GEORGIA DOT RESEARCH PROJECT 20-11

Final Report

TOWARDS THE IMPLEMENTATION OF A GEOTECHNICAL ASSET MANAGEMENT PROGRAM IN THE STATE OF GEORGIA

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16. Abstract

Experiences at U.S. departments of transportation (DOTs) have demonstrated the value of geotechnical asset management (GAM) to enable a framework for informed decisions that align the DOT's objectives with investment and performance targets. However, because Georgia currently lacks a such a program, this study was performed to set the stage for developing a GAM program in the state with a primary focus on retaining walls. While walls were identified as the asset of the highest importance in Georgia, other critical infrastructure assets (i.e., slopes, embankments, and bridge foundations) were also considered. The proposed GAM system consisted of three phases: (1) inventory during design, (2) as-built inventory, and (3) maintenance inspection. Towards the development of a state-wide GAM program, a computational platform that accommodated the different proposed phases was developed and tested in metro Atlanta areas. The study also reviewed image-based and remote-sensing technologies for GAM. In particular, proof-of-concept studies that combined image-based and machine learning technologies for optimizing GAM processes for retaining walls in the metro Atlanta area were conducted, showing promising results. The study concluded by providing a road map for establishing a GAM program in the state of Georgia, considering short-term and long-term recommendations.

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Final Report

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2000)

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EXECUTIVE SUMMARY

The Georgia Department of Transportation (GDOT) has been managing transportation assets according to Georgia's Transportation Asset Management Plan (TAMP), which delineates the best practices and priorities to enhance asset preservation over time. Bridges and pavements are managed by their respective divisions, which are responsible for periodically assessing the asset's condition and establishing long-term life-cycle strategies by considering critical assets and limited funding. However, geotechnical assets have rarely been tracked, although their potential failure may lead to significant traveler delay, damage to other assets, and safety concerns. Because of this interdependence, an effective management of geotechnical assets is necessary to maintain the level of transportation safety and service required by the GDOT.

This study sets the stage for enabling a new geotechnical asset management (GAM) program in Georgia by developing a framework for implementing a GAM program in sequential phases. The proposed framework is developed based on the guidance in the National Cooperative Highway Research Program (NCHRP, 2019) "Geotechnical Asset Management for Transportation Agencies - Research report 903" but also considers previous experiences in the U.S. when required. Consistent with the recommended approach in the NCHRP (2019) report, the value of a lean start, which can be continuously refined, is emphasized. The geotechnical assets to be considered were defined in consultation with the Geotechnical Bureau of the Office of Materials and Testing at the GDOT, including retaining walls, slopes, embankments, and bridge foundations. They have been selected as they are critical pieces of the infrastructure that provides mobility, safety, cost-effectiveness, and economic viability of the overall transportation system in

Georgia. Moreover, among these assets, retaining walls were identified as having the highest importance for the state of Georgia, constituting this study's focus.

In proposing the GAM system, a literature review of GAM and asset management practices overseas, in the U.S., and in the state of Georgia is first conducted. The proposed GAM system considers the definition of relevant geotechnical features for different assets, separating them into mandatory and optional based on the ease of collecting them and their relative importance for the GDOT. In addition, different phases are considered for the GAM system, namely, (1) inventory during design, which includes the inventory of geotechnical assets in upcoming GDOT projects; (2) as-built inventory, considering the inventory of assets after construction and existing assets; and (3) maintenance inspection, which considers periodic inspections of previously inventoried assets. Towards enabling a GAM program in Georgia, this study also develops a computational platform for the inventory and condition assessment of geotechnical assets, with an initial focus on retaining walls. As part of the project scope, in-house and field training was conducted for selected GDOT personnel using the proposed platform. Considering the potential use of technology to optimize GAM processes, a literature review of image-based and remote-sensing techniques for GAM applications is conducted, providing suggestions to the GDOT. Finally, proof-of-concept assessments of the potential use of image-based technologies combined with machine learning for optimizing processes in the inventory of retaining walls and the extraction of retaining wall features in the metro Atlanta area are conducted, finding promising results. The report closes by providing a road map for establishing a GAM program in the state of Georgia, considering short-term and long-term recommendations.

CHAPTER 1. INTRODUCTION

Geotechnical assets are critical components of safe and effective transportation systems; however, currently, the Georgia Department of Transportation (GDOT) does not have a Geotechnical Asset Management (GAM) program, which has implications for safety and may impose additional non-quantified costs in the management of the transportation corridor in the state. In this context, this study sets the stage for enabling a GAM program in the state of Georgia by developing a framework for implementing a GAM program in sequential phases. The proposed framework is developed based on the guidance in the National Cooperative Highway Research Program (NCHRP, 2019) "*Geotechnical Asset Management for Transportation Agencies - Research report 903*" but also considers previous experiences in the U.S. when required. Consistent with the recommended approach in the NCHRP (2019) report, the value of a lean start, which can be continuously refined in time, is emphasized.

After consultation with the Geotechnical Bureau of the Office of Materials and Testing at the GDOT, the assets considered in the first phase of the GDOT GAM program include retaining walls, rock and soil slopes, embankments, and bridge foundations. These assets are critical pieces of the infrastructure that provides mobility, safety, cost-effectiveness, and economic viability of the overall transportation system in the state of Georgia (Figure 1). Thus, they play a vital role in GDOT risk management strategies and require asset management to ensure operational effectiveness.

Figure 1. Photo. Examples of different geotechnical assets: a) retaining wall, b) slope system, c) embankment, and d) bridge foundation. Modified from NCHRP (2019).

As described in the NCHRP (2019) report, the management of geotechnical assets in the United States has been delayed compared to the management of bridge and pavement assets, which have garnered significant attention from state transportation agencies for many years. Traditionally, geotechnical assets have been treated as unpredictable hazard sites with significant potential liability.That is, the failure of any geotechnical asset may lead to traveler delay, damage to other assets, or safety/loss of life issues (NCHRP, 2019). The current management practices for geotechnical assets in the transportation environment have been primarily focused on restoring the asset after failure rather than proactively identifying and remediating hazardous conditions before their occurrence. However, geotechnical assets are vital to the successful operation of transportation systems and present an opportunity for system owners and operators to realize new economic benefits. Developing a financially sustainable GAM system transportation agencies can use to enable more proactive infrastructure risk assessment is critical for strategic investment and long-term management of United States transportation infrastructure (Wolf et al., 2015).

While the GDOT has been routinely managing transportation assets such as bridges and pavements, geotechnical assets have rarely been tracked or inventoried despite the fact that all transportation system components are interrelated. Because of this interdependence, effective management of geotechnical assets is necessary to maintain the level of transportation safety and service required by the GDOT. There are significant advantages that a GAM implementation can provide to a transportation agency, with economic benefits that may ultimately be on the order of several million dollars (NCHRP, 2019). In particular, a GAM program enables the transition from a reactionary approach where the magnitude of risk is not known (imposing challenges on decision-making and allocation of resources) into a risk-based approach where, through continuous application, the risk is reduced to an acceptable (i.e., known) residual level that is cost-effective. This process is illustrated in Figure 2 and constitutes the long-term goal of a matured GAM program.

