-first" approach.

7.3 Activities for successful implementation

Successful implementation of the recommended procedures and new inspection manual was initiated through a training session by the research team for MDOT personnel who will be involved in relevant projects.

7.4 Criteria for judging the progress and consequences of implementation

The judging of progress was achieved by close supervision of the graduate student researcher, Mr. Kidus Admassu and post doctoral researcher involved in this research project, Dr. Athena Grizi, the field instruments installation, and the data analyses. Close collaboration with the subcontractor, Mannik & Smith allowed for consistent progress with the inspection manual. Regular meetings of the U-M based research team were made during the project to monitor progress and supervise the literature review and analyses. Additional meetings were also scheduled with Mannik & Smith senior engineers who worked on putting together the new inspection manual for retaining walls. An additional quality assurance and control of the research investigation will be implemented during submission of interim and final research publications in peer-reviewed scientific journals and conferences. This review process typically involves 2-3 independent reviews by researchers knowledgeable on the research topic.

7.5 Costs of implementation

The primary cost of implementation was the preparation of the final report and the preparation of the training session/s as needed for successful implementation of the final product of this research. This cost was included in the proposed budget.

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APPENDICES

A - 1 Materials from FHWA-NPS WIP (2010)

Field Inspection Form (Front Page)

-NPS RETAINING WALL INVENTORY PROGRAM (WIP) FIELD FORM-					
NPS Park Name		Route/Parking No.		Wall Start Milepoint	
Inspected By		Route/Parking Name		Wall End Milepoint	
Inspection Date		Side of Centerline	(R/L/P# #)	Visidata Event Milepoint	
WALL FUNCTION, DIMENSIONS, and DESCRIPTION					
Wall Function		Primary Wall Type		Architectural Facings	
Approx. Year Built		Secondary Wall Types		Surface Treatments	
Wall General Description Notes: *(e.g., wall purpose, setting, construction, consequence of failure, special design, etc.)*					
Wall Length (ft)		Wall Face Area (ft^2)		Wall Start Offset (ft)	
Max. Wall Height (ft)		Vertical Offset (+/- ft)		Wall End Offset (ft)	
Photo Description/No. *(e.g., approach, elevation, wall top, alignment, face detail, deficiencies, etc.)*				Face Angle (deg)	
Park Designated Wall ID					
REPAIR /REPLACE RECOMMENDATIONS AND WORK ORDER					
Wall Condition Rating		Design Criteria		Failure Consequence	
Investigation Req'd?	(Y/N)	Cultural Concern?	(Y/N)	Action	
Brief Work Order Description *(5-10 word maximum, key work elements)*					
Repair/Replace Recommendations *(itemized description of wall repairs, methods, estimated quantities, and costs per repair item, including consideration of constructability issues such as access, traffic control, staging, safety hazards, etc.)*					
Rev. 07-10-2007				Repair/Replace COST:	

Field Inspection Form (Back Page)

Element	Condition Narrative	Condition Rating X	Weighting Factor =	Condition Score	Data Reliability
Primary Wall Elements					
Piles and Shafts		1-10	8		1-3
Lagging		1-10	8		1-3
Anchor Heads		1-10	8		1-3
Wire/Geosynthetic Facing Elements		1-10	8		1-3
Bin or Crib		1-10	8		1-3
Concrete		1-10	8		1-3
Shotcrete		1-10	8		1-3
Mortar		1-10	8		1-3
Manufactured Block/Brick		1-10	8		1-3
Placed Stone		1-10	8		1-3
Stone Masonry		1-10	8		1-3
Wall Foundation Material		1-10	8		1-3
Other Primary Wall Element		1-10	8		1-3
Secondary Wall Elements (WF=0.5 for CR=8-10/ WF=1.0 for CR=4-7/WF=5 for CR=1-3)					
Wall Drains		1-10	0.5-5		1-3
Architectural Facing		1-10	0.5-5		1-3
Traffic Barrier/Fence		1-10	0.5-5		1-3
Road/Sidewalk/ Shoulder		1-10	0.5-5		1-3
Upslope		1-10	0.5-5		1-3
Downslope		1-10	0.5-5		1-3
Lateral Slope		1-10	0.5-5		1-3
Vegetation		1-10	0.5-5		1-3
Culvert		1-10	0.5-5		1-3
Curb/Berm/Ditch		1-10	0.5-5		1-3
Other Secondary Wall Elements		1-10	0.5-5		1-3
Wall Performance					
Performance		1-10	8		
WALL RATING	Weighting Factor (x10) and Condition Score Totals				
	Wall Condition Rating (= [Condition Score Total/Weighting Factor Total (x10)] X 100)				

WIP Field Guide (Page 1)

- NPS Retaining Wall Inventory Program Field Guide (WIFG)-	
Retaining Wall Acceptance Criteria	
*All classes of paved roadways and parking areas included in the RIP Route Investigation Report and/or identified by Park staff. *Walls must reside within the constructed roadway/parking area prism. *Maximum wall height, including only that portion actively retaining soil and/or rock, must be ≥ 4 ft (≥ 6 ft for culvert headwalls). *Consider known/verifiable wall embedment in determining maximum retaining wall height. Include fully buried retaining structures. *Walls have an internal wall face angle ≥ 45° (≥ 1H:1V face slope ratio). *Include all walls where the intent is to support/protect the travelway, and where failure would require replacement with a retaining wall.	
Definitions	
Design Criteria	Measure of how well current design criteria are satisfied: **None** - Does not meet any known standards. **Non-AASHTO** - Does not meet AASHTO, but is consistent with other structures of its type/period with good performance. **AASHTO** - Apparently meets current AASHTO Geometric, Design, Materials, and Construction Standards.
Consequence of Failure	**Low** - No loss of roadway, no to low public risk, no impact to traffic during wall repair/replacement **Moderate**- Hourly to short-term closure of roadway, low-to-moderate public risk, multiple alternate routes available **High**- Seasonal to long-term loss of roadway, substantial loss-of-life risk, no alternate routes available
Action	Select from: **No Action, Monitor, Maintenance, Repair Elements, Replace Elements,** and **Replace Wall**
Weighting Factor	Weighting Factor to be applied to the Condition Rating (CR). When indicated on the Condition Assessment Input Form: **WF=0.5** for CR=8-10; **WF=1.0** for CR=4-7; and **WF=5** for CR=1-3.
Data Reliability	Estimate of how well observed conditions represent wall performance, and if additional investigations may be warranted. **1-Poor** Conditions cannot be sufficiently observed to rate element(s), warranting additional investigations to better define element performance and/or to determine the cause(s) or poor performance. **2-Good** Observed conditions are sufficient to rate the conditions of wall element(s); however, additional investigations would be useful to better understand element performance. **3-Very Good** Observed conditions clearly describe wall performance. Additional investigations are not needed.

Wall Function Codes
[FW] Fill Wall [CW] Cut Wall [BW] Bridge Wall [SW] Switchback Wall [HW] Head Wall [SP] Slope Protection [FL] Flood Wall

Wall Type Codes		
[AH] Anchor, Tieback H-Pile	[CC] Crib, Concrete	[MG] MSE, Geosynthetic Wrapped Face
[AM] Anchor, Micropile	[CM] Crib, Metal	[MP] MSE, Precast Panel
[AS] Anchor, Tieback Sheet Pile	[CT] Crib, Timber	[MS] MSE, Segmental Block
[BC] Bin, Concrete	[GB] Gravity, Concrete Block/ Brick	[MW] MSE, Welded Wire Face
[BM] Bin, Metal	[GC] Gravity, Mass Concrete	[SN] Soil Nail
[CL] Cantilever, Concrete	[CD] Gravity, Dry Stone	[TP] Tangent/ Secant Pile
[CP] Cantilever, Soldier Pile	[GG] Gravity, Gabion	[OT] Other, User Defined
[CS] Cantilever, Sheet Pile	[GM] Gravity, Mortared Stone	[NO] None

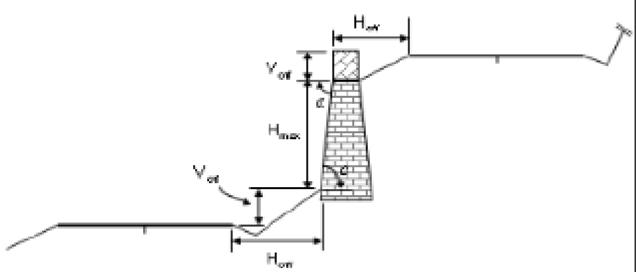
Architectural Facing Type Codes		
[BV] Brick Veneer	[PF] Planted Face	[SS] Simulated Stone
[CO] Cementitious Overlay	[SC] Sculpted Shotcrete	[SV] Stone Veneer
[FF] Fractured Fin Concrete	[SH] Shotcrete (nozzle finish)	[TI] Timber
[FL] Formlined Concrete	[SM] Steel/Metal	[OT] Other, User Defined
[PC] Plain Concrete (float finish or light texture)	[SO] Stone	[NO] None

Surface Treatment Codes		
[BG] Bush Gun (tool-textured concrete)	[PS] Preservative	[WS] Weathering Steel
[CA] Color Additive	[SE] Silane Sealer	[OT] Other, User Defined
[GL] Galvanized	[ST] Stain	[NO] None
[PA] Painted	[TR] Tar Coated	

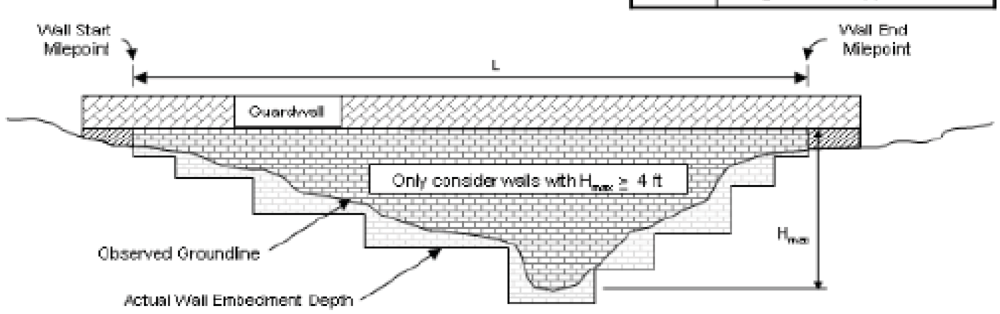
WIP Field Guide (Page 2)

Condition Ratings	
Condition Ratings apply to all Primary and Secondary Wall Elements, and are intended to assist in consistently defining element severity, extent, and repair/replace urgency of wall element distresses.	
9-10 (Excellent)	-Any defects are minor and are within normal range for *newly constructed or fabricated* elements. -Defects may include those typically caused from fabrication or construction.
7-8 (Good)	-Low-to-moderate extent of low severity distress. -Distress present does not significantly compromise the element function, nor is there significantly severe distress to major structural components of an element.
5-6 (Fair)	-High extent of low severity distress and/or low-to-medium extent of medium to high severity distress. -Distress present does not compromise element function, but lack of treatment may lead to impaired function/elevated risk of element failure in the near term.
3-4 (Poor)	-Medium-to-high extent of medium-to-high severity distress. -Distress present threatens element function, and strength is obviously compromised and/or structural analysis is warranted. -The element condition does not pose an immediate threat to wall stability and road closure is not necessary.
1-2 (Critical)	-Medium-to-high extent of high severity distress. -Element is no longer serving intended function. Element performance threatening overall stability of the wall at the time of inspection.

Wall Performance Condition Ratings		
Performance	Evaluation of overall wall performance as indicated by observations not necessarily captured by observed distresses for specific elements, including global wall distresses (rotation, settlement, translation, displacement, etc.) and/or evidence of prior repairs that may further indicate component problems.	**Good to Excellent** - No observation of distresses not already captured by individual element condition assessment. No combination of element distresses indicating unseen problems or creating significant performance problems. No history of remediation or repair to wall or adjacent elements. **(7-10)**
		Fair - Some observed global distress is not associated with specific elements. Some observation of element distress combinations that indicate wall component problems. Minor work on primary elements or major work on secondary elements has occurred improving overall wall function. **(5-6)**
		Poor to Critical - Global wall rotation, settlement, and/or overturning is readily apparent. Combined element distresses clearly indicate serious stability problems with components or global wall stability. Major repairs have occurred to wall structural elements, though functionality has not improved significantly. **(1-4)**



H_{max}	Maximum exposed wall height, ft
V_{ot}	Average vertical distance from pavement to cut wall toe or groundline at top of fill wall (+ above/- below roadway), ft
H_{ow}	Horizontal distance to wall face from edge of roadway, ft
α	Wall face angle measured from the horizontal, degrees
L	Maximum earth retaining length of the wall (excluding guardwalls). Wall length is the actual length of the structure, not simply the projected length along the roadway, ft



WIP Field Guide (Page 3)

Element	Element Definition
Primary Element Condition Ratings	
Piles and Shafts	Soldier piles, sheet piles, micropiles or drilled shafts; supplemental structures such as walers, comprising all/part of the visible wall.
Lagging	Structural lagging between piles and walers.
Anchor Heads	All visible parts of tieback anchor, including pad (observed without removing cap).
Wire/Geosyn. Facing Elements	Visible facing/basket wire, soil reinforcing elements, hardware cloth, geotextile/geogrids, and facing stone.
Bin or Crib	Visible portion of cellular gravity wall.
Concrete	Visible precast or cast-in-place concrete wall and footing elements (does not include piles, lagging, crib blocks, manufactured block/brick, and architectural facing).
Shotcrete	Visible shotcrete (does not include piles, lagging, architectural facing or other specific elements).
Mortar	Visible mortar used between uncut or masoned rock, manufactured blocks or brick, or used for wall repairs.
Manufactured Block/Brick	Manufactured blocks and bricks, including CMU's segmental blocks, large gravity blocks, etc. (does not include concrete lagging or crib wall components).
Placed Stone	Dry-laid or mortar-set *uncut* rock.
Stone Masonry	Dry-laid or mortar-set cut rock.
Wall Foundation Material	Soil or rock immediately adjacent to and supporting the wall.
Other Primary Wall Element	Any primary wall element not listed (provide detailed narrative definition).
Secondary Element Condition Ratings	
Wall Drains	Function and capacity of visible drain holes, pipes, slot drains, etc., that provide wall subsurface drainage.
Architectural Facing	Facing that is not relied on for structural capacity, including concrete, shotcrete, stone, timber, vegetation, etc.
Traffic Barrier/ Fence	Traffic barrier or fence above or below wall, and within the influence of the wall.
Road/ Sidewalk/ Shoulder	Road and/or sidewalk surface above or below a wall, and within the influence of the wall.
Upslope	Groundslope area above a wall affecting wall condition and/or performance.
Downslope	Groundslope area below the wall, distinct from the Wall Foundation Material element, affecting wall condition and/or performance.
Lateral Slope	Groundslope laterally adjacent to a wall affecting wall condition and/or performance.
Vegetation	Vegetation near wall or on wall face affecting wall condition and/or performance.
Culvert	Culverts and inlets/outlets through, below, or adjacent to walls.
Curb/ Berm/ Ditch	Lined or unlined surface drainage feature above or below wall.
Other Secondary Wall Element	Any secondary wall element not listed (provide detailed narrative definition).

Element Condition Rating Guidance

Good to Excellent Rating (minor to no distress, minimal to no impact, few to no occurrences)

Corrosion/Weathering
- No evidence of corrosion/staining, contamination or cracking/spalling due to weathering or chemical attack.
- Compacted, placed or masoned rock, and associated chinking, is dense, angular, fresh, and without post-placement fracturing or chemical degradation.
- No significant weathering/weakening of bedrock, softening of soil, or saturated ground conditions evident.
- No impacts from vegetation noted within the wall or within adjacent elements.

Cracking/Breaking
- No evidence of element cracking, breaking, or construction/post-construction damage, opening of discontinuities in rock, or cracks or gullies in soils.
- Concrete, shotcrete, and mortar is sound, durable, and shows little or no signs of shrinkage cracking or spalling.
- Drains are clearly open (flowing), and in full working order.

Distortion/Deflection
- Wall elements are as constructed, and/or show no signs of significant settlement, bulging, bending, heaving, or distortion/deflection beyond normal prescribed post-construction limits.

Lost Bearing/Missing Elements
- No wall elements are missing.
- Wall elements are fully bearing against retained soil/rock units.
- Foundation soils/rock are more than adequate to support the wall, consistently dense, drained and strong.
- No slope failures have occurred either removing or adding materials to the wall area.

Fair Rating (moderate distress, significant to substantial impact, multiple occurrences)

Corrosion/Weathering
- Moderate corrosion/staining, contamination or cracking/spalling due to weathering or chemical attack.
- Compacted, placed or masoned rock is not fresh or angular, showing significant weathering, post-placement fracturing, chemical degradation, and/or localized loosening.
- Significant weathering/weakening of bedrock, softening of the soil, or saturated ground conditions evident.
- Moderate impacts from vegetation are evident within the wall or within adjacent elements.

Cracking/Breaking
- Localized element cracking, breaking, abrasion and/or construction/post-construction damage, opening or discontinuities in rock or cracks or gullies in soil.
- Concrete, shotcrete, and mortar is occasionally soft or drummy, has lost durability, and shows occasional cracking and/or spalling sufficient to intercept reinforcement.
- Drains cannot be clearly determined to be fully operational.

Distortion/Deflection
- Wall elements show significant localized settlement, bulging, bending, heaving, misalignment, distortion, deflection, and/or dispacement beyond normal prescribed post-construction limits (e.g., wall face rotation, basket buldging, anchor head displacement, bin displacement).

Lost Bearing/Missing Elements
- Some wall elements are missing (e.g., chinking, lagging, brick-work) or non-functional.
- Wall elements are generally bearing against retained soil/rock units, but localized open voids may exist along the back and top of the wall.
- Foundation soils/rock are adequate to support the wall, but susceptible to shrink-swell, erosion, scour, or vegetation impacts.
- Isolated slope failures have occurred either removing or adding material from the wall area.

Poor to Critical Rating (severe distress, failure is imminent, pervasive occurrences)

Corrosion/Weathering
- Metallic wall elements are corroded and have lost significant section affecting strength.
- Concrete/shotcrete is extensively spalled, cracked, and/or weakened, and may show evidence of widespread aggregate reaction.
- Compacted, placed or masoned rock is highly weathered, showing extensive post-placement fracturing, chemical degradation, and/or loosening within the placed volume.
- Extensive weathering/weakening of bedrock, softening of soil, or saturated ground conditions evident.
- Severe impacts from vegetation are evident within the wall or within adjacent elements.

Cracking/Breaking
- Extensive severe element cracking, breaking, abrasion or construction/post-construction damage, opening of discontinuities in rock, or cracks or gullies in soils.
- Concrete, shotcrete, and mortar is consistently soft, drummy, or missing, has lost durability and strength, and shows pervasive cracking and/or spalling intercepting corroding/weathering reinforcement.
- Drainage is missing, clearly damaged, and/or obviously clogged and non-functional.

Distortion/Deflection
- Wall elements show extensive settlement, bulging, bending, distortion, misalignment, deflection, and/or dis-placement well beyond normal post-construction limits, including loss of ground reinforcement and retention.