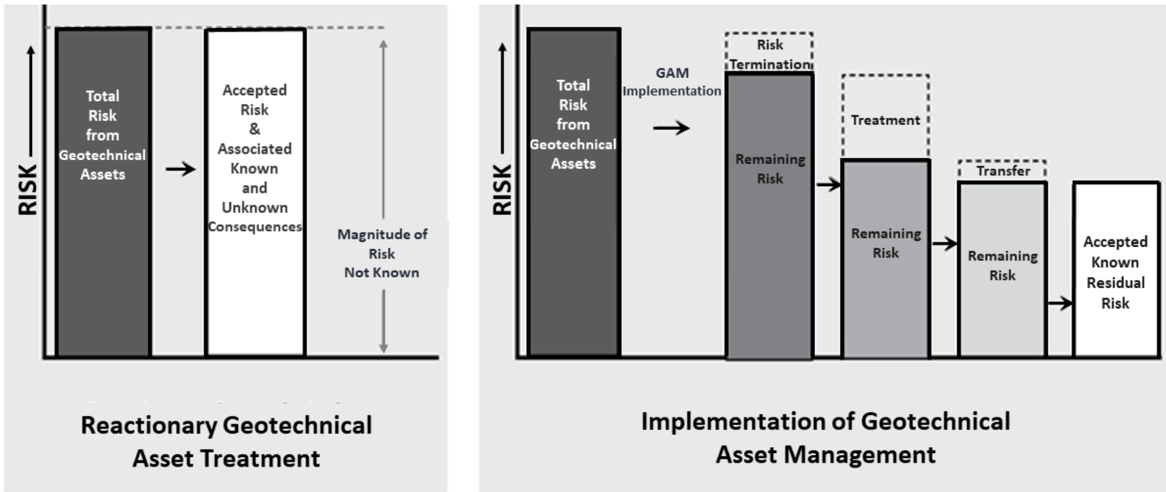

Figure 2. Graph. a) Reactionary geotechnical asset treatment (typical approach), b) risk reduction through a GAM process. Notice how a GAM plan in b) allows risk reduction through actions.

Given this context of transportation asset management in the state of Georgia, this report is organized as follows:

- Chapter 1: General aspects of this study and the motivations.
- Chapter 2: A literature review of GAM practices in the United States and overseas.
- Chapter 3: GAM framework for the state of Georgia proposed in this study. In addition, a GAM system for the state of Georgia, which considers inventory and inspection components, is presented.
- Chapter 4: A review of different technologies that can be used in GAM, focusing on remote sensing and image-based techniques. This section also presents the results of proof-of-concept studies using image-based techniques on retaining walls for metro Atlanta areas.

- Chapter 5 and 6: conclusions of this study and recommendations for future stages. In particular, a road map for a robust long-term GAM implementation in the state of Georgia is provided.

CHAPTER 2. GAM PRACTICES: INTERNATIONAL, UNITED STATES, AND THE STATE OF GEORGIA

This chapter provides a literature review of GAM practices in the United States. First, selected overseas efforts that have influenced the practice in the U.S. are highlighted, followed by GAM practices in different U.S. Departments of Transportation (DOTs), followed by GAM practices in the state of Georgia.

GEOTECHNICAL ASSET MANAGEMENT OVERSEAS

In the past few decades, the U.S. Federal Highway Administration (FHWA), seeking to strengthen the management of transportation assets, contracting procedures, risk-based decision making and planning, has explored more than 60 international GAM best practices and disseminated those findings nationwide (Geiger et al., 2005). In particular, asset management practices from the United Kingdom, Australia, and New Zealand (OIP, 1990) have focused on the following: (1) United Kingdom has developed innovative technologies and methods to manage its geotechnical assets in rail and road networks; (2) New Zealand has developed performance-based and performance-oriented decision making structures to improve maintenance operations and funding allocation; (3) Switzerland has gravitated towards risk-based management tools, depicting that balanced risk allocation policies maximize benefits for the agency and the private sector; and, (4) Australia has enhanced asset management strategies focusing on system performance and aging infrastructure (Geiger et al., 2005). More details of notable asset management systems overseas that have influenced the practice of transportation asset management in the U.S., including geotechnical assets, are summarized in Table 1.

Table 1. Selected International Asset Management Systems that have Influenced the Practice in the U.S.

Country	Asset	Comments	Reference
New Zealand	Transportation	• Transit New Zealand and Land Transport New Zealand (NZ) Agencies; • 6,733 miles of paved road, 2,600 bridges, more than 1,400 culverts, tunnels, and public transportation; • managing to develop sustainable transportation systems; • five to ten years of maintenance and operations contracts focused on performance; • high-quality information during inventory and condition assessment; • regional network plans should incorporate local asset management practices to ensure consistency within the nation.	Geiger et al., 2005
Switzerland	Natural hazards	• National Platform for Natural Hazards (PLANAT) (1997); • public and private involvement (e.g., insurance companies, multiple stakeholders) to share and maximize benefits from mitigation and risk-reduction procedures; • risk reduction tools implemented for infrastructure projects that cost more than 1 million pounds.	Bründl et al., 2009

Country	Asset	Comments	Reference
United Kingdom	Rail network	• 19,200 miles of infrastructure; • risk-based analyses on inventory and intervention processes; • proactive management of embankments in the UK produced life-cycle cost savings of up to 80 percent compared to standard reactive practices.	Perry et al., 2003 Network rail, 2021
United Kingdom	National Highways (previously Highways England)	• 44,000 miles of roadway and approximately 45,000 geotechnical assets (e.g., embankments and slopes); • calculation of risk failure based on five categories, including cause, defect, exposure, effect, and risk event; • inspection plan recommends visiting assets at a minimum once every five years to assess, inspect, and update.	Perry et al., 2003 Geiger et al., 2005
Queensland, Autralia	Road Network by the Department of Main Roads	• Responsible for 34,000 km (21,127 mi) of Queensland's road network, managing 20% of the state's road network but carries 80% of the traffic.; • The Roads Alliance program encourages local governments to identify and prioritize roads of regional significance, which will have access to additional resources, such as regional investment funds; • Their road asset management system is comprised by the Road Asset Data, Decision Support Tools, Reporting Tools and Investment Studies.	Geiger et al., 2005

GEOTECHNICAL ASSET MANAGEMENT IN THE UNITED STATES

Historically, U.S. DOTs have used asset management systems to maintain an inventory of critical transportation assets, such as roads, bridges, traffic signs, and other high-value or high-maintenance system elements. However, geotechnical assets have rarely been inventoried or periodically inspected through a GAM program. This is critical as all transportation components, including geotechnical components, contribute to the ability of infrastructure agencies to deliver reliable transportation networks and perform their strategic missions. Before the establishment of GAM systems in the United States, the vulnerability associated with the failure of the geotechnical assets (e.g., retaining walls, embankments, slopes, or bridge foundations) and the implication of the value of transportation networks had been overlooked (NCHRP, 2019). One of the most comprehensive compilations on how GAM practices have evolved in the United States is documented in the NCHRP Research Report 903.