Lost Bearing/Missing Elements
- Many or key wall elements are missing (e.g., placed wall stone, chinking, lagging) or non-functional.
- Many or key wall elements are no longer bearing against retained soil/rock units, with visible open voids evident behind a large portion of the wall.
- Foundation soils/rock show signs of failure, excessive settlement, scour, erosion, substantial voids, bench failure, slope oversteepening, and/or may be adversely impacted by vegetation.
- Substantial slope failures have occurred either removing or adding materials to the wall area.

WIP Field Guide (Page 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.

Road/Sidewalk/Shoulder: Rate only when these elements lie within the influence of the wall. The shoulder is generally defined as extending no greater than 5 ft horizontally from the roadway/sidewalk, and less than -5 ft vertical offset.

Upslope: Rate the upslope condition for all walls above roadway grade, regardless of slope ratio. Rate the upslope condition for all walls below roadway grade, regardless of slope ratio, when the vertical offset to the wall from the roadway/shoulder is greater than 5 ft (otherwise evaluate the condition of the upslope under the "Road/Sidewalk/Shoulder" element).

Downslope: Rate the downslope condition for all walls below roadway grade, regardless of slope ratio. Rate the downslope condition for all walls above roadway grade, regardless of slope ratio, when the vertical offset to the wall from the roadway/shoulder is greater than 5 ft (otherwise evaluate the condition of the downslope under the "Road/Sidewalk/Shoulder" element).

A - 2 Materials from North Carolina DOT (2015)

Wall Identification and Data Attributes Form

Page 1

Wall ID: [ ] Date: [ ] NCDOT Reviewer(s): [ ]

Revision Date: [ ]

Picture(s): [ ]

LOCATION DATA

County: [ ] Division: [ ] Travel Direction: [ ]

Route Number: [ ] Route Name: [ ] Latitude: [ ] Longitude: [ ]

Location Description: [ ]

Bridge Association: [ ] Bridge Number: [ ] Culvert Association: [ ] Culvert Number: [ ]

Road System: [ ] Tier: [ ]

DIMENSION DATA

Embedment (ft): [ ] Max. Wall Height (ft): [ ] Extension (ft): [ ] Total Length (ft): [ ]

Wall Batter: [ ] Back Slope: [ ] Front Slope: [ ] Berm Dimension: [ ] Distance to Stream (ft): [ ]

Roadside Features: [ ]

Plan View:

Profile View:

WALL TYPE AND FUNCTION DATA

Wall Type: [ ] Wall Facing [ ] Veneer: [ ]

Construction Type: [ ] Function Type: [ ] Traffic Volume: [ ]

Protected Features: [ ] Purpose: [ ]

Wall Identification and Data Attributes Form

Page 2

HISTORY AND OWNERSHIP

Current Owner: Year Built: Design Life: Engineer of Record:

T.I.P. Number: Design Type: Design Category: Inspection Frequency:

Special Access Needs: Work Zone Requirments:

STRUCTURAL DATA

Wall Support: Foundation Dimension: Fill Material:

Bridge Foundation Type: Soil Reinforcement Type: Surcharge:

Reinforcement off ROW: External Drainage: Internal Drainage:

Wall Top Feature: Scour Depth: Wall Obstruction(s):

As-Built Drawings: Design Calculations: Subsurface Plans:

Conflict(s):

Comments On Design:

Comments On Construction Details:

Maintenance/Repair Details:

ERS Field Condition Inspection Data Collection Form

Wall ID: ______ Date: ______ NCDOT Inspector(s): ______

Division: ______ County: ______ Route Number: ______ Route Name: ______

Location Description: ______

Latitude: ______ Longitude: ______ Wall Type: ______

CATEGORY OBSERVATIONS		PERCENT BY RATING				AVERAGE RATING	COMMENTS
		1	2	3	4		
Facing	Facial Deterioration						
	Staining						
	Damage						
	Cracking						
	Joint Alignment						
	Joint Spacing						
	Material Loss						
Movement	Deflection/ Rotation						
	Bulges/ Distortion						
	Settlement						
	Heaving						
Drainage	Erosion						
	Scour						
	Internal/ External Drains						
Exterior	Wall Top Attachment						
	Road/Sidewalk /Shoulder						
	Vegetation						

Note: If the average rating for any of the criteria listed above is $\geq$ 2.5, please include a corresponding picture and comment for each observation respectively.

A - 3 Materials from Colorado DOT (2016)

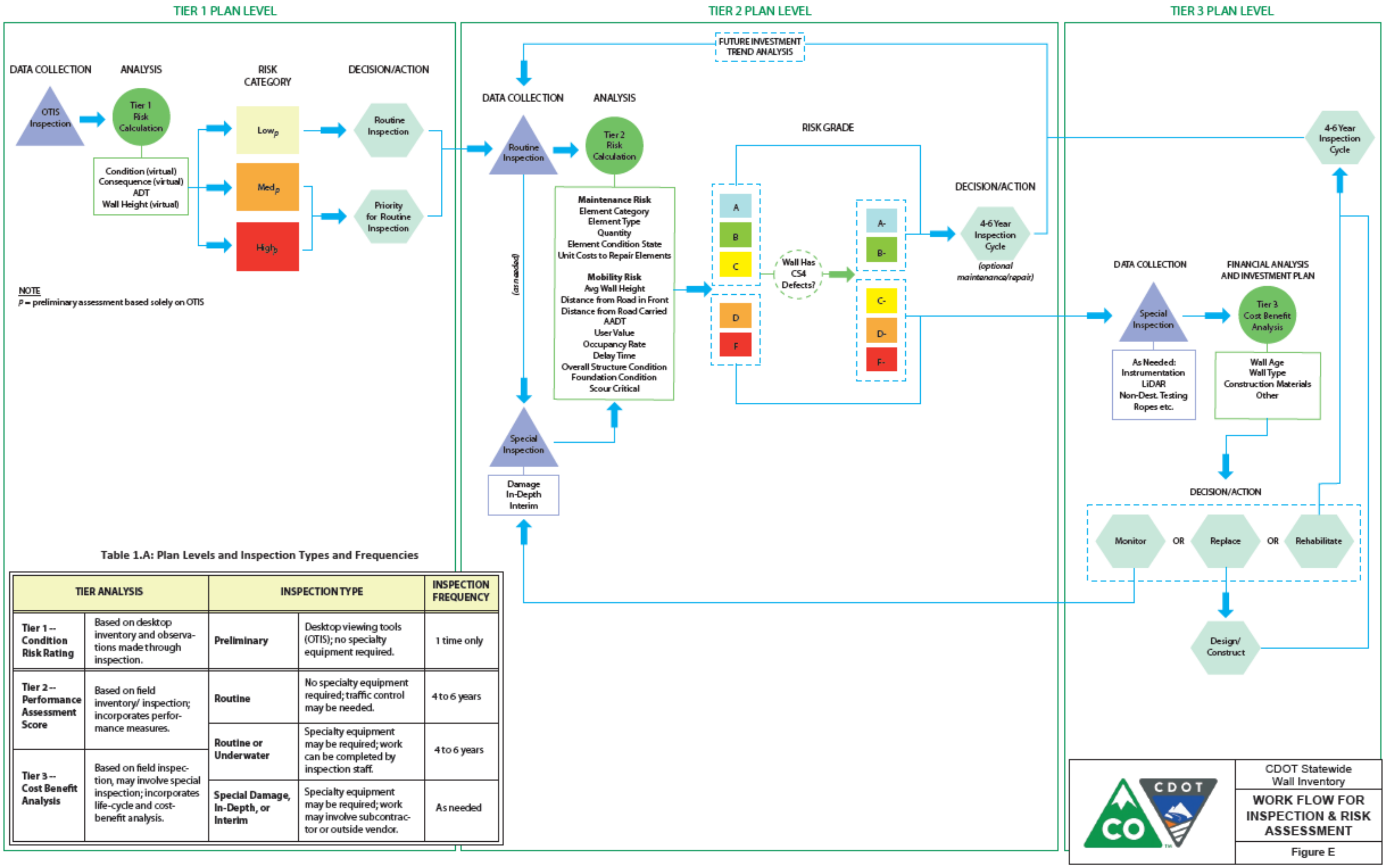


Table 1.A: Plan Levels and Inspection Types and Frequencies

TIER ANALYSIS		INSPECTION TYPE		INSPECTION FREQUENCY
Tier 1 -- Condition Risk Rating	Based on desktop inventory and observations made through inspection.	**Preliminary**	Desktop viewing tools (OTIS); no specialty equipment required.	1 time only
Tier 2 -- Performance Assessment Score	Based on field inventory/ inspection; incorporates performance measures.	**Routine**	No specialty equipment required; traffic control may be needed.	4 to 6 years
		Routine or Underwater	Specialty equipment may be required; work can be completed by inspection staff.	4 to 6 years
Tier 3 -- Cost Benefit Analysis	Based on field inspection, may involve special inspection; incorporates life-cycle and cost-benefit analysis.	**Special Damage, In-Depth, or Interim**	Specialty equipment may be required; work may involve subcontractor or outside vendor.	As needed

Condition Ratings

Code	Description
N	**NOT APPLICABLE**
9	**EXCELLENT CONDITION** - like new condition
8	**VERY GOOD CONDITION** - Main structure has very minor (and isolated) deterioration. • Concrete: minor cracking, leaching, scaling, or wear (no delamination or spalling). • Timber: minor weathering - isolated (minor) splitting. • Steel: no corrosion (paint/protection system remains sound). • Masonry: slight weathering or cracks (joints have no deterioration).
7	**GOOD CONDITION** - Main structure has minor (or isolated) deterioration. Evidences of light leakage may be present. • Concrete: minor cracking, leaching, scaling, or wear (isolated delamination, spalling, or temporary patches). • Timber: minor weathering or splitting (no decay or crushing) - all planks are secure. • Steel: minor paint failure or corrosion (no section loss) - all connections are secure. • Masonry: minor weathering or cracking (joints have little or no deterioration)
6	**SATISFACTORY CONDITION** - Main structure has minor to moderate deterioration (no repairs are necessary). Areas of slight backfill loss. Areas of leakage are minor and isolated. Scour or erosion (if present) is minor and isolated. • Concrete: moderate cracking, leaching, scaling, or wear (minor delamination or spalling). • Timber: moderate weathering or splitting (isolated decay or crushing) - some planks may be slightly loose. • Steel: moderate paint failure and/or surface corrosion (minor section loss) – some connections may have worked loose. • Masonry: moderate weathering or cracking (joints may have minor deterioration). Evidence of slight freeze-thaw.
5	**FAIR CONDITION** - Main structure has moderate deterioration (repairs may be necessary). Areas of backfill loss are minor and isolated. Areas of leakage are minor. There may be moderate scour, erosion, or undermining. There may be slight settlement, movement, misalignment, or bulging. Change in vertical batter is <4% different from intended design. • Concrete: extensive cracking, leaching, scaling, or wear (moderate delamination or spalling). • Timber: extensive weathering or splitting (moderate decay or crushing) - some planks may be loose, broken, or require replacement. • Steel: extensive paint failure and/or surface corrosion (moderate section loss) – several connections may be loose or missing, but deck components remain secure. • Masonry: extensive weathering or cracking (joints may have slight separation or offset). Evidence of minor freeze-thaw.
4	**POOR CONDITION** - Main structure has advanced deterioration (replacement should be planned). Moderate backfill loss and/or leakage may be present. There may be extensive scour, erosion, or undermining. Minor settlement, movement, misalignment, or bulging may be present. Changes in vertical batter are within 4%-10% compared to intended design. • Concrete: advanced cracking, leaching, scaling, or wear (extensive delamination or spalling) - isolated full-depth failures may be imminent. • Timber: advanced weathering, splitting, or decay - numerous planks may be loose, broken, or require replacement. • Steel: advanced corrosion (significant section loss) – main structure elements may be loose or slightly out of alignment. • Masonry: advanced weathering or cracking (joints may have separation or offset). Evidence of moderate freeze-thaw.

3	**SERIOUS CONDITION** - Main structure has severe deterioration - immediate repairs may be necessary. Heavy and/or active backfill loss or leakage may be present. Scour, erosion, or undermining may have resulted in severe settlement, movement, or misalignment. Significant settlement, movement, misalignment, or bulging may be present. Changes in vertical batter may be >10% compared to intended design. • Concrete: severe cracking, leaching, delamination, or spalling - full-depth failures may be present. • Timber: severe splitting, crushing or decay - majority of planks may need replacement. • Steel: severe section loss – main structure elements may be severely out of alignment. • Masonry: severe cracking, offset or misalignment. Evidence of severe freeze-thaw.
2	**CRITICAL CONDITION** - advanced deterioration of primary structural elements or extreme backfill loss. Severe backfill loss may be affecting the structural integrity of the wall. Cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the routes carried or in front of the wall until corrective action is taken.
1	**"IMMINENT" FAILURE CONDITION** - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Route carried or in front of the wall is closed to traffic but corrective action may put back in light service.
0	**FAILED CONDITION** - out of service - beyond corrective action.

Appraisal ratings

Description	Code
Not applicable	N
Superior to present desirable criteria	9
Equal to present desirable criteria	8
Better than present minimum criteria	7
Equal to present minimum criteria	6
Somewhat better than minimum adequacy to tolerate being left in place as is	5
Meets minimum tolerable limits to be left in place as is	4
Basically intolerable requiring high priority of corrective action	3
Basically intolerable requiring high priority of replacement	2
This value of rating code not used	1
Wall failure	0

APPENDIX 2.A: STRUCTURE INVENTORY AND APPRAISAL SHEET

1.	State Name:		50A.	Curb or Sidewalk, Carried (lt)	
2E,M	Region/Maint. Section		50B.	Curb or Sidewalk, Carried (rt)	
3.	County Code		50C.	Curb or Sidewalk, In Front (lt)	
4,4A.	Place Code		50D.	Curb or Sidewalk, In Front (rt)	
5A.	Inventory Rte (On/In Front)		51.	Width, Curb-to-Curb, Carried	
5B.	Inventory Rte (Signing)		51A.	Width, Curb-to-Curb, In Front	
5C.	Inventory Rte (L.O.S.)		52.	Average Wall Height	
5DN.	Inventory Rte (Rte. Num)		53.	Maximum Wall Height	
5E.	Inventory Rte (Dir. Suffix)		54.	Minimum Wall Height	
6.	Features Carried		58.	Main Structure	
7.	Features In Front		60.	Foundation	
8.	Structure Number		61.	Channel & Channel Protection	
8A.	Structure ID Number		71.	Waterway Adequacy	
9.	Location		72.	Adjacent Roadway Alignment	
11.	Reference Point		90.	Inspection Date	
12.	Base Hwy. Network		91.	Frequency	
13.	LRS Rte, Sub. Rte Number		92A.	UW Frequency	
16.	Latitude - Start of Wall		92B.	Special Frequency	
16A.	Latitude - End of Wall		93A.	UW Inspection Date	
16B.	Elevation - Start of Wall		93B.	Special Inspection Date	
17.	Longitude - Start of Wall		98A.	Border Wall State Code	
17A.	Longitude - End of Wall		98B.	Percent Responsibility	
17B.	Elevation - End of Wall		99.	Border Wall Structure No.	
18A.	Range		100.	STRAHNET Highway Desc.	
18B.	Township		102.	Direction of Traffic	
18C.	Section		103.	Temporary Structure	
19.	Bypass, Detour Length		104.	Highway System	
20.	Toll		105.	Federal Lands Highways	
21.	Maintenance Resp.		106.	Year Reconstructed	
22.	Owner		107.	Vertical Support Struct. Type	
23.	Orig. Project Number		109.	Truck ADT	
23E.	Subaccount Number		110.	Designated National Network	
23EE.	Project Indicator		113.	Scour Critical Walls	
26.	Functional Class		114.	Future ADT	
27.	Year Built		115.	Year of Future ADT	
28.	Lanes On Structure		125A,B.	Type of Wall Rail on Top	
	Lanes In Front		125C,D.	Type of Wall Rail In Front	
29.	Average Daily Traffic		133.	Special Inspection Equipment	
30.	Year of ADT		136.	Mileage Log Section Letter	
33.	Median		143A.	Avg. Dist Fr. Route, Carried	
36AD	Traffic Safety Feat. on Top			Max. Dist Fr. Route, Carried	
36H.	Height of Rail on Top			Min. Dist. Fr. Route, Carried	
36IL.	Traffic Safety Feat. in Front		143B.	Avg. Dist Fr. Route, In Front	
36M.	Height of Rail In Front			Max. Dist Fr. Route, In Front	
37.	Historical Significance			Min. Dist. Fr. Route, In Front	
42.	Type of Service, Carried		144A.	Speed Limit, Route Carried	
	In Front		144B.	Speed Limit, Route In Front	
43.	Struct Type, Wall Face Mat.		145.	Wall System	
	Type of design/const		146.	Associated Bridge	
47.	Total Horz. Clearance, Carried		147.	Vertical Batter	
47A.	Total Horz. Clearance, In Front		148.	Slope Angle Carried & In Front	
49.	Structure Length		149.	Type of Protective Coating	

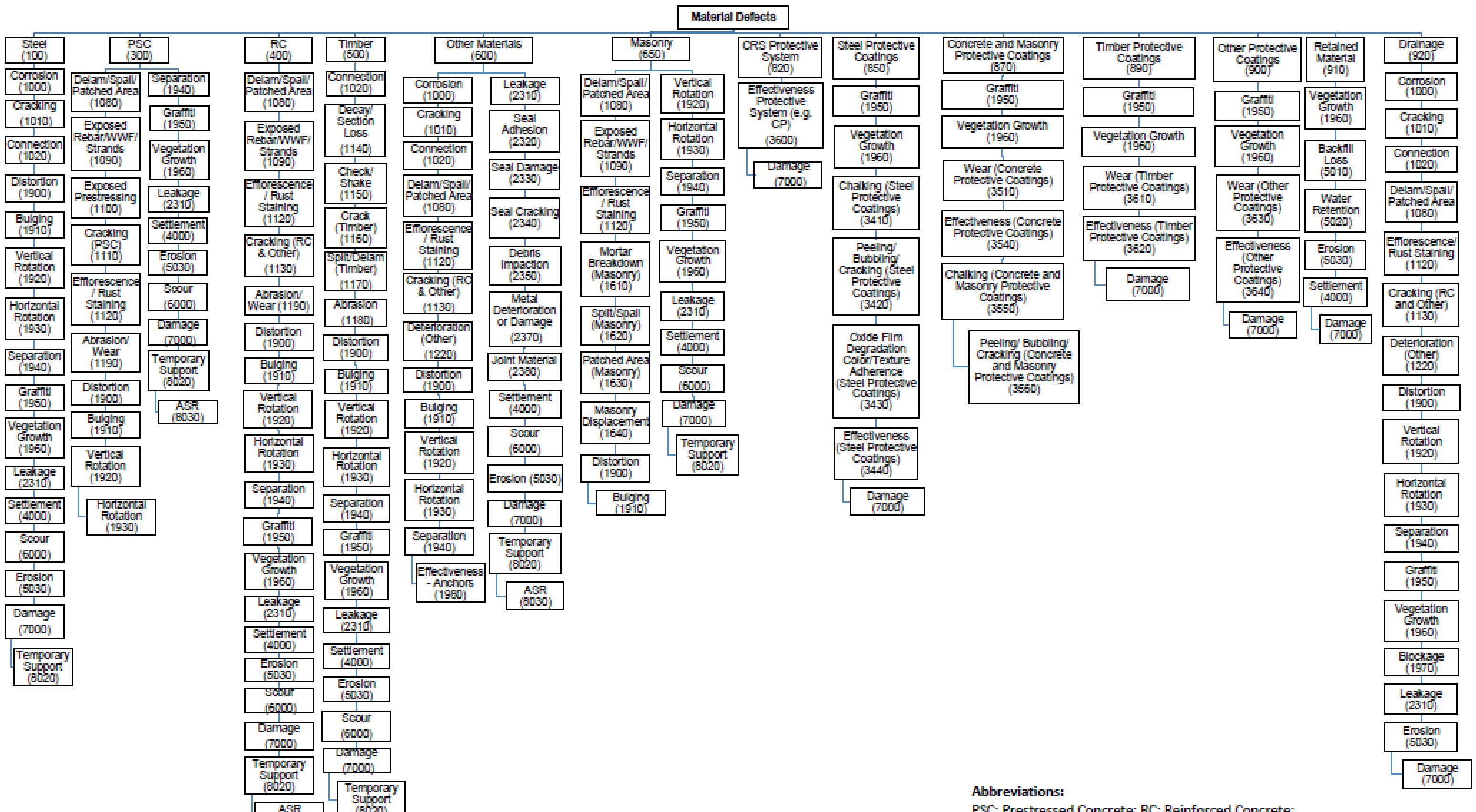


Figure 3.B-1 Material Defects

Abbreviations:
PSC: Prestressed Concrete; RC: Reinforced Concrete;
Delam: Delamination; CRS: Concrete Reinforcing System; ASR: Alkali-Silica Reactivity