In the United States, most GAM-related work has evolved from rock hazard rating systems (RHRS) initiated on a state-by-state basis in the early 1990s, with one of the first programs developed by the Oregon DOT with support from the FHWA and other states (Pierson, 1991). The RHRS has since been adopted or modified by several states, with some agencies including slope types as well. These systems have evolved substantially in the following decades, with current work focusing on developing risk-based GAM plans, which are currently the recommended state-of-the-art (Vessely, 2017). Other agencies, such as the United States Army Corps of Engineers (USACE), were also crucial in the early development of asset management systems, which were focused on water infrastructure. The central federal lands division of FHWA also explored GAM concepts as part of its planning strategies (Vessely, 2013). Other efforts to implement GAM-related tracking include the inventory and assessment of retaining walls in Cincinnati, Ohio, between 1990-2006, where 1800 walls were identified, with a $170M replacement value, and the inventory of 3500 walls in the U.S National Park System between 2005- 2008, identifying $18.5M in deferred maintenance, with a $407M replacement value (Vessely, 2017).

The first efforts to develop comprehensive GAM plans in the U.S. started in Alaska, Colorado, and Vermont. The Alaska DOT performed studies on geotechnical asset management performance measures for unstable slope management (Stanley and Lawrence, 2011) and in 2017 published a "Geotechnical Asset Management Plan" report (Thompson, 2017), identifying several million dollars in needs. This study also discusses recommended practices for a sustainable GAM program for Alaska, taking as reference the studies by Verhoeven and Flintsch (2011), Anderson and Rivers (2013), and the recommendations followed by the Washington State DOT in 2010. By 2017, the Colorado DOT identified approximately 3000 walls and approximately 1600 geological hazard sites, reporting wall conditions and associated levels of risk. In a different effort, the Vermont DOT included rock cuts in a risk-based program where 4% were identified as having a high hazard (Vessely, 2017). Other GAM-related studies in the U.S. include the work by Wolf et al., (2015), who explored the application of remote sensing to GAM with their work focused on the state of Michigan. Another effort in the state of Michigan was the work by Admassu et al., (2019), who examined the implementation of wireless monitoring for the risk management of highway retaining walls. In 2018, the Louisiana DOT started the "Geotechnical Asset Management for Louisiana" project to establish the initial steps for a GAM implementation in Louisiana. More recently, the Washington State DOT published a transportation asset management plan (Millar, 2019), and the National Cooperative Highway Research Program (NCHRP) developed the Research Report 903 "Geotechnical Asset Management for Transportation Agencies" (NCHRP, 2019) to guide the implementation of GAM programs in transportation agencies in the United States. In terms of the development of new GAM systems for DOTs, the experience has shown that there is a significant advantage towards initiating a minimal framework early, even though it may not be comprehensive, then using continuous improvement to tailor the management system to the ongoing user needs, rather than developing a comprehensive plan before implementation (NCHRP, 2019).

GAM practices in the U.S. have evolved from simple inventory to risk-based assessments and historically have focused on slopes and retaining walls. Notable contributions include the studies by Brutus and Tauber (2009), DeMarco et al. (2009), and the recommendations of Walters et al. (2016). Additional studies that include inventory and inspection strategies for GAM include the studies by DeMarco et al., (2010a; 2010b), Butler et al., (2016), and Ramakrishna et al., (2021). Although DOTs benefit from inventorying geotechnical assets as a tracking database for maintenance and operation purposes, federal mandates, such as the Moving Ahead for Progress in the 21st century Act (MAP-21) and Fixing America's Surface Transportation (FAST) Act in 2012 and 2015, encourage risk and performance-based approaches to deal with all assets within the right-of-way (ROW). In terms of risk assessment, the studies by Govindasamy et al., (2017) and Bush et al., (2011) have highlighted the value of early GAM implementation in improving the risk management of levee systems, bridges, and slope networks, respectively. GAM can also provide insights on decision support. For example, Boadi et al., (2017) studied decision-support concepts in the corridor-level analysis of transportation systems. Other studies oriented to decision-support practices include a collaborative decision-support system for improving roadway maintenance programs (Tsai et al., 2008), decision-making enhancements based on evidence from Transportation Asset Management (TAM) implementations (Smith-Colin et al., 2014), and management of risks and geotechnical assets aligned with transportation performance objectives (Anderson et al., 2017).

Well-documented cases that illustrate financial and investment decisions based on GAM planning are currently limited within U.S. transportation agencies. However, as summarized in Vessely (2017), there are other systems-level models that can be emulated, including domestic infrastructure sectors such as water resources and utilities, and some select international transportation agencies that provide valuable examples of GAM practices that have been successfully implemented throughout the asset management cycle and at all levels of an organization. For example, the USACE reported financial savings across the geotechnical life-cycle on the order of 30% for tracked assets. The Alaska Department of Transportation and Public Facilities noted the negative impact of reducing funding on structured annual maintenance programs of geotechnical assets, resulting in agencies losing the opportunity to save up to 16% of the same annual budget, given that the network conditions will not improve and future expenses will accrue if preservation or improvements are not completed (Beckstrand et al., 2017).

Existing GAM systems in the United States

Currently, several U.S. state DOTs have implemented GAM systems in diverse regions across the country (notable implementations are summarized in Table 2). These GAM programs have been developed over the last two decades and have varying levels of complexity. Additional detailed descriptions and experience on the performance of GAM programs in these U.S. states can be found in **Error! Reference source not found.**A.

Table 2. Summary of GAM Programs in the United States

Agency	System/Platform	Managed Assets	References
Alaska DOT	Alaska's TGIS ArcGIS Online Map Portal	• Embankments • Material storage sites • Retaining walls • Slopes, rock • Slopes, soil	Geotechnical Asset Management Program (Beckstrand et al., 2017)
Colorado DOT	• CDOT Online Transportation Information System (OTIS) • C-Plan: Interactive online mapping platform • GeoHub: Internal ArcGIS for Portal site for CDOT employees	• Bridges • Culverts • Embankments • Geohazards • Slopes • Subgrades • Tunnels	Wall and Geotechnical Asset Management Implementation at the Colorado Department of Transportation (Vessely et al., 2015)
Louisiana DOTD	La DOTD ArcGIS Online	• Embankments • Levees near highways • Retaining walls • Slopes • Soil borings • Tunnels with retaining walls	Geotechnical Asset Management for Louisiana: Research Project Capsule [18-4GT]. (Gautreau,2018)
Vermont DOT	• Vermont Asset Management Information System (VAMIS) • Deighton Total Infrastructure Asset Management System (dTIMS)	• Bridges • Culverts • Pavements • Slopes • Retaining walls	Transportation Asset Management Plan: Vermont DOT (VTrans, 2018)