Scoring criteria for Annual Average Daily Traffic (AADT)

Score	Descriptor
Wall Condition	
1	New condition or no noticeable condition loss
2	Acceptable performance, prior maintenance/repair evident
3	Deterioration or condition loss occurring
4	Potentially unstable conditions
Consequence of Failure	
1	Negligible: No impacts to structures, roadway, or off ROW property
2	Minor: No to slight impact to traffic (temporary: less than 1 day)
3	Major: Impact beyond CDOT ROW and/or debris on roadway
4	Critical: Collapse of at least one travel lane (essential structure)
Annual Average Daily Traffic (AADT)	
1	AADT below the 25 percent quartile (less than 13,000)
1.25	AADT between 25 and 50 percent quartile (13,000-31,000)
1.5	AADT between 50 and 75 percent quartile (31,000-107,000)
2	AADT greater than 75 percent quartile (greater than 107,000)

Maintenance and mobility risk parameters

Performance Area	Factor	Parameter
Maintenance		
	Consequence	Element Category (primary or secondary)
		Element Type
		Quantity of Elements
		~Unit Costs
	Likelihood	Condition State
Mobility		
	Consequence	Avg. Wall Height
		Avg. Distance from Road in Front
		Avg. Distance from Road Carried
		AADT
		^Delay Time, 2 hours
		*User Value, $30.50
		*Occupancy Rate, 1.67
		*ADT Delay, 33% of Actual ADT
	Likelihood	Main Structure Condition
		Foundation Condition
		Scour Critical

~Data compiled based on inspector experience and with CDOT input.

^Assumed value based on likely time of delay from an urgent adverse event, similar to delay associated with over-height bridge strikes.

*Per AASHTO 2010, see Footnote 1.

Likelihood estimates for element categories and condition states

Likelihood of Incurring Maintenance Cost		
Condition State	Primary Elements	Secondary Elements
CS1	0%	0%
CS2	11%	7%
CS3	59%	37%
CS4	98%	66%

Probability of event and condition score

Condition	Likelihood
9	2%
8	
7	
6	5%
5	
4	26%
3	
2	78%
1	
0	

Grade categories for parameters

Level of Risk Grade	Maintenance Risk Score	Mobility Risk Score
A	0 to 0.1	$0 to $500
B	0.1 to 0.3	$500 to $5,000
C	0.3 to 0.5	$5,000 to $40,000
D	0.5 to 0.7	$40,000 to $95,000
F	>0.7	$95,000

A - 4 Materials from Wisconsin DOT (2016)

TO: STRUCTURES DEVELOPMENT SECTION (January, 2016)

FROM:

SUBJECT: Noise or Retaining Wall Inventory Data (Complete all data fields applicable)

1. Structure #	2. Region	3. County	4. Municipality	5. Owner	6. Maintainer	10-State 40-Town 42-Vil 30-County 41-City
7. Start. Latitude	8. Start. Longitude	9. End Latitude	10. End Longitude			11. Type (Retaining or Noise)

WALL TYPE AND GEOMETRICS

12. Type
- ☐ CIP Piles ☐ CIP-Spread
- ☐ Block-Gravity ☐ Conc. Bin
- ☐ MSE-Block ☐ MSE-Panel
- ☐ Post and Panel ☐ MSE-CIP Facing
- ☐ SHT Pile-Cant. ☐ Other ________

13. Is Wall Anchored (Y/N) ____________________

14. Installation Type(s) (check all that apply):
- ☐ Ground Mounted
- ☐ Structure Mounted (Bridge ID=____________)

15. Foundation Type (if Applicable):
- ☐ Piles ☐ Spread Footing
- ☐ Other: ____________________________

16. Pile/Post Material & Type (If Applicable):
- ☐ Untreated Timber ☐ Treated Timber
- ☐ Concrete (CIP) ☐ Concrete (Precast)
- ☐ Steel H-Pile ☐ Aluminum Pile
- ☐ Other: ____________________________

17. Pile/Post Size (If Applicable):
- ☐ 8" ☐ 10" or 10 3/4"
- ☐ 12" ☐ 14" ☐ Other ________

GEOMETRIC DATA

18. Structure Length (ft.) ____________________

19. Maximum Wall Height (ft.) ________________

20. Maximum Exposed Wall Height (ft.) __________

21a. Average Wall Thickness (in.) ______________

21b. Wall Area (ft^2)____________________

ROUTE INFORMATION

22. Enter name of closest primary route to Wall (Record in HSIS as Under Route):

____________________________________.

23. Direction: ☐ North ☐ East ☐ South ☐ West

24. Designation: ☐ Mainline ☐ Other ________

25. Inventory Route: ☐ On NHS ☐ Not on NHS

MISCELLANEOUS INFORMATION

26. Wall Functions:
- ☐ Retain Cut ☐ Retain Fill
- ☐ Dockwall ☐ Noise Wall
- ☐ Multiple ____________________

27. Noise Abatement Method (If Applicable):
- ☐ Single Side Absorptive
- ☐ Double side Absorptive
- ☐ Reflective
- ☐ Other________________________

CONSTRUCTION DATA

28. Plans Completed YR _____ MO _____ DAY_______

29. Letting Date YR _____ MO _____ DAY_______

20. Year Built _______

31 WORK Performed
- ☐ New Structure ☐ Other ______________

32. Designer: ________________

33. Fabricator: ________________

34. General Contractor: ________________

35. Project ID: _____-___-______

36. Cost: ___________

FOR INTERNAL USE ONLY

37 Type Service On: Retaining/Noise Wall

38 Type Service Under: Highway

39 Primary Route On: Retaining/Noise Wall

40 Route on Designation: Water/Land/Other

General Instructions and Help

Box 1. Enter the assigned ID for the structure. Structure ID's can be obtained by contacting the Regional Inspection Program Manager.

Box 2. Enter the region where the structure is located. If located on a boundary between two Regions, enter the Region associated with the structure ID.

Box 3. Enter the county where the structure is located. Note that the county must match the structure ID value.

Box 4. Enter the municipality where the structure is located.

Box 5/6. Enter the maintainer/owner of the structure. In some instances these codes will be different, but this is rare.

Box 7/8. Enter the Start Latitude and Longitude of the structure using the following format: DDMMSS.S where DD is degrees, MM is minutes, and SS.S is seconds. This shall be taken at the beginning of the wall, at the lower station value, as shown on the plans.

Box 9/10. Enter the End Latitude and Longitude of the structure using the following format: DDMMSS.S where DD is degrees, MM is minutes, and SS.S is seconds. This shall be taken at the end of the wall, at the higher station value, as shown on the plans.

Box 11. Indicate the type of wall (Retaining or Noise).

Box 12. Indicate the type of wall system that was designed.

Box 13. If the wall uses anchorages to tie back into the soil mass, indicate that here.

Box 14. Walls may either be ground mounted, structure mounted, or a combination. If the wall is attached to another structure, indicate that structure number as well.

Box 15. If applicable, enter the type of foundation used for the wall system.

Box 16. If applicable, enter the type and material of the posts/piles used in the wall system.

Box 17. If posts/piles are used, please indicate the size.

Box 18. Enter the overall length of the wall structure, in feet.

Box 19. Enter the maximum overall height of the wall, in feet.

Box 20. Enter the maximum exposed wall height, in feet. In general, this is the height of fill the wall is holding back.

Box 21. Enter the average wall thickness, in inches for 21a. Enter the cross-sectional area of the wall, in square feet for 21b.

Box 22. Enter the closest route for public highway traffic to the wall.

Box 23 Enter the direction of travel for the highway listed in box 22.

Box 24. Enter the function the primary roadway under performs (i.e. Mainline, Ramp, Frontage Road, etc.)

Box 25. Indicate if the primary roadway under carries the National Highway System. All IH and USH carry the system, but so do some other roads. More information on this can be found on this website: http://www.fhwa.dot.gov/planning/national_highway_system/nhs_maps/wisconsin/index.cfm

Box 26. Enter the primary functionality of the wall. If multiple, check all that apply and describe in the multiple space provided.

Box 27. Enter the noise abatement method as described on the plans.

Box 28. Indicate the date the plans were completed, if known.

Box 29. Enter the letting date, if known.

Box 30. Enter the year built, or the estimated year the work will be performed.

Box 31. Enter the type of work that was done on the structure.

Box 32. Enter the designer of record for the structure.

Box 33. Enter the primary fabricator of the structure.

Box 34. Indicate the contractor who installed or will install the structure in the field.

Box 35. Enter the construction project ID, if known.

Box 36. If project has been completed, enter the total cost of the structure. Otherwise leave blank.

Box 37-40 Used by Central Office staff in entering data into HSIS. No further information is required.

A - 5 Materials from British Columbia Ministry of Transportation (2013)

Ministry of Transportation and Infrastructure

Retaining Wall Inventory

Legend
Optional
Mandatory

Structure Number R **Structure Name** WALL **Inventory Date (yyyy/mm/dd)**
(Not entered in system)

Retaining Wall Details

Total Length (m):
Slope of Wall Face (degree):
Year Built: (yyyy)

Average Wall Height (m): .
Max. Wall Height (m): .
Slope Above Wall (degrees)

Length Slope Above Wall (m)

Retaining Wall Information

Wall Type:
Reinforcing Material:
Drainage System Type

☐ Approach Flares

Wall Location Relative To Road
Offset Side
Offset From Center Line Distance (m)

Inspections

Month:
Inspection Type:
Inspection Interval (months):

Sequence No.:
Inspection Type:
Inspection Interval (months):

Present Value ($):
Present Value Date (yyyy/mm/dd):
Construction Cost ($):

Retaining Wall Details LOV

Wall Type Description:

Concrete:
- C01. Concrete Cast in Place
- C02. Precast Small Block - No Mortar
- C03. Precast Small Block - Partial Height Mortar
- C04. Precast Small Block - Full Height Mortar
- C05. Precast Lockblock - unreinforced
- C06. Precast Lockblock - reinforced
- C07. Precast Panel "Hexagonal" - MSE
- C08. Precast Panel "Plus" - MSE
- C09. Precast Panel "Diamond" - MSE
- C10. Precast Panel "Rectangular" - MSE
- C11. Precast Crib
- C12. Shotcrete
- C13. Precast Stacked CRB
- C14. Precast - Stesswall
- C15. Concrete - Other

Landscape Wall:
- L01. Landscape Precast RECO
- L02. Landscape Precast Crib
- L03. Landscape Precast Concrete
- L04. Landscape Geosynthetic, Cellular Type Wall
- L05. Landscape Geosynthetic Wrapped Slope
- L06. Landscape - Other

Rockfill Faced Wall:
- R01. Rock Wall: Mortar
- R02. Rock Wall: No Mortar
- R03. Rock Gabion
- R04. Rock - Other

Sandbags:
- B01. Sandbags
- B02. Concrete Filled Sandbags

Steel Face Walls:
- S01. Steel Binwall Concrete Paneled
- S02. Steel Binwall Wood Paneled
- S03. Steel Binwall Steel Panel
- S04. Steel RECO MSE
- S05. Steel Welded Wire/Wire Mesh
- S06. Steel Sheet Pile
- S07. Steel Soldier Pile
- S08. Steel Piles Wood Lagging
- S09. Steel Piles Concrete Lagging
- S10. Steel Multiplate
- S11. Steel Other

Wood:
- W01. Wood Log Crib - Treated
- W02. Wood Log Crib - Untreated
- W03. Wood, Sawn Crib - Untreated
- W04. Wood, Sawn Crib - Treated
- W05. Wood Soldier Piles
- W06. Wood Piles Wood Lagging
- W07. Wood - Other

X. Other

Z. Unknown

Reinforcing Material

Code:	Description:
A	Concrete
B	Metal
C	Plastic
D	Timber
E	Other
F	Unknown
G	None

Wall Location Relative to Road

Code:	Description:
A	Above
B	Below

Drainage System

Code:	Description:
A	Drain pipes or weep holes visible on wall face
B	Base Draining Type Only
C	Through Wall Facing
D	Unknown
E	None

Offset Side

Code:	Description:
L	Left
R	Right
B	Both Left and Right

Jurisdiction Agency ID

Number:	Name:
1	Ministry of Transportation
2	Other Provincial Ministry
3	Railroad
4	Federal government Agency
5	Municipal Government
6	Company or Corporation
7	Private Citizen
8	Unknown (Historical)
9	Other

Ministry of Transportation and Infrastructure

Ministry of Transportation and Highways

RETAINING WALL CONDITION INSPECTION

Inspection Type: Routine ☐ Detailed ☐ Partial ☐

Structure Number ________ **Structure Name** ________ **Inspection Date (yyyy/mm/dd)** ________

COMPONENT		PERCENT CONDITION RATING Enter % in each condition. See BMIS User Manual 15.2.7							INSPECTION NOTES BY COMPONENT All poor or very poor conditions should be explained with notes and documented by photos. Label explanation(s) with component numbers.
	HYDROTECHNICAL	E	G	F	P	V	X	N	
1	Channel								
2	Erosion Protection								
3	Substructure Scour								
	FOUNDATION								
4	Wall Foundation								
	STRUCTURE								
5	Movement of Wall								
6	Retaining Wall								
7	Embankment								
8	Tie back/Connectors								
9	Wall Drainage System								
10	Coating								
11	Railings								
12	Roadway Flares								

Partial Inspection Notes:

General Inspection Notes:

Utility Concern Notes:

Urgency Rating Notes:

Condition Codes	
E Excellent	V Very Poor
G Good	X Not Inspected
F Fair	N Not Applicable
P Poor	

For Condition Guidelines see BMIS User Manual 15.2.2

Urgency Rating ____

For definition see BMIS User Manual 15.2.9 "4" and "5" rating must be explained.

________ Inspector (please type or print) ________ Signature

H0382F.doc (Updated 2011-02-24)

Structure Number

Instrumentation Notes

Drainage Area Description *(water level fluctuation, logging debris, etc.)*

Scour Notes

Rehab Work Notes

Maintenance Work Notes

A - 6 Materials from Victoria Roads (2014)

VicRoads Level 2 structure condition inspection

Condition rating sheet

Structure ID No.: S	Location (Km): (Fwd/Rev)
Road name:	Road number:
Crossing/General Location:	
Region:	Map reference: (Melways/VicRoads)
Inspector:	Date:

Component			Widening		% of component in each condition											
	No.		L/R	1/2		1			2			3			4	

Notes

Sheet of

VicRoads Level 2 structure condition inspection

Structure defect sheet

Structure ID No.: S	Location (Km): (Fwd/Rev)
Road name:	Road number:
Crossing/General Location:	
Region:	Map reference: (Melways/VicRoads)
Inspector:	Date:

COMP. No.	COMP. Name	Location	Quantity	Photo Nos.	Defect description

Sheet of

VicRoads Level 2 structure condition inspection

Structure information sheet

Structure ID No.: S		Location (Km): (Fwd/Rev)
Road name:		Road number:
Crossing/General Location:		
Region:	Map reference: (Melways/VicRoads)	
Inspector:		Date:

COMP. No.	Information or comment (Including: Load, Height, speed limits; hydraulic performance or similar; and location of any material testing & sampling)

Sheet of

VicRoads Level 2 structure condition inspection

Sketch sheet

Structure ID No.: S	Location (Km): (Fwd/Rev)
Road name:	Road number:
Crossing/General Location:	
Region:	Map reference: (Melways/VicRoads)
Inspector:	Date:

Sheet of

vicroads

VicRoads Level 2 structure condition inspection

Inventory and photographic record sheet

 Visual Screen Walls (SV) Noise Walls (SZ) Retaining Walls (SR)

Structure ID No.:	Location (Km): (Fwd/Rev)
Road name:	Road number:
Crossing/General Location:	
Region:	Map reference: (Melways/VicRoads)
Inspector:	Date:

GPS start of wall

Latitude South:	Longitude East:
Location:	

GPS end of wall

Latitude South:	Longitude East:
Location:	

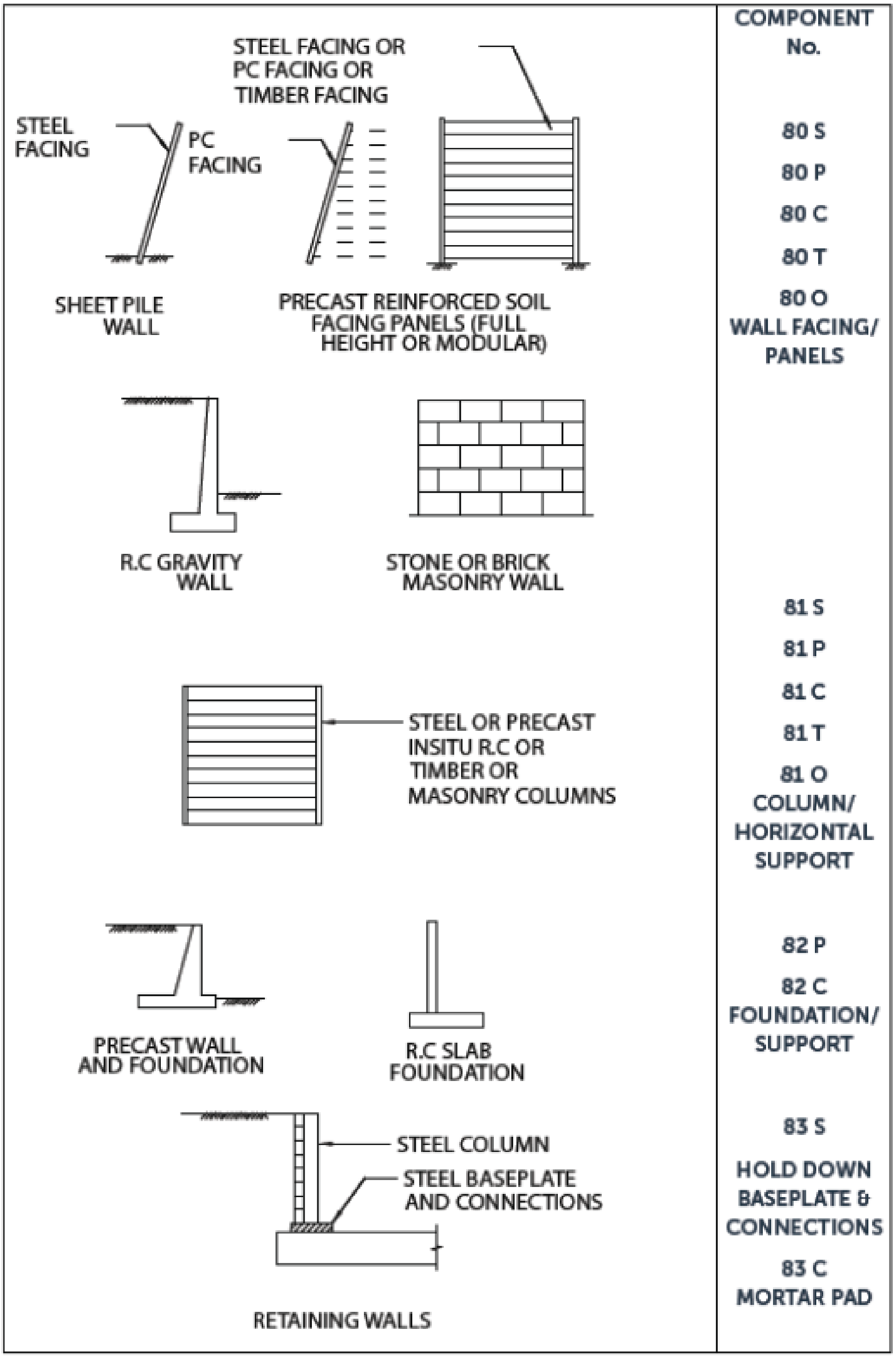
For Visual Screen or Noise Wall	Type of wall: (freestanding, on parapet or retaining wall, other)
	Material: (steel, concrete, timber, masonry, other)
For Retaining Wall	Materials: Facing, Supports
Side of road: (left or right)	Clearance from carriageway: m

Photos

No.	Location	Description	Comment
1.			
2.			
3.			