Agency	System/Platform	Managed Assets	References
Washington DOT	• WSDOT Geospatial Open Data Portal • WSDOT Online Map Center • WSDOT GeoPortal	• Bridges • Embankments • Foundations • Retaining walls • Roadways • Slopes	Best practices in geographic information systems-based transportation asset management (Hector-Hsu, Jessica, et al., 2012)
Ohio DOT	• Ohio Transportation Information Mapping System (TIMS) • UA Slope 2.3 Program • Web-based geographic information system application (WebGIS)	• Geohazards • Retaining walls • Slopes, rock • Soil Borings	Best practices in geographic information systems-based transportation asset management (Hector-Hsu, Jessica, et al., 2012) Transportation Asset Management Plan: ODOT (ODOT, 2022)
Minnesota DOT	Enterprise MnDOT Mapping Application (EMMA)	• Drainage systems • Earth retaining walls • Instrumentation systems • Slopes • Subgrades	MnDOT's Asset Management Strategic Implementation Plan (MnDOT, 2021a)
North Carolina DOT	NCDOT GO!NC Portal	• Bridges • Culverts • Embankments • Retaining Walls	Transportation Asset Management Plan: NCDOT (NCDOT, 2019)

Previous efforts in managing retaining walls, slopes, embankments, and bridge foundations

Retaining walls

Existing GAM practices for retaining walls (e.g., inventory, condition assessment) at multiple transportation agencies have been reviewed, focusing on the agencies with the most mature or structured wall management plans (Beckstrand et al., 2017; Walters et al., 2016; Ohio DOT, 2018; Athanasopoulos-Zekkos et al., 2020; Rasdorf et al., 2015; New York State DOT, 2018). In addition, the FHWA Bridge Inspector's Reference Manual (Ryan et al., 2012) and the FHWA Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (FHWA, 1995) were also reviewed, seeking to consider relevant strategies from long-standing management programs.

According to the Athanasopoulos-Zekkos et al. (2020), at least 24 transportation agencies have implemented inventory and/or inspection programs for retaining walls in the United States. Table 3 summarizes the development of retaining wall management programs by several federal and state agencies, including the year of the last updated wall inventory or management program, the recommended routine inspection frequency in years, the minimum height threshold for walls to be part of the program, if bridge walls are included or not, software and/or database management systems, the levels considered in the rating system for evaluating the condition and performance of walls, and relevant references associated with the program structure.

Table 3. Review of Key Retaining Wall Features Inventoried in Other Agencies

Transportation Agencies	Retaining Wall Management Programs						Relevant References
	Version	Inspection Frequency (years)	Min. Height (ft)	Include Bridge Walls	Data Management	Condition Rating System	
Alaska DOT-PF	2017	<5 and based on storm events	4	Yes*	AGOL Environment	Elements: 4-division rating. Overall: good, fair, poor	- Beckstrand et al., 2017
Colorado DOT	2016	< 6 for RW and < 4 for BW	4	Yes*	SAMI (GIS database)	Elements: good, fair, poor, severe. Overall: 0-9.	- Walters et al., 2016
Indiana DOT**	2018		5	Yes*	AGOL Environment	Overall: excellent, good, fair, poor, critical	- Khan, 2018
Michigan DOT**	2020		4	Yes	GIS database	Elements and Overall: good, fair, poor, severe	- Athanasopoulos-Zekkos et al., 2020
National Park Services (WIP)	2010	<10	4	Yes	WIP Database, VisiData (Oracle, Access)	Elements: excellent, good, fair, poor, critical. Overall: 5 - 100.	- DeMarco et al., 2010b
New York State DOT	2018	< 10 for RW and < 5 for MSE	4	Yes*	FDC, RWIS (Oracle, GIS database)	Elements and Overall: good, fair, poor, severe	- NYSDOT, 2018
North Carolina DOT	2015	Based on likelihood of failure		Yes	WICAS (Access)	Elements: good, fair, poor, severe. Overall: 1-4	- Rasdorf et al., 2015 - Butler et al., 2016
Ohio DOT	2018	<10		Yes	TIMS (GIS database)	Overall: good, fair, poor	- Ohio DOT, 2018
Oregon DOT	2005	< 5	4	Yes	Access	Overall: good, fair, poor	- Brutus and Tauber, 2009, p. 11
Tennessee DOT	2021		6		GIS database	Overall: good, fair, poor, severe	- Wu et al., 2021
Vermont Agency of Transportation	2019			Yes	VAMIS-dTIMS (GIS database)	Risk-based: 5-division rating	-VTrans, 2020
Wisconsin DOT	2017	< 6		Yes*	HSIS (GIS database)	Elements and Overall: good, fair, poor, severe	- WisDOT, 2017

Note: (*) Certain conditions apply, such as minimum length, position related to the abutment, or if it is already considered in another program. (**) Programs under R&D

It is relevant to highlight that the Alaska, Ohio, Colorado, and North Carolina DOTs had already implemented their retaining wall inventory systems before the NCHRP (2019) report was published, relying on the recommendations provided in the studies by Rasdorf et al., (2015), Brutus et al., (2011), and DeMarco et al., (2009), which are schematically illustrated in

Figure **3** and Figure 4.

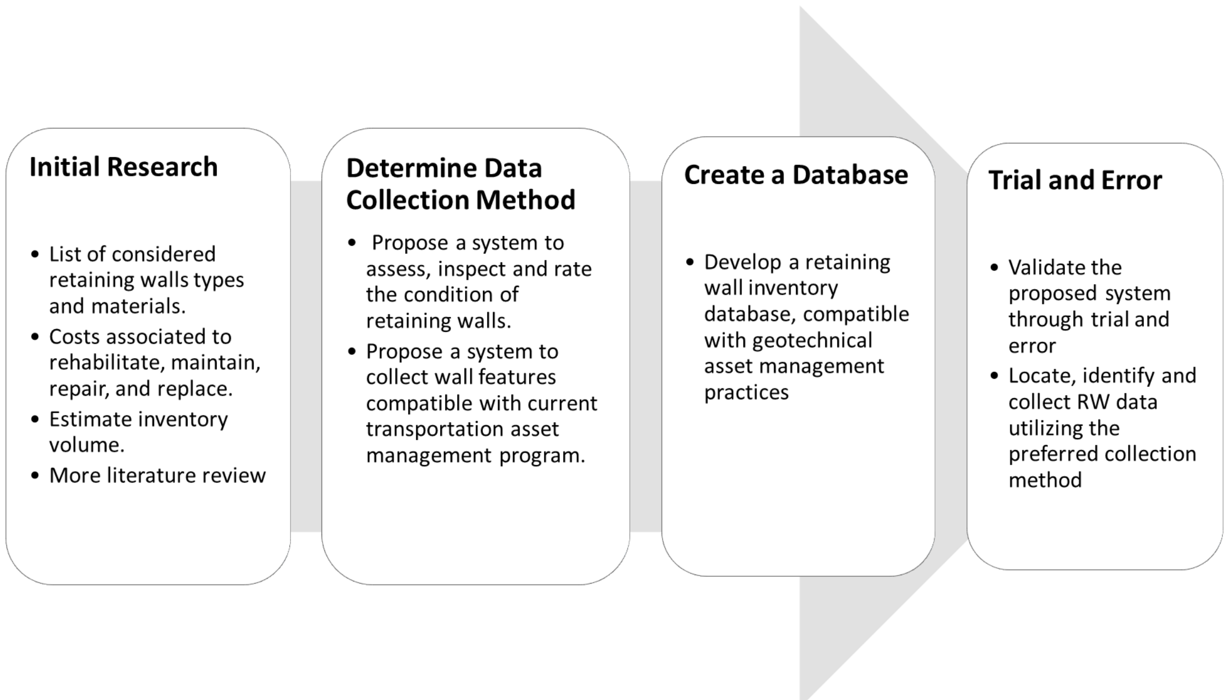

Figure 3. Illustration. Modified process for developing a wall inventory program (DeMarco, et. al. 2009).

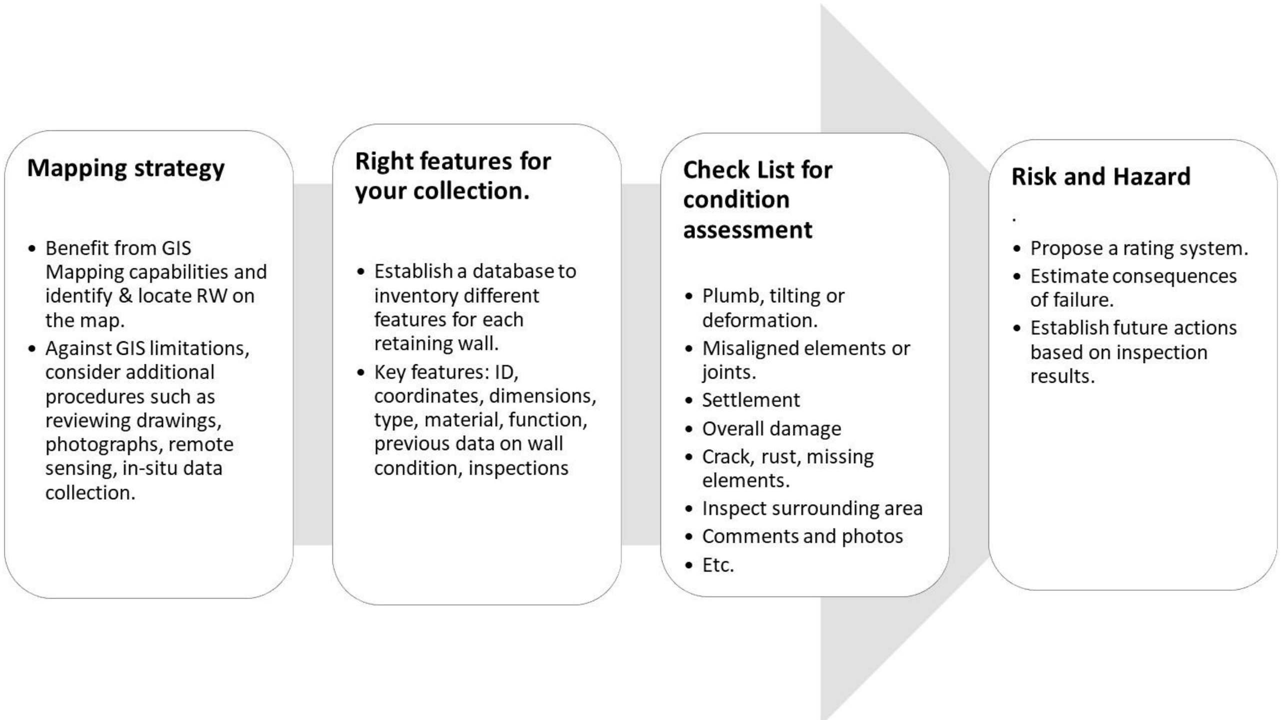

Figure 4. Illustration. Modified process for inventory and inspection program (Brutus, et al., 2011).

The NCHRP (2019) report recommends inventorying walls that are 4 feet in height or taller, with an inclination threshold of 70 degrees. A more complex list of criteria was issued by North Carolina DOT (Rasdorf et al., 2015) based on a comprehensive assessment proposed by DeMarco et al., (2010a), which gathers additional features such as qualifying roads, relation to roadway assets, wall embedment, and general acceptance. These criteria are summarized in Table 4.

Table 4. Earth Retaining Walls Inventory Criteria (Rasdorf et al., 2015)

Criteria Subject	Criteria Definition
Qualifying Roads	The inventory includes retaining walls, together with qualifying culvert headwalls, located on all classes of paved park roadways and parking areas as described in the local agency route inventory report or identified by park facilities, maintenance, or resource staff.
Relation to Roadway Asset	Retaining walls and culvert headwalls that meet the minimum height requirements must reside within the known or assumed construction limits of the existing roadway or parking area and must support or protect the roadway or parking area.
Wall height	The maximum wall height, measuring only that portion of the wall structure intended to actively retain soil and/or rock, must be greater than or equal to 4 ft. For culvert headwalls or wing walls, maximum wall heights must be greater than or equal to 6 ft.
Wall Embedment	Include fully- or partially-buried retaining wall structures in the inventory that are known to meet the minimum wall height requirements and when wall locations are known or verifiable.
Wall Face Angle	Individual walls are further defined by an internal wall face angle, measured at the wall face, greater than or equal to 45^o ($\geq$1H:1V face slope ratio). This criterion also applies to the internal angle of tiered wall systems (when considered as a single wall system), measured along the top edges of each wall tier.
General Acceptance	When wall acceptance based on the above criteria is marginal or difficult to discern, include the wall in the inventory, particularly where the intent is to support and/or protect the roadway or parking area and where failure would significantly impact the roadway or parking area and/or require replacement with a similar structure.

In terms of classifying retaining walls, one of the most comprehensive programs has been proposed by DeMarco et al., (2010a) in the *Wall Inventory and Condition Assessment Program* (WIP) after analyzing 3,500 wall assets located around 32 National Parks. The program classifies walls by function and type. The type of wall refers to the construction material and engineering concepts behind every retaining structure. The vast majority of walls were between 60 and 70 years of age and included multiple types of retaining structures such as mortared stone gravity structures, dry-laid stone walls, and concrete walls working as gravity walls and in cantilevers. Even though approximately 90% of inventoried walls were constructed to retain fills, DeMarco et al., (2010a) identified seven different functions within the National Parks. Colorado DOT (Walters et al., 2016) considered four of these categories and added one, "soundproof". Alaska DOT (Beckstrand et al., 2017b) also added functions such as pedestrian under-crossing, access ramp, and grade separation; and expanded the list of functions to ten. The wall functions recommended in the National Park Services Wall Program are listed in Table 5.