General comments

Sheet of


COMPONENT No.
STEEL FACING OR
PC FACING OR
TIMBER FACING
STEEL FACING
PC FACING
SHEET PILE WALL
PRECAST REINFORCED SOIL FACING PANELS (FULL HEIGHT OR MODULAR)
80 S
80 P
80 C
80 T
80 O
WALL FACING/ PANELS
R.C GRAVITY WALL
STONE OR BRICK MASONRY WALL
81 S
81 P
81 C
81 T
81 O
COLUMN/ HORIZONTAL SUPPORT
STEEL OR PRECAST
INSITU R.C OR
TIMBER OR
MASONRY COLUMNS
PRECAST WALL AND FOUNDATION
R.C SLAB FOUNDATION
82 P
82 C
FOUNDATION/ SUPPORT
STEEL COLUMN
STEEL BASEPLATE AND CONNECTIONS
83 S
HOLD DOWN BASEPLATE & CONNECTIONS
83 C
MORTAR PAD
RETAINING WALLS

Component 85 P – Walls - precast concrete

Condition state 1

The elements are in good condition with no damage visible. There may be minor dampness or efflorescence powder visible in a few locations. No separation or relative movement between units is apparent

Condition state 2 (no photo)

Component 85 C – Walls - cast-insitu concrete

Condition state 1

The elements are in good condition with no damage visible. There may be minor dampness or efflorescence powder visible in a few locations. Wall slopes are true to line with no separation of the cast sections.

Condition state 2

Shrinkage cracks obvious and early signs of corrosion of reinforcement.

Component 86 S – Columns - steel

Condition state 1

Steel supporting I beams in sound condition. No signs of corrosion or deflection

Condition state 2

Incomplete filling of concrete around supporting steel posts with potential for water penetration and corrosion

Component 86 C – Columns - cast-insitu concrete

Condition state 1

Exposed bored pile retaining wall in sound condition with no evidence of significant cracking, movement, water penetration or corrosion.

Condition state 2 (no photo)

Component 87 P – Foundations/Supports - pre-cast concrete

Condition state 1

The foundations or supporting walls are in sound condition. No visible evidence of damage from vehicle impact. No visible movement due to settlement or rotation of wall. Drainage system at base of wall is structurally intact and operating effectively.

Condition state 2 (no photo)

A - 7 Materials from the Kentucky Transportation Cabinet (1998)

RETAINING WALL DATA SHEET

COUNTY: ______________
ROUTE: ______________
MILEPOST: ______________
DIRECTION: ______________
GPS: ______________
WALL HEIGHT: ______________
WALL LENGTH: ______________

[illegible]	WALL USE
1. RIGID	1. END BENT
2. GRAV	2. WING WALL
3. CANT	3. EARTH RET.
4. ANCH	4. NOISE
5. M.S.E	5. OTHER
6. PREFAB	
7. MOD	

THERMO	DISK NO.	
	IMAGE NO.	
PHOTO	ROLL NO.	
	PHOTO NO.	
VIDEO	TAPE NO.	
	START	
	END	

DISTRESS		1	2	3
1. VERT. DISP.	5. SPALLING	4	5	6
2. HORIZ. DISP.	6. RUSTING	7	8	9
3. FORWARD DISP.	7. STAINING	WALL PROFILE		
4. CRACKING	8. OTHER			

GENERAL NOTES OR SKETCH OF WALL

QUAD	DISTRESS	PHOTO	THERMO	COMMENTS
1				
2				
3				
4				
5				
6				
7				
8				
9				

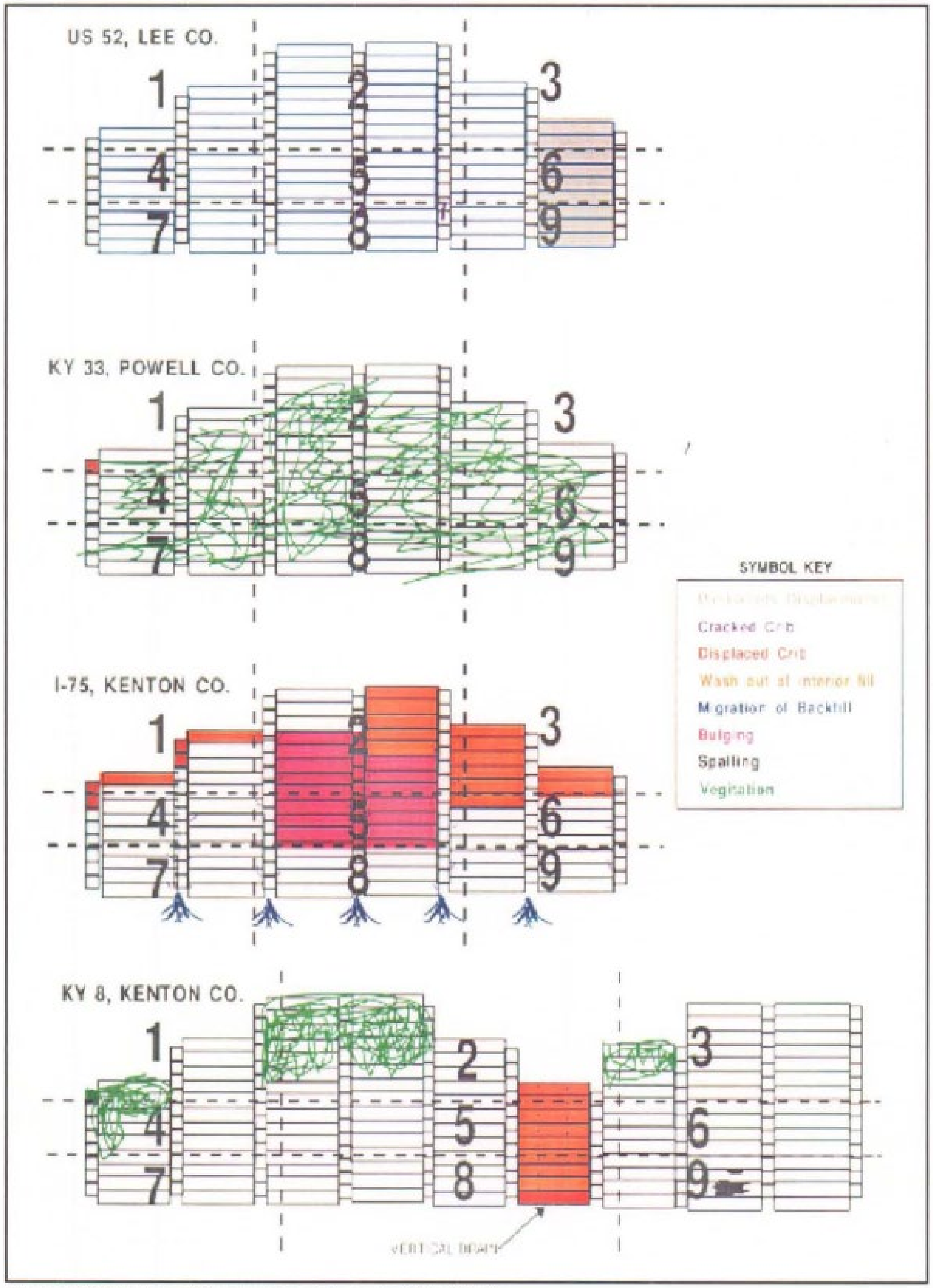


Figure 12: Distress Observed on Concrete Crib Walls

TABLE 1. Soil Retention Crib Wall (open and closed face)

LOCATION				SECTIONS								
				OBSERVED DISTRESS								
COUNTY	RT	MP	DIR	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Lee (open) fig. 6,10	US 52	n/a	n/a	7b	7b	3b,7b	7b	7b	3b,7b	7b	4b,7b	3b,7b
Powell (open) fig. n/a	KY 33	n/a	n/a	5a,4a,10b	10b	10b	10b	10b	10b	10b	10b	10b
Kenton (cld) fig. 4,5,8,11,15	175/71	187.7	N	4b,5b,6a	4b,6c,8b	4b,6c	4b	4b,8b	4b,6c	4b,7b	4b,7b	4b,7c
				DISTRESS OBSERVED AVG. (%)								
				3a=33%	4b=33%	3b=33%	4b=33%	4b=33%	3b=33%	4b=33%	4b=66%	3b=33%
				4a=33%	6c=33%	4b=33%	7b=33%	5a=33%	4b=33%	7b=66%	7b=66%	4b=33%
				4b=33%	7b=33%	6c=33%	10b=33%	7b=33%	6c=33%	10b=33%	10b=33%	7b=33%
				5b=33%	8b=33%	7b=33%		8b=33%	7b=33%			7c=33%
				6a=33%	10b=33%	10b=33%		10b=33%	10b=33%			10b=33%
				7b=33%								
				10b=33%								

TABLE 2. Soil Retention Crib /Wing Wall (closed face)

LOCATION				SECTIONS								
				OBSERVED DISTRESS								
COUNTY	RT	MP	DIR	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Kenton (cld) fig. 7,9,16	KY 8	7.57	W	4b,5b	10b	6c		10b	5b,6c		9b,10b	5c,6c,9b
				DISTRESS OBSERVED AVG. (%)								
				4b=100%	10b=100%	6c=100%		10b=100%	5b=100%		9b=100%	5b=100%
				5b=100%					6c=100%		10b=100%	6c=100%
												9b=100%

DISTRESS
1. VERT. DISP.
2. HORIZ. DISP.
3. BACKWARDS DISP.
4. CRACKED CRIB MEMBERS
5. DISP. CRIB MEMBERS(DUE TO EROSION)
6. WASH OUT OF INTERIOR FILL
7. MIGRATION OF BACKFILL
8. BULGING
9. SPALLING
10. VEGETATION

<u>SIGNIFICANCE OF DISTRESS</u>
A = SLIGHT B = MODERATE
C = SEVERE

A - 8 Materials from the City of Seattle (2014)

3/27/2017 11:26

Street Appurtenance Asset Type

Asset ID	RTW-018
Asset Description	3RD AVE W BETWEEN FLORENTIA AND DRAVUS
Asset Type	RTW
Compkey	512661
Current Status	INSVC

Location

Location Information

City Sector	W
Neighborhood District	MGNL-QA
Maintenance District	

Location Measurements

On Street	
Low Cross Street	
Curb Space #	
Feet To	0.0
Measured From?	no
High Cross Street	
Feet To	0.0
Dir From Cross Street	
Measured From?	no
Measurement Origin	
Side of Street	

Address

Street Appurtenance Address

	Address
Street #	
Pre Dir	
Street Name	
Suffix	
Post Dir	
Subdesignation	
Cross Street	
Cross Street	
City, State, ZIP	
City Sector	
Neighborhood	

Structural

(Tab Not Loaded)

Associated

(Tab Not Loaded)

Attachments

(Tab Not Loaded)

Comments

(Tab Not Loaded)

Associated Assets

(Tab Not Loaded)

Perf Indicators

(Tab Not Loaded)

Life History

(Tab Not Loaded)

Retaining Wall Info

Retaining Wall Information

Year Built	12/31/1923
Built By	
Built to City Standard	
Year	0
Year Rehabilitated	0
Year Replaced	0
Structure Integrity Status	
Monitor	no
Local Slide History	
Detour Length	0.00
Summit Activity ID	
Summit SCAT	
	Miles
	Installation and Maintenance Agreement
Field Book No.	
LID	3626
Historic Register	
SU Permit No.	

Retaining Wall

	Concrete Gravity
Retaining Wall Material Type	CRGRAV
Wall Length	275.00
	Feet

Components

Wall Min. Height	3.00
Wall Max. Height	12.00
	Feet
Post Material Type	
Rail Material Type	
Rail Length	0.00
	Feet
	Feet

Features / Functions

Retaining Wall Function	
Affected Features	
Affected Private Property	
Affected Street	
Fall Protection	
Weep Hole	
Subsurface Drain	
Tilt Monitoring Reference	

Record

Modified Date	
Modified By	
Added By	RS_INV_2013 AM
Added Date	12/27/1990 00:00

Related Assets

ID 1	
ID 2	
ID 3	
ID 4	
ID 5	

Status and Condition

Status and Condition

Current Status	INSVC
Current Status Date	12/21/2009
Asset Condition	
Condition Assessment Date	
Design Life	0
Last Asset Verification Date	
Anticipated Useful Life	0
Remaining Useful Life	0

Asset Disposition

Asset Disposition	
Disposal Reason	
Disposal Date	
Disposal Cost	0.00
Salvage Date	
Salvage Value	0.00

Asset Ownership

Ownership	SDOT
Date Ownership Assumed	
Maintained By	SDOT
Installation and Maintenance Responsibility/Agreement	
Maintenance Financial Responsibility	

Council Districts

Primary Council District	DISTRICT7
Secondary Council District	
Override	no
Override Comments	

Financial

Financial Information

Replacement Value	0.00
Replacement Value Date	
Lifecycle Cost	0.00
Planned Maintenance Cost	0.00

Acquisition/Improvement Grid

Acquisition/Improvement Comments
1

(No Data)

Work Order History

1

Work Order History Information

(No Data)

A - 9 Materials from the Ohio DOT (2007)

STATE OF OHIO DEPARTMENT OF TRANSPORTATION

MSE WALL INSPECTION CHECKLIST

District ☐ ☐ Date Inspected ☐ Name of Inspector

Is MSE wall at a bridge? (Y/N) ☐ ☐ County ☐ Route ☐ Section ☐ L/R ☐ RA/FA ☐ End Sec.

Instructions are on the 2nd page.

Yes No N/A		Measure-ment
	Joints	
○ Y ○ N ○ X	1. Is sand or gravel coming out of joints or are there piles of sand or gravel at the base of the wall? (Photos 2 & 3)	
○ Y ○ N ○ X	2. Is sand or gravel visible in the horizontal joints? (Photo 4)	
○ Y ○ N ○ X	3. Are the joints wide enough to see the sand, gravel or fabric behind the panels when looking perpendicular to the wall face using a flashlight? (Photo 5) If yes, record the approximate maximum joint width, in inches.	
○ Y ○ N ○ X	4. If fabric is visible in the joints, is it torn? IMPORTANT - DO NOT POKE OR CUT THE FABRIC.	
○ Y ○ N ○ X	5. Do the joints have a nonuniform size, or are some joints noticeably wider than others? (Photo 6)	
○ Y ○ N ○ X	6. Are the panels offset at the joints either in or out of the wall? (Photo 7) If yes, record the approximate maximum offset.	
○ Y ○ N ○ X	7. Is there vegetation growing in the joints? (Photo 8)	
	Wall Facing	
○ Y ○ N ○ X	8. Are there cracks in more than two facing panels? (Photos 9 & 10) If yes, record the approximate number of panels that are cracked.	
○ Y ○ N ○ X	9. Is the face of the wall bowed or bulged? (Photo 11)	
	Drainage	
○ Y ○ N ○ X	10. Are there any signs of water flow along the base of the wall?	
○ Y ○ N ○ X	11. Is there erosion of the embankment at the base of the wall? (Photo 12)	
○ Y ○ N ○ X	12. If there is erosion, is the leveling pad exposed at the base of the wall? (Photo 13)	
○ Y ○ N ○ X	13. Are the catch basins or the catch basin outlets near the wall blocked? (Photo 14)	
○ Y ○ N ○ X	14. Is the roadway drainage system above the wall malfunctioning?	
○ Y ○ N ○ X	15. Does water at the top of the wall collect behind the concrete coping?	
	Top of Wall	
○ Y ○ N ○ X	16. Is there settlement at the top of the wall?	
○ Y ○ N ○ X	17. Are there any open cracks in the concrete coping (not hairline cracks)? If yes, record the approximate maximum crack width.	
○ Y ○ N ○ X	18. Have the construction joints in the concrete coping opened up? (Photo 6) If yes, record the approximate maximum joint width.	
○ Y ○ N ○ X	19. Is there a gap larger than 1 inch between the approach slab and the approach pavement? (Photo 15) If yes, record the approx. max. gap size.	
○ Y ○ N ○ X	20. At abutments, has the joint between the wall coping and the abutment opened up more than two inches? (Photo 16)	

Revised 12/15/2005

STATE OF OHIO DEPARTMENT OF TRANSPORTATION

MSE WALL INSPECTION CHECKLIST

District		Date Inspected		Name of Inspector

Is MSE wall at a bridge? (Y/N)

County	Route	Section	L/R	RA/FA	End Sec.

Instructions are on the 2nd page.

Comments

Instructions

1. Enter the District, date inspected, and the name of the inspector.

2. Identify the MSE wall location.
   For MSE walls at bridges, use the section for the bridge in the C/R/S. For twin bridges with separate MSE walls, identify if the MSE wall is on the left or right. Identify if the MSE wall is at the rear or forward abutment.
   For MSE walls away from bridges, use the section at the beginning of the wall in the C/R/S. Identify if the wall is on the left or right of the roadway. Fill in the section for the end of the MSE wall.

3. Inspect the wall and answer the 20 questions. Refer to the example photos to identify the parts of an MSE wall and for guidance as to what to look for. A "Yes" answer to any of the questions may indicate a potential problem with the wall. When required, take an approximate measurement and record it in the box to the right of the question.

4. Take photos showing the entire height of the wall. For long walls, take multiple photos to show the entire length of the wall. For walls at bridges, take one photo of each section of wall.

5. For each "Yes" answer to a question, take a photo that shows the relevant item in sufficient detail to understand the reason for the "Yes" answer.

Necessary equipment

Digital camera, ruler, and flashlight.

A - 10 Materials from the Utah DOT (2009)

STATE OF UTAH MSE WALL INSPECTION FORM

Compiled As Part of Research By The Utah Department of Transportation

Instructions:

1-Fill out required sections for MSE Wall Inspector and Wall Characteristics.

2-Inspect the wall using the attached form. Questions that require a 'Yes' answer should be documented by noting the extent of the problem in the right most column and photo documentation. Photo documentation should consist of wall or bridge number, nature of problem, date, photo number for wall, and a size reference, which should be indicated in the photo (white board/paper). Photos taken should be placed on the Top View layout and indicated with the appropriate number. Note should be taken by the inspector that often anomalies are due to construction and should be distinguished from those that are a result of post-construction. If it is observable that they existed at the time of construction note should be taken in the space provided for drawings.

3- Shoot digital photos of the entire wall. This may require the use of a variety of shots and angles on each wall to cover the wall in its entirety.

4- Indicate Layout of MSE Wall in respect to major intersections, roadways, potential hazards, irrigation, vegetation, locations of conditions for which 'Yes' was marked, etc. in space provided below. Also Indicate approximate GPS Coordinates of Site of Interest in space provided below

Inspector Information

Inspection Date		**Names Of Inspectors**	
Region		**Identifying Road/Intersection**	

MSE WALL CHARACTERISTICS

MSE Wall at Bridge	Y N	**Bridge Number if applicable:**		**Wall Number**	

Surrounding Structures		Maximum Height of Wall (ft)	
Distance to Each Structure		One Stage, Two Stage or Block Wall	
State Route Number		Estimated Max Length of Wall Abutment:	
Approximate Mile Marker		Max Slope of Ground in front of wall:	
GPS Datum	WGS/84, NAD/83, or NAD/27	Max Height of wall burial line above surrounding level ground:	
MSE Wall GPS Coordinates (Location of Measurement shown on plan view)		Please draw rough layout of panel with approximate dimensions in space provided below:	
If known, Panel or System Manufacturer			
Are there coupons availabe for this wall? If so, how many?			

Summary of Key Observations:

Plan/Drainage View:

Cross Sections:

Cross Sections:

SPECIFIC WALL CHARACTERISTICS

DRAINAGE

Required Tools: Nylon Mallet-Water Bottle-Camera-Tape Measure

Yes	No	N/A	UKN	Drainage	Measurement/Explanation (if applicable)	Percentage of wall affected/Extent of Problem/Photo Number										
Y	N	N/A	UKN	Is there an active water source near the toe of the wall (is the wall near a body of water with scour potential) (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	If applicable, are the catch basins at the base of the wall blocked?(Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are there culverts protruding through the wall? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are there vertical drains that travel through the backfill? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there erosion at the base of the wall or leveling pad? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there erosion along the wing walls? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are there any signs of water flow along the base of the wall? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there less than 14 feet between irrigation sprinklers and wall? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Does the backfill or joint fabric appear to be saturated? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there vegetation growing in panel joints? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are the deck drains and outlets at the top of the wall blocked? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Can water enter the wall between coping and slab (i.e.. Drain appropriately)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there evidence at discharge point of fill washing through drain pipes? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	

MSE Wall Joints

Required Tools: Long Level-String-Camera-Tape Measure

Yes	No	N/A	UKN	Joints	Measurement/Explanation (if applicable)	Percentage of wall affected/Extent of Problem/Photo Number										
Y	N	N/A	UKN	Is backfill coming out of joints or are there piles of backfill at the base of the wall? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are the joints wide enough to see fabric or backfill behind panels when looking into joints? (Percentage of wall affected?) If yes, record the approximate maximum joint width in inches.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is exposed backfill visible in the horizontal joints? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are there visible tears in the fabric? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there evidence of backfill or water leaking through tears in fabric behind panels? (Do not induce additional damage to fabric) (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Do the joints have a non-uniform horizontal spacing/size? (I,e. Are some horizontal joints larger/smaller than others?) (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Do the joints have a non-uniform vertical spacing/size? (I,e. Are some horizontal joints larger/smaller than others?) (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are the panels offset at the joints either in or out of the wall? (Percentage of wall affected?) If yes, record the approximate maximum offset.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Does the fabric appear brittle, or appear as if it has undergone excessive UV exposure? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	

WALL FACING

Required Tools: Long Level-String-Camera-Crack Gauge-Tape Measure

Yes	No	N/A	UKN	Wall Facing	Measurement/Explanation (if applicable)	Percentage of wall affected/Extent of Problem/Photo Number										
Y	N	N/A	UKN	Were the panels built using "Tilt-Up" construction? (Percentage of wall affected?) Is there excessive cracking in the panels?		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Is there excessive cracking in panels? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are there cracks that continue vertically through adjacent panels? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are there cracks that continue horizontally through adjacent panels? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are the panel corners making contact with each other? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Are the panel corners "popped-off" or chipped from contact with adjacent panel(s)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	
Y	N	N/A	UKN	Does crack spacing suggest differential settlement? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%	

Y	N	N/A	UKN	Does the overlying coping exhibit vertical offset? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are the coping and parapets loose or detaching? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are the panels in danger of falling off? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Do the panels exhibit bulging? (Percentage of wall affected?) If so, record maximum deformation from accessible coping to leveling pad.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there 'tipping' at the top or bottom of the wall? (Percentage of wall affected?) (Record maximum degree of tipping from azimuth using vertical level and affected area).		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there excessive degradation of wall panels? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%

MSE TOP OF WALL

Required Tools: Long Level-Crack Gauge-Camera-Tape Measure

Yes	No	N/A	UKN	Top Of Wall	Measurement/Explanation *(If applicable)*	Percentage of wall affected/Extent of Problem/Photo Number									
Y	N	N/A	UKN	Is there evidence of settlement at the top of the wall (pavement cracking, etc)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are there any non-hairline cracks in the concrete coping? (Percentage of wall affected?) If yes, record the approximate maximum crack width.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Have the construction joints in the concreting coping opened up? (Percentage of wall affected?) If yes, record the maximum joint width.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there a large gap between the approach slab and pavement? (Percentage of wall affected?) Often this produces a bumping sensation as the overpass is crossed. Record the approximate maximum gap size.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N		UKN	At the abutments, has the joint between the wall coping and abutment opened up significantly? (Percentage of wall affected?) If so record maximum distance.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N		UKN	Is the coping/wall pulling away from pavement and roadway section? (Percentage of wall affected?) Please record maximum displacement for wall.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%

FOUNDATION CONDITIONS AND EXTERNAL STABILITY

Required Tools: Shovel, GEO-Probe-Tape Measure

Yes	No	N/A	UKN	Foundation Conditions & External Stability	Measurement/Explanation *(If applicable)*	Percentage of wall affected/Extent of Problem/Photo Number									
Y	N	N/A	UKN	What is the location depth of Leveling pad? (Percentage of wall affected?) Pound Geo-Probe into soil located 2 inches from wall to a maximum depth of 24 inches (24 inches is the minimum depth for MSE Wall)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is the leveling pad exposed?		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there cracking in the leveling pad? (Percentage of wall affected?) If so, record maximum crack size with gage.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there a four foot bench (level slope) along the base of the wall before the slope changes? (Percentage of wall affected?) If not record width of bench?		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there a slope steeper than H: 1.5 to V:1 behind the wall? (Percentage of wall affected?) Please record slope.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there a slope greater than V: 1.5 to H:1 below/in front of the wall? (Percentage of wall affected?) Please record slope.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%

CORROSION

Required Tools: Nylon Mallet-Camera-Zip Lock Bag-Trowel-Tape Measure

Yes	No	N/A	UKN	Corrosion	Measurement/Explanation *(If applicable)*	Percentage of wall affected/Extent of Problem/Photo Number									
Y	N	N/A	UKN	Is there excessive corrosion on guardrails or other exposed metal that might indicate corrosive conditions? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are there significant rust stains on face of the wall? Along joints? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are any internal straps exposed? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	If exposed, does there appear to be corrosion on straps? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Was a resistivity sample taken of soil? If so, please indicate depth taken in inches.		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there indication of rebar corrosion (i.e, swelling bars, rust, exposed metal inside epoxy coating)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is there evidence of Test Wires or Coupons included in the wall? If so, please indicate the possible number of Test wires available?		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%

IMPACT AND COLLISION

Required Tools: Camera

Yes	No	N/A	UKN	Impact and Collision	Measurement/Explanation *(if applicable)*	Percentage of wall affected/Extent of Problem/Photo Number									
Y	N	N/A	UKN	Are guardrails/wall protections in place at the base of the wall (to protect it from potential traffic hazards)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Does it appear that the wall has been involved in an accident (replaced panel, recent dings in the wall)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Does it appear the walls functionality and integrity has been compromised by a collision or accident? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%

MISCELLANEOUS

Required Tools:				Available drawings-Camera-Tape Measure											
Yes	No	N/A	UKN	Miscellaneous	Measurement/Explanation *(if applicable)*	Percentage of wall affected/Extent of Problem/Photo Number									
Y	N	N/A	UKN	Are there acute wall angles (<90)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are there available drawings for the wall? Please indicate type (Situation and Layout, Design, As Built, etc.) (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Is the layout in general accordance with drawings? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are the panels CIP (Cast in Place)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Was Geofoam used in the construction of the wall? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are there any structures on or near wall that were not included in initial drawings? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are there any irrigation, utilities, or intrusions that are not part of the initial drawings? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Have there been any excavations or evidence of excavations near the wall? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Have local property owners changed the dynamics of the wall (additional structures, irrigation, vegetation, etc.)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%
Y	N	N/A	UKN	Are there piles or other bridge support systems located in the wall (bridge abutment)? (Percentage of wall affected?)		0/No	1%	5%	10%	25%	50%	75%	90%	95%	100%

B. MOVEMENT OF THE M-10 WALL PANEL DURING JANUARY 2020

B.1. Introduction

In early January, during a period of high precipitation and cold temperatures, the M-10 wall panel instrumented in this study was reported to have failed. On January 14, 2020, the Structure Management Section (SMS) of Michigan Department of Transportation (MDOT) issued an emergency contract to closely inspect the M-10 retaining wall panel located at Thatcher Avenue (on the South Bound (SB)) along M-10 corridor in Detroit, MI. The wall section that was suspected of failing was identical to where the long-term wireless monitoring system was deployed in November 2018 offering the unprecedented opportunity to compare the wall response measured with the field observations. It should also be noted that the panel suspected of failing in January 2020 is within 1000 feet of the wall panel that failed in 2013 due to corrosion of the panel tieback rod (MDOT, 2013). The visual inspection of the suspected wall panel in January 2020 revealed significant displacement at the top of the wall (Figure B.1). The suspicion of the wall failing was further confirmed from a detailed analysis of the wall response data collected. This Appendix will highlight the data collected to assess the wall performance; the quantitative data is correlated to the visual observations made during inspection in January 2020.

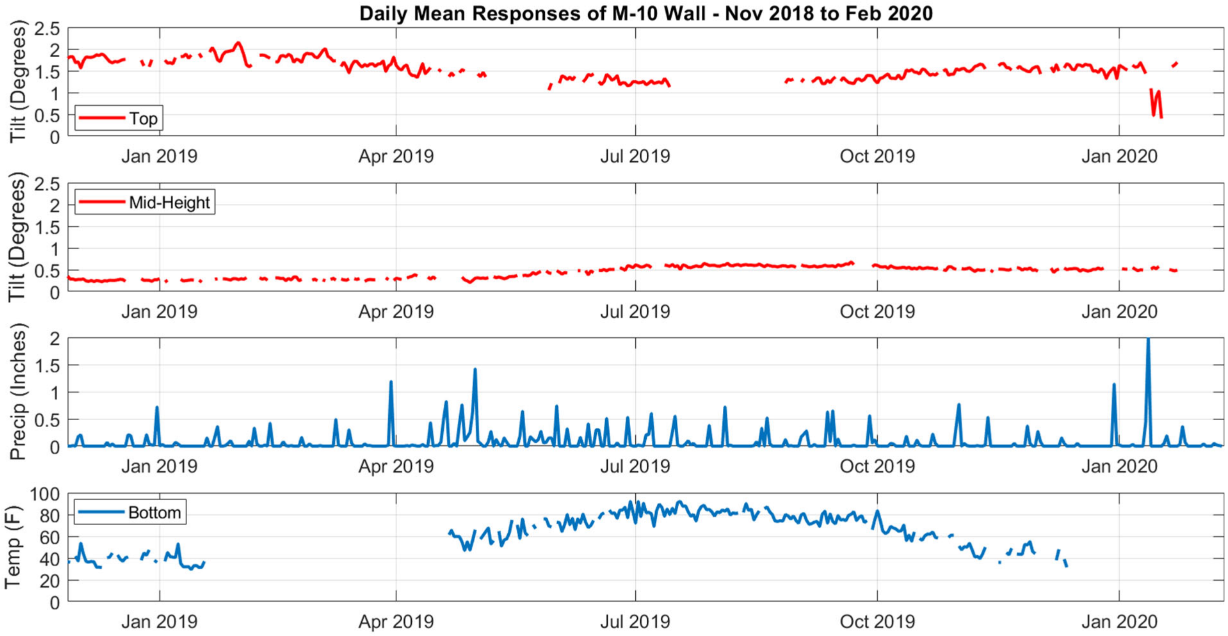
B.2. Visual Inspection of Wall

Upon visual inspection of the wall, two signs of potential wall panel failure were evident in January 2020. First, the concrete parapet at the top of the M-10 wall panel was evidently to have displace. Inspectors measured the movement of the parapet on the suspect failed wall panel was compared to the parapets of the adjacent wall sections. A displacement of 1 inch was measured by inspectors at both ends of the wall panel parapet. Figure B.1 highlights the measured displacement by inspectors using a ruler. These displacements were lower than those observed in 2013 during the failure of another panel along the M-10 freeway (that displacement was in the 3 to 4 inch range). Additional evidence of wall movement was a noticeable crack in the road asphalt surface running parallel to the wall. This crack was suspected to have developed when the wall panel thrusted forward; the thrusting of the wall forward would place the asphalt in tension resulting in the parallel crack observed (Figure B.2) .

(a) (b)

Figure B.1. Manually measured movement of the M-10 wall panel at the top wall parapet in January 2020.

Figure B.2. Top road surface at the top of the suspected failed M-10 wall panel (January 2020); major tensile crack in asphalt surface evident parallel to wall face.



(b)

Figure B.3. Measurement of the M-10 wall panel including early January 2020 with a high precipitation event on January 12, 2020 evident.

B.3. Measured Wall Movement

The top and mid-height tilt of the M-10 panel was continuously measured up to the point when the monitoring system was removed in February 2020. The monitoring system was operational during the time period of possible wall failure with the wall tilt data presented in Figure B.3. There was one major rain event on January 12, 2020 where the city of Detroit had a daily sum precipitation of 2.1 inches. This January 12, 2020 rainstorm was the largest rainfall event observed in the metro region of Michigan during the monitoring study (Weather Underground, 2020). A day after the rainstorm, the movement of the M-10 retaining wall panel caught the attention of MDOT managers who elected to pursue visual inspection and investigation. Prior to the rain event, the instrumented M-10 wall behaved normally as had been observed over the prior year with the top and mid-height tilts at approximately 1.6 degrees and 0.5 degrees, respectively (with positive tilt towards the freeway). However, immediately following the heavy rain, the wall mid-height tilt remained unaltered but the top wall tilt significantly changed to 0.34 degrees. A few days after the rain event, the wall appeared to have returned at the top portion to a tilt of 1.6 degrees. The dramatic change in rotation in the wall during and after the rain event resulted in a permanent

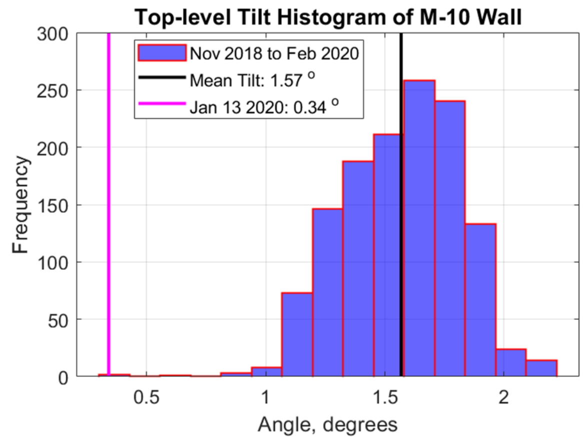
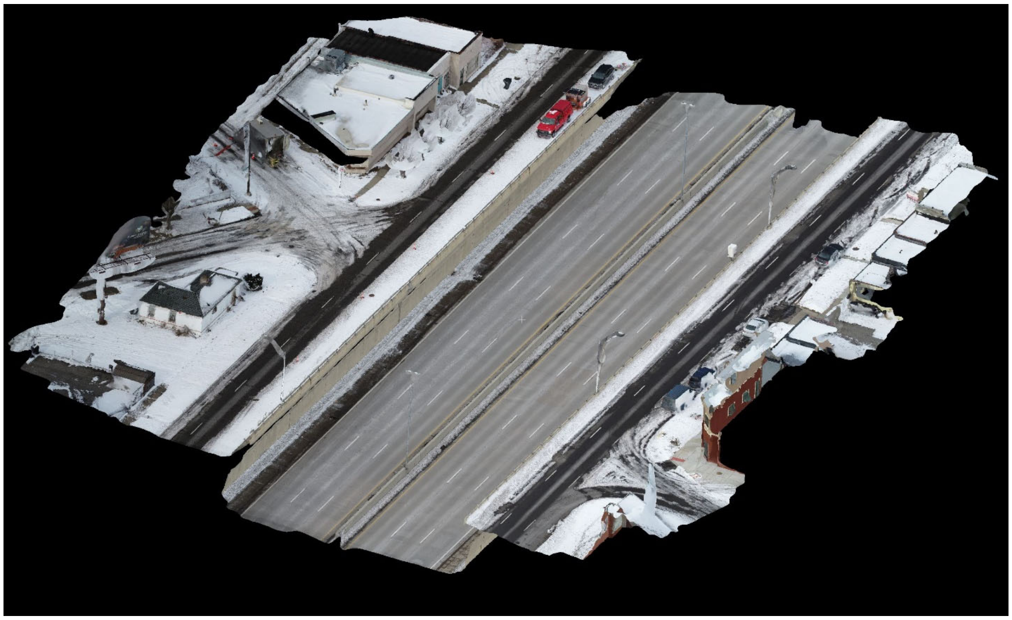


Figure B.4. Top tilt of instrumented M-10 retaining wall panel histogram

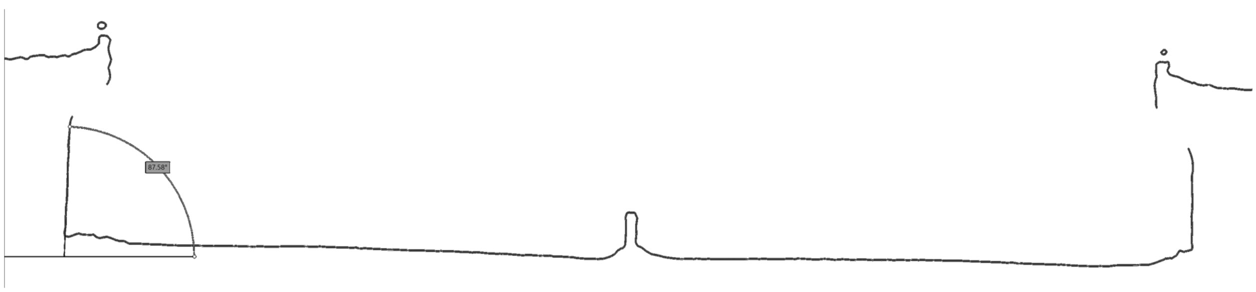
deformation of the wall top as observed by inspectors. The dramatic movement of the wall over the course of a few days was likely the culprit of the parallel crack observed in the asphalt road surface.