Table 5. Recommended Wall Functions by the National Park Services (DeMarco et al., 2010a)

Fill wall	Retains soil, rock, or mixed backfill
Cut wall	Retains natural terrain
Bridge wall	Wingwalls longer than 40 ft beyond the bridge abutment
Culvert/ Head-wall	£ 20 ft total span
Switchback wall	Between multiple-level roadways inside the switchback curve.
Flood-wall	Related to channels, surge walls, and seawalls.
Slope protection	Related to riprap, rockfall, rock buttresses, and stacks.

The FHWA - Central Lands Highway Division, as part of their National Park Service program (NPS), also classifies several wall types considering broader and generic subcategories employed within the parks system (DeMarco et al., 2010b). Table 6 contrasts the FHWA-NPS wall types with the wall types in both the Georgia Standard Specifications Construction of Transportation Systems (GDOT, 2021) and the Georgia

LRFD Bridge and Structure Design Manual (GDOT, 2022a). Finally, Figure 5 shows some of the different types of retaining walls tracked by the Alaska DOT GAM Program, as reference.

Table 6. Wall Types According to the FHWA and Georgia Construction Practices

Wall Type	Georgia 2021 Standard Specifications	Georgia LRFD Bridge and Structure	FHWA - NPS
Gravity Wall (Gabion, Modular Blocks)	x	x	x
Gravity Wall (Mass Concrete, Dry Stone, Gabion, Mortared Stone)			x
Gravity, Rubble Masonry and Brick Masonry	x		x
Gravity, Doublewal^{TM} Precast Wall	x		
Bin, Concrete, and Metal			x
Crib, Criblock^{TM} Retaining Wall	x		
Crib, (Concrete, Soldier Pile, Sheet Pile)			x
Permanent Anchored Walls (Tie-back), H-Pile, and Sheet Pile	x	x	x
Permanent Anchored Walls, Micropile			x
Permanent Anchored Walls (Tie-down)	x		
Permanent Anchored Walls (Slurry Diaphragm Wall)	x		
Tangent/Secant Pile wall			x
Soil Nail Walls	x	x	x
Mechanically Stabilized Embankment Retaining wall	x		
Mechanically Stabilized Embankment Wall, Tensar Geogrid^{TM}	x		
Mechanically Stabilized Earth (MSE) Wall (Contractor Design)		x	
Mechanically Stabilized Earth (MSE), Geosynthetic Wrapped Face, Precast Panel, Segmental Block, Welded Wire Face			x
Mechanically Stabilized Earth, Keystone^{R} and Genesys^{R} Walls	x		
Cantilever, Soldier Pile, and Reinforced Concrete Wall (with or without tie-backs)		x	x
Cantilever, Sheet Pile			x
GDOT Standard Wall (Type 2, Type 6, Parapet, Gravity)		x	
RECo T-Wall, Gravix Wall			

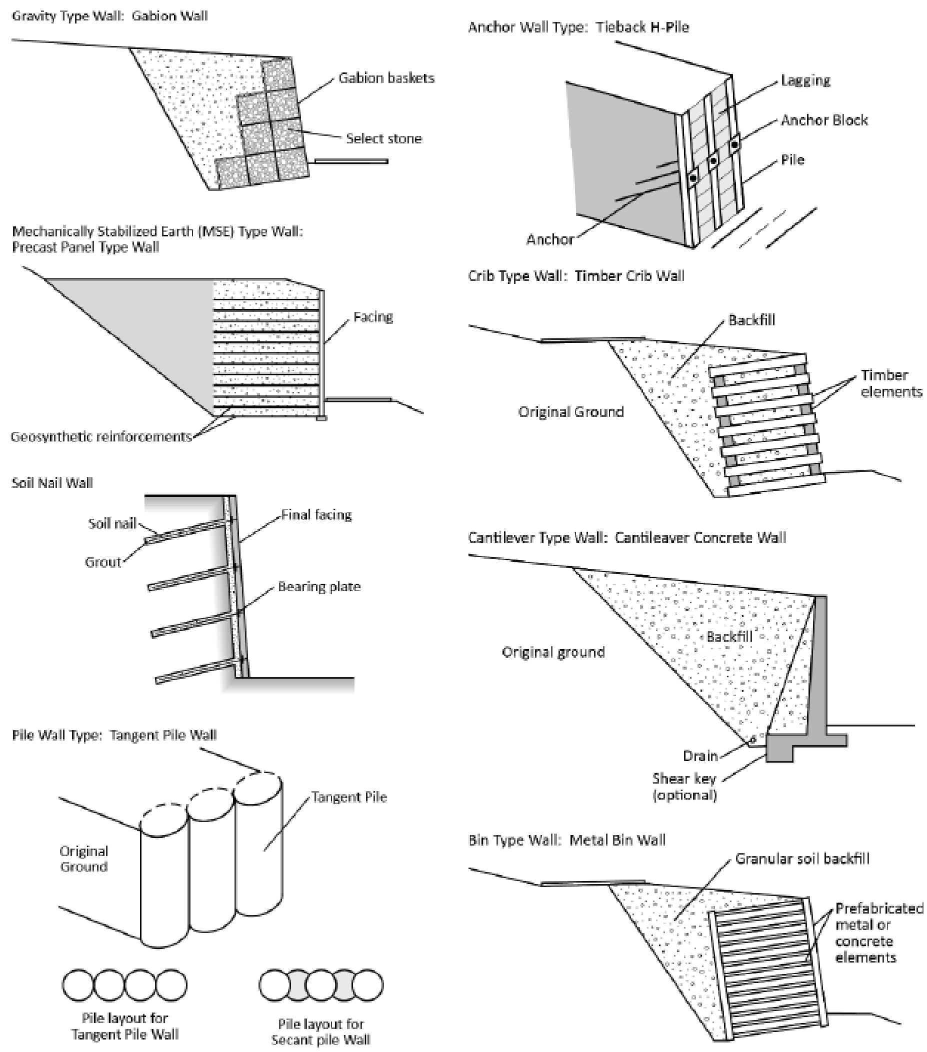

Figure 5. Illustration. A selection of retaining wall types is considered by the AKDOT (Beckstrand et al., 2017b).

Slopes

The NCHRP (2019) report defines slopes as "a type of geotechnical asset involving cut excavations that enable a roadway to traverse through the surrounding ground with acceptable design profiles." Another definition is provided by the Ohio DOT (ODOT), a slope asset is "any slope which has been modified by construction activities through the removal of soil materials" (ODOT, 2013). Some DOTs and Transportation

Agencies (e.g., ODOT, WSDOT, NHDOT, PRHTA) also consider natural slopes as assets, especially when they are near, adjacent, or represent a potential hazard to a roadway. Of note, cut slopes are often mistakenly inventoried as embankments due to their similarities. However, as inferred by the definitions provided above, slope assets come from excavating natural terrains rather than being part of man-made fills. In general, slope assets could be comprised of soil, rock, or mixtures of the two, whether naturally deposited or man-made, and be within or beyond the ROW. A distinction is that the latter group (i.e., beyond the ROW) is mostly comprised of natural slopes, and some agencies define special terminologies; for example, the Ohio DOT uses the terminology natural backslope (ODOT, 2013). Figure 6 shows examples of slope assets documented by the Alaska DOT (Beckstrand, 2017c)

Figure 6. Photo. Soil and rock cut slopes as slope assets (Beckstrand, 2017c).

The NCHRP-903 Report describes the following slope features when identifying slope geotechnical assets within a slope inventory:

- Slope within the ROW: A constructed, excavated, or cut slope as a complementary geotechnical asset that forms part of the roadway template, property boundary, or easement.
- Slope beyond the ROW: A natural slope hazard feature that is not within the ROW where an unstable behavior can cause potential harm to transportation assets, disrupt network operations, and/or impact pedestrians. This type of geotechnical asset would consider rockfalls from any geological formation, unstable cuts or slopes, and debris flows or landslides that could have impacts that slightly interrupt traffic or generate massive damage. Differentiating between slopes beyond and within the ROW would help planners, and state officials develop specific mitigation, treatment, and risk management plans based on location, condition, and hazard level.

The existing work in slope inventory (e.g., AKDOT, NCDOT West Branch, CDOT) has already shown significant advantages in controlling, mitigating, and predicting landslides and rockfalls (Beckstrand et al., 2017a; Oester et al., 2019). Currently, most of the DOTs practices reviewed in this study have implemented slope management systems as a reactive effort to quantify unstable slopes around critical transportation assets and to estimate maintenance costs associated with natural geohazards. For instance, the Alaska, Ohio, Washington State, and North Carolina DOTs have integrated landslides, rockfalls, and/or rockslides as part of their GAM practices by inventorying slopes that could potentially jeopardize a transportation corridor (ODOT, 2013; Johnson and Kuhne, 2016; Beckstrand et al., 2017a). The NCHRP (2019) report states that an initial slope inventory system could only lead to a comprehensive GAM program if its long-term implementation is developed along with their rockfall and slope hazard rating systems. Additionally, the report suggests highlighting the functional, tangible, and intangible values of a slope asset. Selected examples of these values are presented in Table 7. Lastly, the NCHRP (2019) report recommends inventorying slopes greater than or equal to 10 feet in height. If the slope asset represents a potential risk to the transportation network due to its location, aging, or deterioration, it should also be inventoried regardless of its dimensions or condition.

Table 7. Value of Managing Cut Slope Assets (NCHRP, 2019)

Cut-slopes assets	Asset values
	**Functional values:** Highway design **Tangible financial values:** Initial construction costs Erosion maintenance Rockfall debris removal **Intangible financial values:** Environmental resources Safety Aesthetics characteristics and agency reputation
	**Functional values:** Highway design in hilly terrain **Tangible financial values:** Initial construction costs Erosion maintenance Rockfall debris removal **Intangible financial values:** Environmental resources Safety Aesthetics characteristics and agency reputation

In terms of efforts that provide insight into inventorying slope assets, Lian (2007) proposed a list of slope material types to the Ohio DOT for their Landslide Hazard Rating Matrix Database (Table 8). Vessely (2015) suggested a list of geohazards based on the material types of slope and embankment assets for the Geotechnical Asset Management Implementation at the Colorado Department of Transportation (Table 9). Additionally, the Washington State DOT (WSDOT, 2018) considered the height and the slope material type as input for the development of an unstable slope management system rating criteria.

Table 8. Slope Material Types (Lian, 2007)

• Boulders	• Stone fragments	• Gravel	• Sand
• Fine sand	• Silty gravel	• Silty sand	• Clayey gravel
• Clayey sand	• Silty soil	• Clayey soil	• Organic
• Combination	• Others		

Table 9. Potential Geohazards from Slopes and Embankments (Vessely, 2015)

• Debris flow	• Seepage	• Embankment distress	• Landslide
• Rockfall	• Rockslide	• Sinkhole	

Embankments

The NCHRP (2019) report defines embankment assets as "a constructed fill comprising rock, soil, or other engineered materials that enables a roadway to maintain a required design elevation above lower-lying ground." According to the GDOT Design Policy Manual, embankment assets are also considered earthwork structures that allow roadways to be at a higher elevation than surrounding terrain (GDOT, 2020a), while in some DOTs, embankments are defined as slopes. For example, the Alaska DOT defines embankments as a type of soil slope because of similarities in associated costs, engineered treatment alternatives, and materials (Beckstrand et al., 2017a). Other agencies, such as Ohio and Washington DOTs, inventory embankments within the category of landslides or unstable slopes. Figure 7 shows an example of an embankment asset taken from the GDOT's Earthwork Inspection Training, which states that most Georgia embankments are made of Class I and Class II materials, such as: (1) inundated embankments, (2) intermittently inundated embankments, or (3) bridge structures (GDOT, n.d.). Detailed descriptions of all "Class materials" approved for Georgia projects are available in the GDOT Design-Build repository (GDOT, 2005).

Figure 7. Photo. Embankments as part of the transportation network in Georgia.

Embankment assets are not only earth fills with two downslopes that overlay natural ground within the ROW but can be comprised of one cut-slope of natural ground and one downslope made of engineered fill (Figure 8). When inventorying embankments, Vessely (2013) suggests that these features (one or two downslopes) should be collected and documented to facilitate the understanding and assessment of the risks involved in a highway performance. The GDOT benches the existing ground before laying new embankment material on a slope.

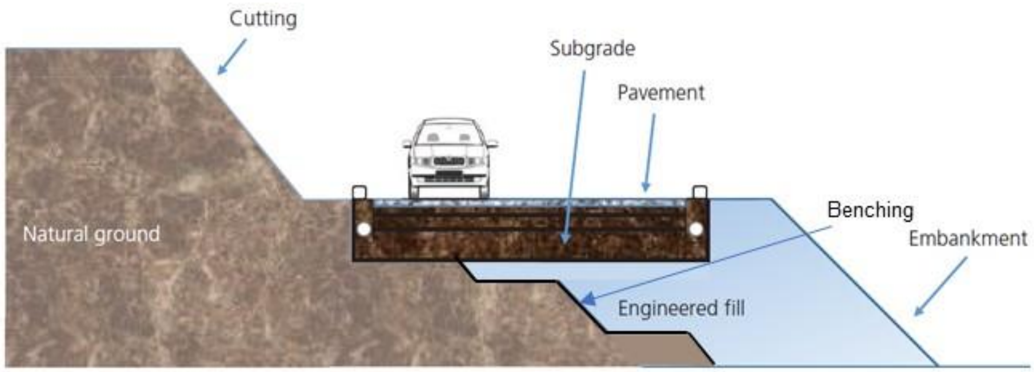

Figure 8. Illustration. Sketch of an engineered fill as an embankment (modified from Bhreasail et al., 2019).