To provide a sense of the dramatic wall response, a histogram of the top tile of the wall is plotted in Figure B.4. The tilt of the top portion of the M-10 wall panel in January 13, 2020 is shown relative to the variation of wall tilt during the project monitoring period. The normal tilt changes at the top of the wall panel appear to be relatively Gaussian with a mean of approximately 1.57 degree and standard deviation of 0.14 degrees; the tilt observed on January 13, 2020 was approximately 7 deviations away from the distribution mean.

On January 22, 2020, an autonomous UAV flight was executed with MDOT personnel to collect additional aerial imagery of the retaining wall. This flight was conducted using a DJI Phantom 4 Professional UAV equipped with a high-resolution RGB camera. Evenly spaced, overlapping, geotagged imagery was collected of the site using flight capture software. Approximately 2.5 acres were surveyed in a total of 355 images. Using the collected imagery, a 3D model was generated using the Structure-from-Motion (SfM) photogrammetry technique which uses overlapping imagery to compute 3D data using the software package Pix4D Capture. The model achieved a ground sampling distance (spatial resolution) of 0.29 inches per pixel. An snapshot taken from the 3D model mesh can be seen in Figure B.5. Cross sections taken along the retaining wall point cloud model were extracted and exported into AutoCAD to compute the angle at which the wall is leaning at different locations. The yellow lines in Figure B.6 identify the locations of



(a)



(b)

Figure B.5. (a) 3D point cloud generated by Pix4D from aerial UAV imagery collected on January 22, 2020; (b) cross section of Panel 4.

the cross sections that were analyzed. Panels 1 through 9 span the entire area that was surveyed with the UAV. It should be noted that "Panel 4" corresponds to the instrumented panel. As shown, the panels are indeed tilted with tilts ranging from 1 degree (Panel 9) to 2.5 degrees (Panels 2 and 4). These tilts are larger than that measured by the long-term monitoring system (1.6 degrees as measured at Panel 4 by the monitoring system). These differences are likely due to calibration errors in the UAV photogrammetry method; specifically, there is an absence of a true sense of the horizontal plane associated with the cross-sectional analysis shown in Figure B.5. None the less, the relative tilt measurements shows more distress at Panels 1 through 5 with less at Panel 6 through 9. The measurements also confirm that the measurement of the wall leaning toward the highway is valid.

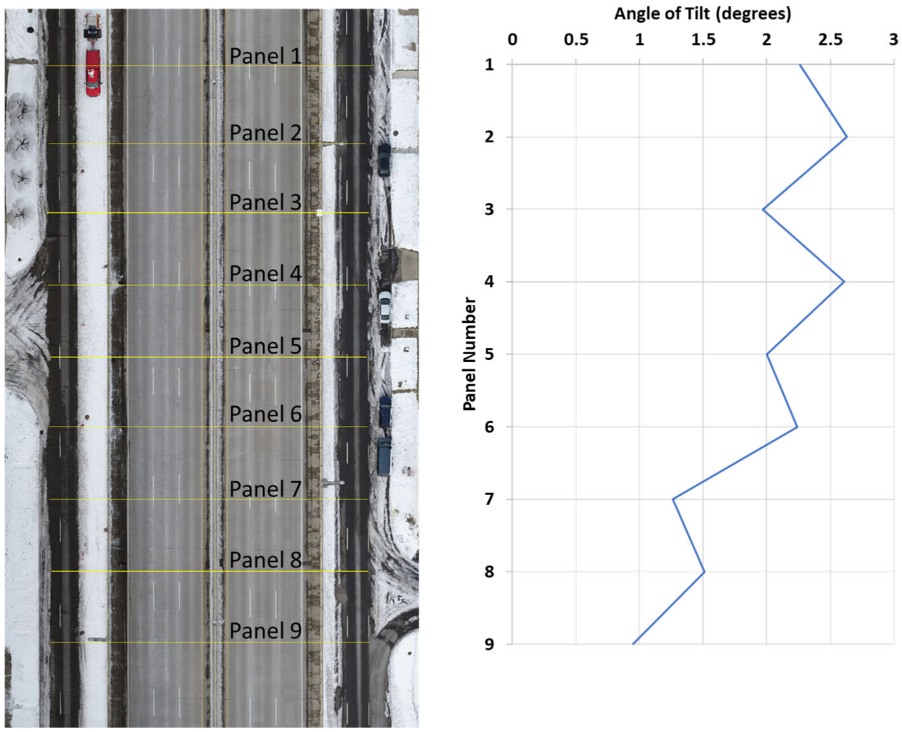


Figure B.6. (Left) plan view of 3D point cloud model with nine panels of the M-10 retaining wall system identified; (right) measured angle of tilt of the wall at each panel.

B.4. Conclusions

The instrument M-10 wall panel showed significant movement during the large rain event of January 12, 2020. The wall movement is hypothesized to be a direct response to the hydrostatic pressures of the undrained backfill during and immediately following the large rain event. Figure B.7 provides a description of the wall deflection before and during the rain event. Prior to rain, the wall deflected shape with the fully engaged caisson is shown as deflected shape (a-b-c) in Figure B.7. The tilt at the top of the wall can be attributed to the earth pressures on the back of the wall with the caisson stabilizing the wall with minimal tilt below its support point. The mid-height tilt is smaller and nearly stationary under environmental variation indicating the caisson is engaged and restraining the bottom portions of the wall from moving. During the rain event, the build-up of hydrostatic pressures near the top of the wall resulted in the wall moving towards the highway but with the top tilt moving to a more upright position as shown by deflected shape (a-b-d). A few days after the hydrostatic pressure subsided, the wall returned to a more normal tilt pattern. These observations suggest the tieback is still engaged but is perhaps offering less horizontal support to the wall indicating a tieback at the early stages of breakdown.

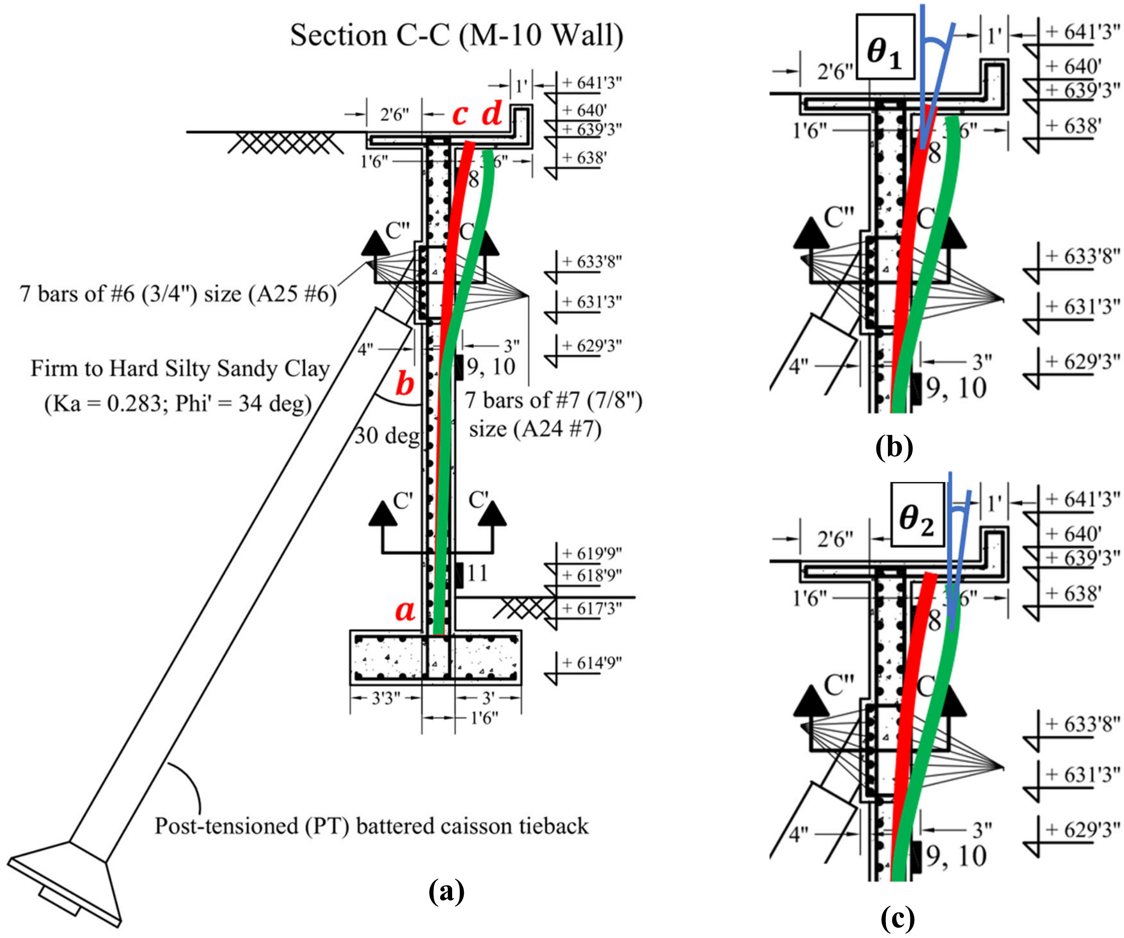


Figure B.7. Deformation curves of the drifted M-10 retaining wall system with the tieback caissons shown: (a) hypothesize deflection curve of the wall panel before the major rain event (a-b-c) and during high hydrostatic pressures immediately following the rain (a-b-d); (b) top-level rotation of retaining wall panel before movement showing a large tilt toward the freeway; (c) top-level rotation of retaining wall panel after the buildup of hydrostatic pressures resulting in displacement and reduced top tilt of the panel. The wall returns to deflected shape (a-b-c) after hydrostatic pressure is relieved.

Michigan Earth Retaining Structure Element Inspection Manual (MiERSEIM)

Michigan Department of Transportation

Civil & Environmental Engineering
University of Michigan

Mannik Smith Group

07/01/2019

PREFACE

The Michigan Earth Retaining Structure Element Inspection Manual (MiERSEIM) provides condition state information for earth retaining structures that are maintained within the state of Michigan. Earth retaining structures, for the purposes of this manual, are defined as any structure that retains and stabilizes an unstable soil mass by means of lateral support or reinforcement, has an exposed height of 4 ft. or greater, and a vertical, or near vertical face with an angle of inclination greater than 45 degrees from horizontal. Retaining walls are probably the most familiar type of earth retaining structures, but structures such as mechanically stabilized earth, crib walls, rock buttresses, gabion walls, rockeries, etc., that meet the previously stated height and face-angle requirements, are also considered important earth retaining structures. This manual is for use by earth retaining structure owners and inspectors when collecting element-level data for the assessment of the condition of earth retaining structures.

The consistent condition assessment of earth retaining structure elements is the most effective tool for the management of earth retaining structures. The element-level inspection method assesses the entire structure by breaking it down into several elements. Each element of the earth retaining structure is inspected closely and thoroughly. Each element is assigned a condition state based upon its observed and recorded amount of deterioration. Element-level inspection is a quantity based inspection method, and each quantity is described with a condition state to reflect the differing categories of deterioration that may exist on an earth retaining structure element.

The generation of a database for an earth retaining structure management system is a benefit of performing element-level inspections. By developing a database, earth retaining structure deterioration rates can be estimated, based upon the earth retaining structure's material, geographic location, age, usage, type, prior rehabilitation or preventative actions, etc. Software models that utilize the database will allow for comparisons between the effectiveness of preventative and corrective actions, predictions of deterioration, and life cycle cost analysis. Owners of earth retaining structures can then more easily make decisions regarding the prioritization of funds, when (or when not) to take action, and what type of action to take, so as to get the most benefit from the capital that is spent on their earth retaining structures.

INTRODUCTION

The purpose of the Michigan Earth Retaining Structure Element Inspection Manual (MiERSEIM) is to provide condition state information for structures inspected within the state of Michigan. These structures typically include highway earth retaining structures with height 4' or greater and angle of face inclination greater than 45 degrees from horizontal. This manual is to be used by earth retaining structure owners and inspectors when collecting element level data. This manual supplements the AASHTO Manual for Bridge Element Inspection, Michigan Bridge Element Inspection Manual and provides further classification of the AASHTO elements and descriptions for Agency Developed Elements.

The element level inspection method breaks the Earth Retaining Structure down into several elements. The element level inspection is a quantity based inspection and each quantity is assigned a Condition State to reflect the differing categories of deterioration that often exist on any Earth Retaining Structure element.

One of the results of performing element level inspections is the generation of a database for an Earth Retaining Structure management system. By developing a database over time, Earth Retaining Structure deterioration rates based upon material, geographic location, age, usage, type of crossing, prior rehabilitation or preventive actions, etc. can be estimated. The software modeling capabilities allow comparisons between the effectiveness of preventive and corrective actions, predictions of estimated future deterioration, and life cycle costs. Decisions can be made regarding prioritizing funds, when (or when not) to take action, and what type of action to take for the maximum benefit of capital spent.

DETAILED ELEMENT DISCRIPTIONS

This manual describes the individual wall elements evaluated in earth retaining system inspection and management processes.

The first section of the manual contains a detailed description for each element and is broken down into the following subsections:

- Element Number and Name
- Condition State Table to Reference
- Description – Detailed identification and classification of the element.
- Quantity Calculation – General guidelines on how to collect the quantity of the element and units.
- Element Commentary – Additional considerations the inspector is to be aware of during data collection, as appropriate.

The condition state tables are in the second section of the manual. They contain the following information:

- Condition State Definitions – Defect descriptions and severity with guidelines for the inspector on defect severity categorization.
- Pictures – Example cases of condition states.

Structural elements described are included in the standard set of National Bridge Elements (NBE), Bridge Management Elements (BME), or MDOT Agency Developed Elements (ADE). The elements are organized by element type; Primary Structural Elements and Secondary Non-Structural Elements.

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INDEX (cont.)

PRIMARY ELEMENTS

The Primary Elements of an Earth Retaining Structure (ERS) describe the structural components that are responsible for retaining earth for transportation purposes.

Included in the Primary Element category are Wall Facings, Foundations, Anchors, and Vertical Supports.

All primary elements can be supplemented with one or more associated protection systems.

WALL FACING (sq. ft.)

Description: The plane of the front surface of the exposed portion of the ERS.

No.	Name	CS Table	Description
860	MSE Walls	13	Mechanically Stabilized Earth (MSE) walls including the reinforced concrete stub, panels, coping, and drainage system. When piles are exposed use the appropriate material specific element.
900	Stone Masonry	5	Randomly laid natural stone, or cut stone laid in courses, with or without mortared joints.
901	Steel	3	Coated or uncoated flat steel plate, cold-formed steel panel sections, or corrugated steel sheets.
902	Prestressed Concrete	2	Shop-cast Portland cement concrete containing prestressed steel tendons in addition to conventional reinforcing steel.
903	Reinforced Concrete	1	Site-cast or shop-cast Portland cement concrete containing conventional reinforcing steel.
904	Timber	4	Pressure treated natural wood, such as sawn lumber or timber, or engineered wood, such as glulam timbers, engineered wood or plywood panels.
905	Placed Stone	6	Natural or cut stone, laid without mortar (dry-laid). Rockery.
906	Grouted Stone	6	Natural stone with cement-grouted interstices.
907	Masonry	5	Concrete masonry units (CMU's) or fired clay brick, laid in courses with mortared joints.
908	Grouted Block/Brick	6	Rectangular block of concrete or clay laid in courses together jointed with grout.
909	Shotcrete	6	Pneumatically placed fine-aggregate concrete.
910	Other	6	Other material earth retaining systems that cannot be classified by any other defined element.

Quantity Calculation: Include the area of the wall from ground elevation to the top of the wall bottom.

Element Commentary:

FOUNDATION (ft.)

Description: Those elements that transfer the loads acting on the ERS to the underlying soil or rock either directly (such as by a spread footing bearing on the soil or rock), or indirectly (such as through piles/caissons, or anchors).

No.	Name	CS Table	Description
220	Reinforced Concrete, Spread Footing	1	Site-cast or shop-cast Portland cement concrete containing conventional reinforcing steel.
225	Pile/ Caisson, Steel	3	Steel H-pile, concrete incased steel H-pile, or concrete filled steel pipe pile.
226	Pile/Caisson, Prestressed Concrete	2	Shop-cast portland cement concrete pile containing prestressed steel tendons.
227	Pile/ Caisson, Reinforced Concrete	1	Site-cast caissons or shop-cast piles consisting of Portland cement concrete with conventional reinforcing steel.
228	Pile/ Caisson, Timber	4	Pressure treated natural wood pile or engineered wood pile.
229	Pile/ Caisson, Other	6	Pile/caissons consisting of a composite of materials, or pile/caissons that cannot be defined as any other pile/caisson element.
231	Pile/ Caisson Cap, Steel	3	Coated or uncoated flat steel plate, cold-formed steel shape sections, or corrugated steel sheets.
233	Pile/ Caisson Cap, Prestressed Concrete	2	Shop-cast Portland cement concrete containing prestressed steel tendons in addition to conventional reinforcing steel.
234	Pile/ Caisson Cap, Reinforced Concrete	1	Site-cast or shop-cast Portland cement concrete containing conventional reinforcing steel.
235	Pile/ Caisson Cap, Timber	4	Pressure treated natural wood, such as sawn lumber or timber, or engineered wood, such as glulam timbers, engineered wood or plywood panels.
236	Pile/ Caisson Cap, Other	6	Pile/caisson cap consisting of a composite of materials, or a pile/caisson cap that cannot be defined as any other pile/caisson cap element.
834	Gabion/ Bin Wall	10	Basket or compartmented rectangular containers made of wire mesh filled with cobbles or other rock.

Quantity Calculation: Include the area of the face of the foundation from beginning to end and reference line to reference line.

ANCHORS (ea.)

Description: Those elements that transfer the loads acting on the ERS to the underlying stable soil or rock mass through tension (such as soil or rock anchors, micropiles, or ties attached to deadmen).

No.	Name	CS Table	Description
911	Wall Anchor, Ground Anchors	7	Also known as earth anchors, or mechanical anchors, either driven by impact into the ground, or run in spirally.
912	Wall Anchor, Soil Nails	7	Slender reinforcing elements, often either conventional reinforcing bars or proprietary solid or hollow-system bars, drilled or driven into a slope, and then pressure grouted tightly into place.
913	Wall Anchor, Micropiles	7	Also known as mini-piles, small-diameter (5-12 in.) cast-in-place, reinforced piles that are post-tensioned.
914	Wall Anchor, Heads	7	The part of the anchor that distributes the anchor loads into that element of the ERS to which it is attached. Often the only visible part of an anchor.
915	Wall Anchor, Others	7	An anchor that cannot be defined as any other anchor element.

Quantity Calculation: The quantity for these elements is each. The condition of one element may affect another causing multiple elements to be recorded.

Element Commentary:

VERTICAL SUPPORTS (ea.)

Description: Those vertical elements that transfer the loads acting on the ERS Wall Facing elements to the ERS Foundation elements, such as soldier pile, counterforts, and buttresses.

No.	Name	CS Table	Description
916	Vertical Support/Column, Steel	3	Hot-rolled steel shapes, including steel H-pile, and/or plates and/or cold-formed steel shapes.
917	Vertical Support/Column, Prestressed Concrete	2	Shop-cast Portland cement concrete containing prestressed steel tendons in addition to conventional reinforcing steel, including precast concrete soldier pile and/or counterforts.
918	Vertical Support/Column, Reinforced Concrete	1	Site-cast or shop-cast Portland cement concrete counterforts and/or buttresses containing conventional reinforcing steel.
919	Vertical Support/Column, Timber	4	Pressure treated natural wood soldier pile or engineered wood soldier pile.
920	Vertical Support/Column, Masonry	5	Buttresses constructed of concrete block, fired clay brick, and/or cut stone, laid in courses with mortared joints.
921	Vertical Support/Column, Other	6	A vertical support element that cannot be defined as any other vertical support element.

Quantity Calculation: The quantity for these elements is each. The condition of one element may affect another causing multiple elements to be recorded.

Element Commentary:

SECONDARY ELEMENTS

The Secondary Elements of an Earth Retaining Structure (ERS) describe the non-structural components which condition could affect the Primary Elements long term.

Included in the Secondary Element category are Vertical Coping/Pilasters, Horizontal Coping, Retained Material, Joints, Drainage Elements, Sidewalks, Railings/Barriers, Architectural Facings, Protective Coatings and Systems, and Overland Condition.

VERTICAL COPING / PILASTERS (ft.)

Description: Relief on the front face of the ERS consisting of a shape of any cross section, that projects out from the plane of the wall facing, and extends vertically upward from the base of the ERS.

No.	Name	CS Table	Description
922	Vertical Coping/Pilaster, Steel	3	Hot-rolled steel shapes, including steel H-pile, and/or plates and/or cold-formed steel shapes.
923	Vertical Coping/Pilaster, Reinforced Concrete	1	Site-cast or shop-cast Portland cement concrete containing conventional reinforcing steel.
924	Vertical Coping/Pilaster, Timber	4	Pressure treated natural wood, such as sawn lumber or timber, and/or engineered wood, such as glulam timbers, engineered wood or plywood panels.
925	Vertical Coping/Pilaster, Masonry	5	Cut stone, concrete block, or fired clay brick, laid in courses with mortared joints.
926	Vertical Coping/Pilaster, Other	6	A vertical coping/pilaster element that cannot be defined as any other vertical coping/pilaster element.

Quantity Calculation: The quantity for these elements is the sum of the vertical heights of the coping.

Element Commentary:

HORIZONTAL COPING (ft.)

Description: Relief on the front face of the ERS consisting of a shape of any cross section, that projects out from the plane of the wall facing, and extends horizontally along the wall at a constant elevation.

No.	Name	CS Table	Description
927	Horizontal Coping, Steel	3	Hot-rolled steel shapes and/or plates, and/or cold-formed steel shapes.
928	Horizontal Coping, Reinforced Concrete	1	Site-cast or shop-cast Portland cement concrete containing conventional reinforcing steel.
929	Horizontal Coping, Timber	4	Pressure treated natural wood, such as sawn lumber or timber, and/or engineered wood, such as glulam timbers, engineered wood or plywood panels.
930	Horizontal Coping, Masonry	5	Cut stone, concrete block, or fired clay brick, laid in courses with mortared joints.
931	Horizontal Coping, Other	6	A horizontal coping element that cannot be defined as any other horizontal coping element.
231	Sheet Pile Cap, Steel	3	Hot-rolled steel shapes and/or plates, and/or cold-formed steel shapes.
234	Sheet Pile Cap, Concrete	1	Site-cast or shop-cast Portland cement concrete containing conventional reinforcing steel.

Quantity Calculation: The quantity for this element is the sum of the length of the coping.

Element Commentary:

RETAINED MATERIAL (ft.)

Description: The difference in the elevation of where the extended plane of the surface of the retained material behind the wall intersects with the plane of the wall facing, and the elevation of the plane of the surface of the material in front of the wall's intersection with the plane of the wall facing.

No.	Name	CS Table	Description
932	Retained Material	9	The difference in the elevation of where the extended plane of the surface of the retained material behind the wall intersects with the plane of the wall facing, and the elevation of the plane of the surface of the material in front of the wall's intersection with the plane of the wall facing.

Quantity Calculation: The quantity for these elements is the sum of the length of the retained material from beginning to end.

Element Commentary:

JOINTS (ft.)

Description: Vertical or horizontal discontinuities in the wall facing, created intentionally to relieve differential movement (such as expansion and contraction joints), as a result of construction procedures (such as construction joints, cold joints, or bolted connections), or as a characteristic of the wall facing material (such as the edges of timbers or precast panels).			
No.	**Name**	**CS Table**	**Description**
959	Expansion Joint	8	Joints that are open and not sealed.
306	Joints, Other	8	Joints that cannot be classified using any other defined joint element.
Quantity Calculation: The quantity for this element is the sum of the lengths of all joints.			
Element Commentary:			

DRAINAGE ELEMENTS (ft.)

Description: Elements that collect and convey water around and/or through the ERS (such as porous backfill, weepholes, underdrains and collector pipes, lined drainage swales, etc.).

No.	Name	CS Table	Description
933	Weep Holes	6	Small diameter conduit cast in the stem of the ERS that dissipates static water pressure behind the wall (backfill side) by allowing water to flow through to the front side of the wall.
934	Area Drainage	6	Underdrains and collector pipes that convey water from the ERS backfill to an outfall.
935	Drainage Swale	11	A shallow ditch either immediately in front of the ERS or behind the ERS (backfill side) for the purpose of conveying water away from the ERS.
936	Drainage Element, Other	6	Drainage elements that cannot be classified using any other defined drainage element.

Quantity Calculation: The quantity for this element is the sum of the lengths of the element from beginning to end.

Element Commentary:

RAILINGS/BARRIERS (ft.)

Description: Either elements that protect the ERS from vehicular impact,(such as barrier along the bottom of the ERS) or elements that protect pedestrian and vehicular traffic from the drop-off created by the ERS (such as barriers, parapets, or railing along the top of the ERS).

No.	Name	CS Table	Description
937	Wall Railing/Barrier, Steel	3*	All types and shapes of metal railing/barrier. Steel, aluminum, metal beam, rolled shapes, etc. will all be considered part of this element. Included in this element are the posts of metal, timber, concrete, masonry, blocking and curb. This includes thrie-beam retrofit.
938	Wall Railing/Barrier, Reinforced Concrete	1	All types and shapes of reinforced concrete railing/barrier. All elements of the railing (not including incidentals such as handrails or pedestrian fencing) must be concrete.
939	Wall Railing/Barrier, Timber	4*	All types and shapes of timber railing/barrier. Included in this element are the posts of metal, timber, concrete, masonry, blocking and curb.
940	Wall Railing/Barrier, Masonry	5	All types and shapes of masonry, stone railing/barrier. All elements of the railing must be masonry, stone.
941	Wall Railing/Barrier, Other	6*	Any type of railing/barrier that cannot be classified using any other defined railing element.

Quantity Calculation: The quantity for this element is the number of railings/barriers times the length of element.

Element Commentary: * Mixed materials on railings may require referring to multiple CS-Tables

ARCHITECTURAL FACING (ea.)

Description: Any of several possible aesthetic treatments that may be done to the wall facing of the ERS that do not affect the structural integrity of the ERS (such as form-lined or precast relief, sculpted surfaces, embedments, thru-color, etc.).

No.	Name	CS Table	Description
942	Architectural Facing, Steel	3	Any type of architectural facing done to a wall with steel facing elements.
943	Architectural Facing, Concrete	1	Any type of architectural facing done to a wall with concrete facing elements.
944	Architectural Facing, Timber	4	Any type of architectural facing done to a wall with timber facing elements.
945	Architectural Facing, Masonry	5	Any type of architectural facing done to a wall with masonry facing elements.
946	Architectural Facing, Other	6	Any type of architectural facing that cannot be classified using any other defined architectural facing element.

Quantity Calculation: The quantity for these elements is each. The condition of one element may affect another causing multiple elements to be recorded.

Element Commentary:

PROTECTIVE COATING AND SYSTEMS (sq. ft.)

Description: Any of several possible surface treatments that may be done to the exposed surfaces of the wall facing or other elements of the ERS to protect the surface from weathering, chemical attack, vandalism, etc. (such as paint, stain, galvanizing, waterproofing, etc.

No.	Name	CS Table	Description
515	Steel Protective Coating	12	This element is for steel elements that have a corrosion inhibiting protective coating.
521	Concrete Protective Coating	12	This element is for concrete elements that have a protective coating. These coatings include silane/siloxane water proofers, crack sealers such as High Molecular Weight Methacrylate (HMWM), or any topcoat barrier that protects concrete from deterioration and reinforcing steel from corrosion.
849	A588 Steel Patina	12	This ADE should be used instead of element 515 and is only for the quantity of A588 steel patina that is exposed directly to the elements and not protected with any other system.
850	Healer Sealer	12	This element is for penetrating sealer (healer sealer) that has been applied as a flood coat to the horizontal surface in order to inhibit moisture and chloride intrusion. The material is designed to wear from the exposed surface over time, and maintain an impermeable seal in cracks that were present prior to application. For the evaluation of healer sealers use CS Table 12 defect Effectiveness – Concrete Protective Coatings.
899	Fiber Reinforced Polymer	12	This element is for FRP sheet and adhesive composite systems that have been applied to columns, beam ends, or other elements.
947	Timber Protective System	12	This element is for timber elements that have a field-applied preservative or fire resistant coating applied to them.
948	Other Protective System	12	Any type of protective coating system that cannot be classified using any other defined protective coating system element.

Quantity Calculation: The quantity for this element should include the entire area of protected surface for the element. The steel protective coating for superstructure elements for superstructure elements will be calculated by first determining the visible surface area of the primary structural elements (i.e. the top face of top flange is excluded) then adding 10% to account for secondary members.

Element Commentary:

OVERLAND CONDITIONS (ea.)

Description: Any additional elements of land or water features adjacent but a part of the ERS.

No.	Name	CS Table	Description
949	Channel Condition	11	This element describes any waterway feature along the front face of the ERS.
950	Channel Protection Material and Condition	11	This element describes the bank condition of a waterway feature along the face of the ERS. The protection material includes soil, fill, stone, rock, or concrete.
951	Upslope Material and Condition	11	This element describes the condition of the slope upward from the back/top of the ERS. The protection material includes soil, fill, stone, rock, or concrete.
952	Downslope Material and Condition	11	This element describes the condition of the slope downward from the face/bottom of the ERS. The protection material includes soil, fill, stone, rock, or concrete.
953	Lateral Material and Condition	11	This element describes the lateral condition of the ERS. The protection material includes soil, fill, stone, rock, or concrete.
954	Leveling Pad/Toe Protection	11	This element describes the condition material that the footing/foundation is set on, and the protection of the foundation of the ERS. The material includes soil, fill, stone, rock, or concrete.
955	Adjacent Slope	11	This element describes any adjacent slopes that may affect the ERS. The protection material includes soil, fill, stone, rock, or concrete.
956	Berm	11	This element describes a flat strip of land, raised bank, or terrace bordering a waterway feature.

Quantity Calculation: The quantity for these elements is each. The condition of one element may affect another causing multiple elements to be recorded.

Element Commentary:

SCOUR PROTECTION

Description: These elements define scour protection devices used to armor piers and abutments.

No.	Name	CS Table	Description
830	Plain Rip Rap	10	Angular interlocking stone with a median diameter of 8" The quantity for this element is measured in square feet.
831	Heavy Rip Rap	10	Angular interlocking stone interlocking with a median diameter of 16". The quantity for this element is measured in square feet.
829	Field Stone	10	Natural rounded stone with diameters varying from 8"-24". The quantity for this element is measured in square feet.
832	Channel Armoring	10	Channel bed, banks or embankment slopes surfaced with cast-in-place concrete to resist erosion and scour. The quantity for this element is measured in square feet.
833	Articulating Concrete Block	10	Preformed units that either interlock, are held together by cables, or both to form a continuous blanket or block matrix. The quantity for this element is measured in square feet.
834	Gabion	10	Basket or compartmented rectangular containers made of wire mesh filled with cobbles or other rock. The quantity for this element is measured in feet along the length of the protected structure.
835	Grout Filled Bags	10	Fabric bags filled with grout used for scour protection. The quantity for this element is measured in feet.
836	Sheet Piling	10	A continuous line of driven steel sheeting used for scour protection. The quantity for this element is measured in feet along the length of the protected structure.
837	Other Scour Countermeasures	10	Countermeasures that cannot be classified by any other defined scour countermeasure. The quantity for this element is measured in feet along the length of the protected structure.

Quantity Calculation: The quantities are measured along the substructure or culvert element protected and the extensions upstream and downstream from the structure. See description for units of measure.

Element Commentary:

APPURTENANCES (ea.)

Description: These elements define the components included in installing an overhead sign or utility conduits mounted to an ERS.

No.	Name	CS Table	Description
960	Wall Sign, Cantilever Mounted	14	This element describes any signage attached to the ERS structure with a cantilever mounted or bracketed system.
961	Wall Sign, Mounted	14	Description: This element describes any signage attached to the ERS structure flush mounted with bolted, anchored, or other attachment hardware.
957	Access Panels	15	This element describes any access panels for utilities or structural access within the ERS structure which failure would have a negative effect on the integrity of the ERS
958	Utilities	14	This element describes any conduits, pipes, or appurtenances that are attached to the ERS that carry a utility or utilities.

Quantity Calculation: The quantity for these elements is each. The condition of one element may affect another causing multiple elements to be recorded.

Element Commentary:

CONDITION STATE TABLES

The condition state descriptions herein are adopted from the National Bridge Elements and Bridge Management Elements and follow guidance provided by the AASHTO Bridge Element Manual and the FHWA. The condition state descriptions for Agency Defined Elements (ADEs) are defined by MDOT. This manual attempts to cover the majority of all conditions observed in the field, but during the course of an inspection, the inspector may find conditions that are not described. In these cases, the inspector should use the general description of the condition states to determine the appropriate condition. Overarching descriptors for the four condition states are as follows:

Condition State 1 (Good) – that portion of the element that has either no deterioration or the deterioration is insignificant to the management of the element, meaning that portion of the element has no condition based preventive maintenance needs or repairs. Areas of an element that have received long lasting structural repairs that restore the full capacity of the element with an expected life expectancy equal to the original element can be coded as good condition.

Condition State 2 (Fair) – that portion of the element that has minor deficiencies that signifies a progression of the deterioration process. This portion of the element may need condition based preventive maintenance. Areas of the element that have received structural repairs that improve the element, but the repair is not considered equal to the original member can be coded as fair.

Condition State 3 (Poor) – that portion of the element that has advanced deterioration requiring repair. The summation of the quantity of the element in poor or worse condition determines the need for repairs, rehabilitation, or replacement activities.

Condition State 4 (Severe) – that portion of the element that warrants a review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge. Elements with a portion or all of the quantity in state 4 may often have load capacity implications warranting a structural review. Within this manual, the term structural review is defined as a review by a person qualified to evaluate the field observed conditions and make a determination of the impacts of the conditions on the performance of the element. Structural reviews may include a review of the field inspection notes and photographs, review of as-built plans or analysis as deemed appropriate to evaluate the performance of the element.

CS TABLE 1 – REINFORCED CONCRETE

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Spalls/ Delaminations/ Patch Areas (1080)	None.	Delaminated. Spall 1 in. or less deep or less than 6 in. diameter. Patched area is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Exposed Rebar (1090)	None.	Present without section loss.	Present with section loss that does not warrant structural review.	
Efflorescence / Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (1) Reinforced Concrete and Other (1130)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Abrasion/Wear (1190)	No Abrasion of wearing	Abrasion or wearing has exposed coarse aggregate	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Settlement – Substructure Elements (4000)	None.	Exists within tolerable limits or arrested with effective actions taken to mitigate.	Exceeds tolerable limits but does not warrant structural review.	
Scour - Substructure / Culvert Elements (6000)	None.	Exists within tolerable limits or arrested with effective countermeasures.	Exceeds tolerable limits but is less than the limits determined by scour evaluation, and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

CS TABLE 1 – REINFORCED CONCRETE (Continued)

(1) The inspector should use judgment when utilizing the condition state defect conditions, especially for concrete cracking. The crack defect description definitions describe generalized distress, but the inspector should consider width, spacing, location, orientation, and structure or nonstructural nature of the cracking. The inspector should consider exposure and environment when evaluating crack width. In general, reinforced concrete cracks less than 0.012 inches can be considered insignificant and a defect is not warranted. Cracks ranging from 0.012 to 0.05 inches can be considered moderate, and cracks greater than 0.05 inches can be considered wide.

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE
		

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE

CS TABLE 2 – PRESTRESSED CONCRETE

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	GOOD	FAIR	POOR	SEVERE
Spalls/ Delaminations/ Patch Areas (1080)	None.	Delaminated. Spall 1 in. or less deep or less than 6 in. diameter. Patched area is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Exposed Rebar (1090)	None.	Present without section loss.	Present with section loss that does not warrant structural review.	
Exposed Prestressing (1100)	None.	Present without section loss.	Present with section loss that does not warrant structural review.	
Cracking [(1)] - PSC (1110)	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Efflorescence / Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Settlement – Substructure (4000)	None.	Exists within tolerable limits or arrested with effective actions taken to mitigate.	Exceeds tolerable limits but does not warrant structural review.	
Scour - Substructure (6000)	None.	Exists within tolerable limits or arrested with effective countermeasures.	Exceeds tolerable limits but is less than the limits determined by scour evaluation, and does not warrant structural review.	
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

CS TABLE 2 – PRESTRESSED CONCRETE (Continued)

(1) The inspector should use judgment when utilizing the condition state defect conditions, especially for concrete cracking. The crack defect description definitions describe generalized distress, but the inspector should consider width, spacing, location, orientation, and structure or nonstructural nature of the cracking. The inspector should consider exposure and environment when evaluating crack width. In general, reinforced concrete cracks less than 0.004 inches can be considered insignificant and a defect is not warranted. Cracks ranging from 0.004 to 0.009 inches can be considered moderate, and cracks greater than 0.009 inches can be considered wide.

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE
		

CS TABLE 3 – STEEL

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Corrosion (1000)	None.	Freckled Rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Cracking/Fatigue (1010)	None.	Cracks that have self-arrested or have been arrested with effective arrest holes, doubling plates or similar.	Identified cracks exist that are not arrested and do not require structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Connections (1020)	Connection is in place and functioning as intended.	Pack rust without distortion is present but the connection is in place and functioning as intended. Loose or missing fasteners accumulating in less than 10% of total fasteners.	Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but do not warrant a structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation but does not require structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Settlement – Substructure Elements (4000)	None.	Exists within tolerable limits or arrested with effective actions taken to mitigate.	Exceeds tolerable limits but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Scour – Substructure Elements (6000)	None.	Exists within tolerable limits or arrested with effective countermeasures.	Exceeds tolerable limits but is less than the limits determined by scour evaluation, and does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

CS TABLE 3 – STEEL (Continued)

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE
 Corrosion	 Corrosion	 Corrosion

CS TABLE 3 – STEEL (Continued)

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE

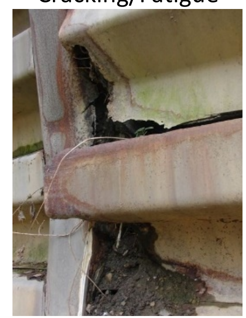

Cracking/Fatigue


Cracking/Fatigue


Cracking/Fatigue


Steel Bin Wall


Steel Bin Wall


Steel Bin Wall

CS TABLE 4 – TIMBER

<table>
<tr><th rowspan="2">Defect</th><th>Condition State 1</th><th>Condition State 2</th><th>Condition State 3</th><th>Condition State 4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Decay/
Section Loss
(1140)</td><td>None.</td><td>Affects less than 10% of the member section</td><td>Affects 10% or more of the member but does not warrant structural review.</td><td rowspan="5">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.</td></tr>
<tr><td>Checks/Shakes
(1150)</td><td>Surface penetration less than 5% of the member thickness regardless of location.</td><td>Penetrates 5% - 50% of the thickness of the member and not in a tension zone.</td><td>Penetrates more than 50% of the thickness of the member or more than 5% of the member thickness in a tension zone. Does not warrant structural analysis.</td></tr>
<tr><td>Cracks - Timber
(1160)</td><td>None.</td><td>Cracks that have been arrested through effective measures.</td><td>Identified cracks exist that are not arrested and do not require structural review.</td></tr>
<tr><td>Splits/
Delamination - Timber
(1170)</td><td>None.</td><td>Length less than the member depth or arrested with effective actions taken to mitigate.</td><td>Length greater than the member depth and does not require structural review.</td></tr>
<tr><td>Abrasion
(1180)</td><td>None or no measurable section loss.</td><td>Section loss less than 10% of the member thickness.</td><td>Section loss 10% or more of the member thickness but does not warrant structural review.</td></tr>
<tr><td>Damage
(7000)</td><td>Not applicable.</td><td>The element has minor damage caused by vehicular or vessel impact.</td><td>The element has moderate damage caused by vehicular or vessel impact.</td><td>The element has severe damage caused by vehicular or vessel impact.</td></tr>
</table>

CS TABLE 5 – MASONRY

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Spalls/ Delaminations/ Patch Areas (1080)	None.	Delaminated. Spall 1 in. or less deep or less than 6 in. diameter. Patched area is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Efflorescence (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Mortar Breakdown - Masonry (1610)	None.	Cracking or voids in less than 10% of joints.	Cracking or voids in 10% or more of the joints.	
Splits or Spalls - Masonry (1620)	None.	Block or stone has split or spalled with no shifting.	Block or stone has split or spalled with shifting but does not warrant a structural review.	
Patched Areas - Masonry (1630)	None.	Sound patches.	Unsound patches.	
Masonry Displacement (1640)	None.	Block or stone has shifted slightly out of alignment.	Block or stone has shifted significantly out of alignment or is missing but does not warrant structural review.	
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

CS TABLE 5 – MASONRY (Continued)

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE
		

CS TABLE 6 – OTHER MATERIALS

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Corrosion (1000)	None.	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Cracking/Fatigue (1010)	None.	Cracks that have self-arrested or have been arrested with effective arrest holes, doubling plates, or similar.	Identified cracks exist that are not arrested and do not require structural review.	
Connections (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but do not warrant a structural review.	
Spalls/ Delaminations/ Patch Areas (1080)	None.	Delaminated. Spall 1 in. or less deep or less than 6 in. diameter. Patched area is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area is unsound or showing distress. Does not warrant structural review.	
Efflorescence / Rust Staining (1120)	None.	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (1) Reinforced Concrete and Other (1130)	Insignificant cracks or moderate-width cracks that have been sealed	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	
Deterioration (Other) (1220)	None.	Initiated breakdown or deterioration.	Significant deterioration or breakdown that does not warrant structural review.	

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	GOOD	**FAIR**	**POOR**	**SEVERE**
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

(1) The inspector should use judgment when utilizing the condition state defect conditions, especially for concrete cracking. The crack defect description definitions describe generalized distress, but the inspector should consider width, spacing, location, orientation, and structure or nonstructural nature of the cracking. The inspector should consider exposure and environment when evaluating crack width. In general, reinforced concrete cracks less than 0.012 inches can be considered insignificant and a defect is not warranted. Cracks ranging from 0.012 to 0.05 inches can be considered moderate, and cracks greater than 0.05 inches can be considered wide.

CS TABLE 7 – ANCHORS

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Corrosion (1000)	None.	Freckled Rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Connections (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but do not warrant a structural review.	
Distortion (1900)	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation but does not require structural review.	
Seal Adhesion – Anchors with Seals Only (2320)	Fully adhered.	Adhered for more than 50% of the joint height.	Adhered 50% or less of joint height but still some adhesion.	Complete loss of adhesion.
Seal Damage – Anchors with Seals Only (2330)	None.	Seal abrasion without punctures.	Punctured, ripped or partially pulled out.	Punctured completely through, pulled out, or missing.
Seal Cracking – Anchors with Seals Only (2340)	None.	Surface cracks.	Cracks that partially penetrate the seal.	Cracks that fully penetrate the seal.
Debris Impaction (2350)	None.	Partially filled, but still allowing free movement.	Completely filled and impacts joint movement.	Completely filled and prevents joint movement.

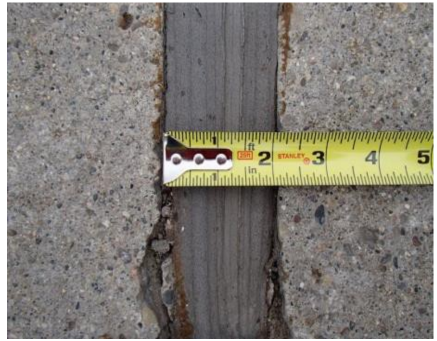
Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

CS TABLE 8 – JOINTS

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	GOOD	FAIR	POOR	SEVERE
Leakage (2310)	None.	Minimal. Minor dripping through the joint.	Moderate. More than a drip and less than free flow of water.	Free flow of water through the joint.
Seal Adhesion – Joints with Seals Only (2320)	Fully adhered.	Adhered for more than 50% of the joint height.	Adhered 50% or less of joint height but still some adhesion.	Complete loss of adhesion.
Seal Damage – Joints with Seals Only (2330)	None.	Seal abrasion without punctures.	Punctured, ripped or partially pulled out.	Punctured completely through, pulled out, or missing.
Seal Cracking – Joints with Seals Only (2340)	None.	Surface cracks.	Cracks that partially penetrate the seal.	Cracks that fully penetrate the seal.
Debris Impaction (2350)	None.	Partially filled, but still allowing free movement.	Completely filled and impacts joint movement.	Completely filled and prevents joint movement.
Adjacent Deck or Header (2360)	Sound. No spalls, delamination or unsound patches.	Edge delamination or spall less than 1 in. deep or less than 6 in. diameter. No exposed rebar. Patched area is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Exposed rebar. Delamination or unsound patched area that makes the joint loose.	Spall, delamination, unsound patched area or loose joint anchor that impacts joint performance.
Damage (7000)	None.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.
Pressure Relief (TBD)	Relief Joint is fully adhered and measures 4” wide	Joint measures 3” wide	Joint measures 2”wide	Joint material is missing, has lost adhesion or measures 1” wide

Condition State 2	Condition State 3	Condition State 4
FAIR	**POOR**	**SEVERE**


PRJ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CS TABLE 9 – RETAINED MATERIALS

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Settlement	None.	within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant a structural review.	**Safety:** Requires **immediate action** to ensure safety of public traffic. **Serviceability:** The condition is beyond the **limits established** in condition state three (3), **warrants a structural review** to determine the strength or serviceability of the element or ERS, or both.
Distortion	None.	Exists but does not require mitigation. Distortion that has been mitigated.	Distortion that requires mitigation that has not been addressed.	
Erosion	None.	Erosion less than 2-ft wide or deep.	Exposed top corner of leveling pad that is on rock.	

CS TABLE 10 – SCOUR PROTECTION

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	GOOD	FAIR	POOR	SEVERE
Scour or Erosion	None.	Countermeasure is substantially effective. Scour or Erosion exists without undermining.	Countermeasure device has limited effectiveness Erosion may be evident with undermining of countermeasure.	The channel protection device or scour countermeasure are unstable, missing or no longer effective.
Material Defect (scaling, abrasion, spalling, corrosion, cracking, splitting and decay)	Insignificant or minor defects.	Countermeasure device is substantially effective. Extensive minor to isolated advanced defects.	Scour countermeasures have limited effectiveness. Extensive advanced to major defects.	
Damage (unraveling, displacement, separation, and sagging)	Insignificant or minor damage.	Countermeasure device is substantially effective. Extensive minor to isolated advanced damage.	Scour countermeasures have limited effectiveness. Extensive advanced to major damage.	

CS TABLE 11 – OVERLAND CONDITIONS

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Counter measures	Present	Minor Damage	Undermined, rip rap washed away, structure is still stable.	**Serviceability or Immediate Safety Deficiency:** The condition is beyond the limits established in condition state three (3), warrants a structural review to determine the strength or serviceability of the element or bridge, or both.
Banks	Stable	Minor Slumping	Slumping	
Alignment	As Constructed	Minor Problems, Misalignment, angle has changed.	Misaligned, flow along foundation to expose footing or behind wall, structure is still stable.	
Embankments or slope protection	Moderate rutting from drainage. Minor bare soil exposed.	Minor Erosion caused by drainage or channel, Evidence of minor or stable foundation settlement, Erosion to embankment impacting guardrail performance or encroaching on shoulder.	Major erosion caused by drainage or channel; Erosion to embankment impacting guardrail (up to 6” of guardrail post exposed) performance or encroaching on shoulder. Evidence of foundation settlement.	

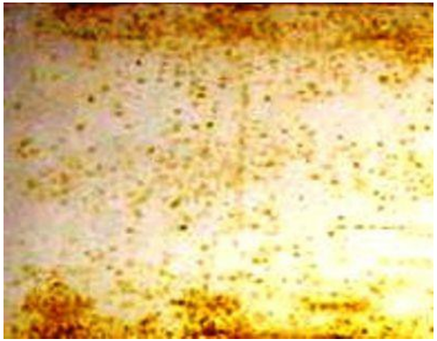
CS TABLE 12 – PROTECTIVE SYSTEMS

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Chalking - Steel Protective Coatings (3410)	None.	Surface dulling.	Loss of pigment.	Not applicable.
Peeling/Bubbling/Cracking - Steel Protective Coatings (3420)	None.	Finish coats only.	Finish and primer coats.	Exposure of bare metal.
Oxide Film Degradation Color/ Texture Adherence – Steel Protective Coatings (3430)	Yellow-orange or light brown for early development. Chocolate-brown to purple-brown for fully developed. Tightly adhered, capable of withstanding hammering or vigorous wire brushing.	Granular texture.	Small flakes, less than 1/2 in. diameter.	Dark black color. Large flakes, 1/2 in. diameter or greater or laminar sheets or nodules.
Effectiveness - Steel Protective Coatings (3440)	Fully effective.	Substantially effective.	Limited effectiveness.	Failed. No protection of the underlying metal.
Wear - Concrete Protective Coatings (3510)	None.	Underlying concrete not exposed. Coating showing wear from UV exposure. Friction course missing.	Underlying concrete is not exposed and thickness of the coating is reduced.	Underlying concrete exposed. Protective coating no longer effective.
Effectiveness - Concrete Protective Coatings (3540)	Good condition. Fully effective.	Substantially effective.	Limited effectiveness.	The protective system has failed or is no longer effective.

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Effectiveness - Protective System [e.g. cathodic, scour monitoring] (3600)	Fully effective.	Substantially effective.	Limited effectiveness.	The protective system has failed or is no longer effective.
Damage (7000)	Not applicable.	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	The element has severe damage caused by vehicular or vessel impact.

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE
		

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE





CS TABLE 13 – MSE WALLS

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Cracking – Reinforced Concrete Stub	Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate-width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.	The condition warrants a structural review to determine the effect on strength and serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element of bridge.
Cracking - Wall Panels/Coping	None.	Insignificant non-structural cracks without surface staining.	Structural cracks or cracking with surface staining.	
Joints	Wall panel joint spacing is substantially uniform.	Wall panel joint width exceeds as-built spacing without geotextile fabric exposure.	Wall panel joint width exceeds as- built spacing or is irregular with exposed geotextile fabric. Does not warrant structural review.	
Wall Tilting & Misallignment	None.	Minor uniform tilting of wall section. Minor wall misalignment.	Moderate uniform tilting of wall section. Moderate wall misalignment.	
Panel Bowing	None.	Panels have bowed without geotextile fabric exposure.	Panels have bowed with geotextile fabric or connections visible. Does not warrant structural review.	
Erosion	None.	Minor erosion visible without exposure of the leveling pad.	Erosion has exposed the leveling pad without undermining. No wall reinforcement exposed or loss of engineered fill. Does not warrant structural review.	
Damage	Not applicable.	The element has minor damage caused by vehicular impact.	The element has moderate damage caused by vehicular impact.	

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE


Loss of Backfill


Joint Spacing


Panel Bowing


Minor Spall


Moderate Misalignment


Deteriorated Panel

CS TABLE 14 – APPURTENANCES

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Alignment	Steel cantilevers, aluminum columns, and elastomeric pads are properly aligned.	Minor misalignment of steel cantilevers, or aluminum columns do not cover the full length of the sign. Elastomeric pad exhibits 20% loss of contact.	Sagging or misalignment of steel cantilever or aluminum columns is evident. Elastomeric pad exhibits between 20% and 60% loss of contact.	Sagging or misalignment of steel cantilever or aluminum columns warrants replacement. Elastomeric pad exhibits greater than 60% loss of contact.
Steel Wall Connections	Bolts are tight, sound, and well engaged. All washers present. Nuts are located on the interior face of the fascia beam. No corrosion present on the bolt, nut, or washer.	There is evidence of misalignment but tight bolts, or bolts missing washers, or small washers in oversized holes.	Bolts are missing, or there is evidence of broken welds. Between 0-20% of bolts in the connection are loose. Between 0-10% of fasteners in the connection are cracked, broken, or missing. Misaligned but tight bolts, or bolts with missing washers.	Greater than 20% of the bolts in the connection are loose. Greater than 10% of the fasteners in the connection are cracked, broken, or missing. Fastener proximity to edge of member is less than 1.5 times the bolt diameter. Fastener is missing, corroded, or improperly aligned. Washers cupped or bolt hole visible.
Concrete Anchored Connections	Bolts are tight, sound, and well engaged. Steel member flush with concrete surface.	Less than 10% of bearing surface exhibits light scaling, honeycombing, or ASR. Insignificant concrete cracking present.	Between 10% to 40% of bearing surface exhibits scaling, honeycombing, or ASR. Moderate concrete cracking or map cracking present.	Greater than 40% of the bearing surface exhibits scaling, honeycombing, or ASR. Wide concrete cracks or heavy map cracking present. Spalling, delamination, or anchor failure present.

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Cracking/Fatigue	None.	There is evidence of superficial concrete cracking in the vicinity of the bridge connection.	Concrete cracking continues to develop or increase in length and width within the vicinity of the bridge connection.	Cracking within the vicinity of the bridge connection, or fatigue cracks in the steel or aluminum sign members have developed.
Vertical Adhesive Anchors	Present with no visible defects.	Adhesively anchored rod, bolt, or bar is exhibiting severe corrosion.	Misalignment or annular gap at one or more adhesively anchored rod/bolt/bar, but no evidence of pull out. Or, anchors into cracked, delaminated, or spalled concrete. Or, loose or missing hardware.	Any evidence of pull out of one or more adhesively anchored rod/bar/bolt. This warrants immediate attention as some adhesives are susceptible to creep resulting in sudden failure.
Damage/Deterioration	Free of damage and debris.	There is minor damage to the sign or bridge connection caused by vehicular impact or environmental conditions.	There is moderate damage to the sign or bridge connection elements caused by vehicular impact, environmental conditions, or graffiti but the message is legible.	There is severe damage to the sign or bridge connection elements caused by vehicular impact, environmental conditions, or graffiti and the message is not legible.
Supports	Properly anchored and sound	Minor problem, active corrosion, loose joints but no exposed wires or leaks	Loose or missing support element but the utility is adequately supported, problems are not affecting ERS elements or public safety.	Broken or missing supports, affecting ERS elements or public safety.

Condition State 2	Condition State 3	Condition State 4
FAIR	POOR	SEVERE

Vertical Anchor

Vertical Anchor

Vertical Anchor

CS TABLE 15 – ASPHALT

Defect	Condition State 1 GOOD	Condition State 2 FAIR	Condition State 3 POOR	Condition State 4 SEVERE
Spalls/ Delaminations/ Patch Areas/ Potholes (3210)	None.	Delaminations. Spalls 1 in. or less deep or less than 6 in. in diameter. Patched areas are sound. Partial depth potholes.	Spalls greater than 1 in. deep or greater than 6 in. in diameter. Patched areas are unsound or showing distress. Full depth potholes.	The asphalt is no longer effective.
Cracks (3220)	Widths less than 0.012 in. or spacing greater than 3.0 ft.	Widths 0.012–0.05 in. or spacing of 1.0–3.0 ft.	Widths of more than 0.05 in. or spacing of less than 1.0 ft.	
Effectiveness (3230)	Fully effective. No evidence of leakage or further deterioration of the protected element.	Substantially effective. Deterioration of the protected element has slowed.	Limited effectiveness. Deterioration of the protected element has progressed.	
Damage (7000)	Not applicable	The element has minor damage caused by vehicular or vessel impact.	The element has moderate damage caused by vehicular or vessel impact.	