Currently, most of the reviewed DOTs have implemented embankment management systems as a reactive effort to quantify unstable embankments around critical transportation assets and to estimate maintenance costs associated with their failure (reference Chapter 2). For instance, the Alaska, Ohio, Washington State, and North Carolina DOTs (Beckstrand et al., 2017; ODOT, 2013; WSDOT, 2018; Johnson & Kuhne, 2016) have integrated embankments within management programs associated with landslides or unstable slopes. Managing embankments should not only be translated to collecting and inventorying static features (e.g., location, height, material) but also documenting factors that could be the most likely failure trigger mechanisms involved in a slope failure. For instance, as part of the field data collection guidelines in mature GAM systems, external factors such as the amount of precipitation, slope drainage, and/or the depth of the water table are often gathered in the management of embankments. Similar to other geotechnical assets, the NCHRP (2019) report suggests highlighting the functional, tangible, and intangible values of an embankment asset (see Table 9 for examples). The NCHRP (2019) 903 report recommends inventorying embankments greater than 10 feet in height above the finished grade. If the embankment asset, due to its location, aging, failure history, or deterioration, represents a potential risk to the transportation network, it should also be inventoried regardless of its dimensions or nature. When the embankments are less than 10 feet and exhibit good performance, they could become part of the inventory of minor earthworks if there is a benefit in tracking it. The type of material should also be considered, and Lian (2007) proposed a list of material types to the Ohio DOT for their Landslide Hazard Rating Matrix Database. The Washington State DOT (WSDOT, 2018) also considered the material type as input for the development of an unstable slope and embankment management system rating criteria.

Table 10. Value of Managing Embankment Assets (NCHRP, 2019)

Embankment assets	Asset values
	**Functional values:** Flood mitigation for roadway Interacts between roadway and bridge asset **Tangible financial values:** Initial construction costs Erosion and annual vegetation maintenance **Intangible financial values:** Environmental protection Aesthetics characteristics and agency reputation
	**Functional values:** Pavement support Boundary between private and public property **Tangible financial values:** Initial construction costs Annual vegetation maintenance **Intangible financial values:** Buffer between road and private property Aesthetics characteristics and agency reputation

Bridge foundations

The Federal-Aid Highway Act of 1968 for the establishment of federal bridge inspection programs was passed after the collapse of the Silver Bridge in Point Pleasant, West Virginia, in 1967. Additionally, the Secretary of Transportation has established National Bridge Inspection Standards (NBIS), which has the goal of managing all bridge inventories by making proper standards for the inspection and evaluation of assets. The NBIS standards cover all bridges on public roads longer than 20 feet (FWHA: Title 23 - Code of Federal Regulations Section 650.305). Bridges are defined as highway structures that span over 20 feet in length (AASHTO LRFD Bridge Design Specifications, 2017). Typical geotechnical bridge assets are represented in Figure 9.

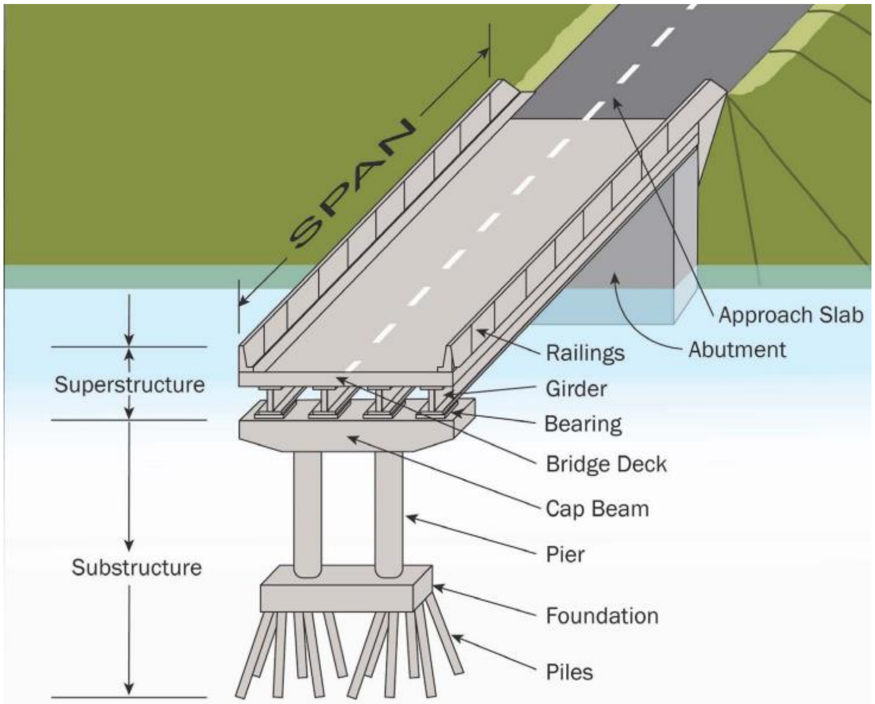

Figure 9. Illustration. Major components of bridge assets (Federal Emergency Management Agency, 2022).

A bridge consists of three structural parts: the deck, superstructure, and substructure. The substructure includes abutments, piles, fenders, and footings, and all substructure elements should be inspected for deterioration impacts, including cracking, section loss, settlement, misalignment, scour, collision damage, and corrosion. Additionally, for bridge asset management, condition assessment of the substructure should be made independently of the deck and superstructure (FHWA, 1995).

Bridge foundations are considered a part of the substructure in bridge asset management. In the inventory for bridge foundations, features including foundation type and material, boring information, and construction technique are essential elements for inventorying, although condition assessment is challenging because the foundations are not available for visual inspection. In the state of Georgia, the most commonly constructed types of bridge foundations include pile bents, tower bents, pile footings, spread footings, pedestal footings, and drilled shafts (Figure 10). In addition, the representative foundation material/technique implemented on GDOT bridge projects includes steel H-piles, prestressed concrete (PSC) piles, metal shell (MS) piles, micro piles, concrete spread footings, drilled shafts (end bearing), and drilled shafts (skin friction). In modern bridge construction that requires deep foundations, piles are the most commonly constructed foundation. In general, the selection of foundation types depends on several criteria, including soil conditions, depth of foundation, and river flow rate. For example, pile foundations are suitable in very soft soil, while micro piles, which have a small diameter (<12 inches), are often used as specialty piles for providing structural support. Drilled shaft foundations are typically larger in size compared to other pile types and used as single shaft support, resting on a hard stratum to ensure high load resistance in the single shaft.

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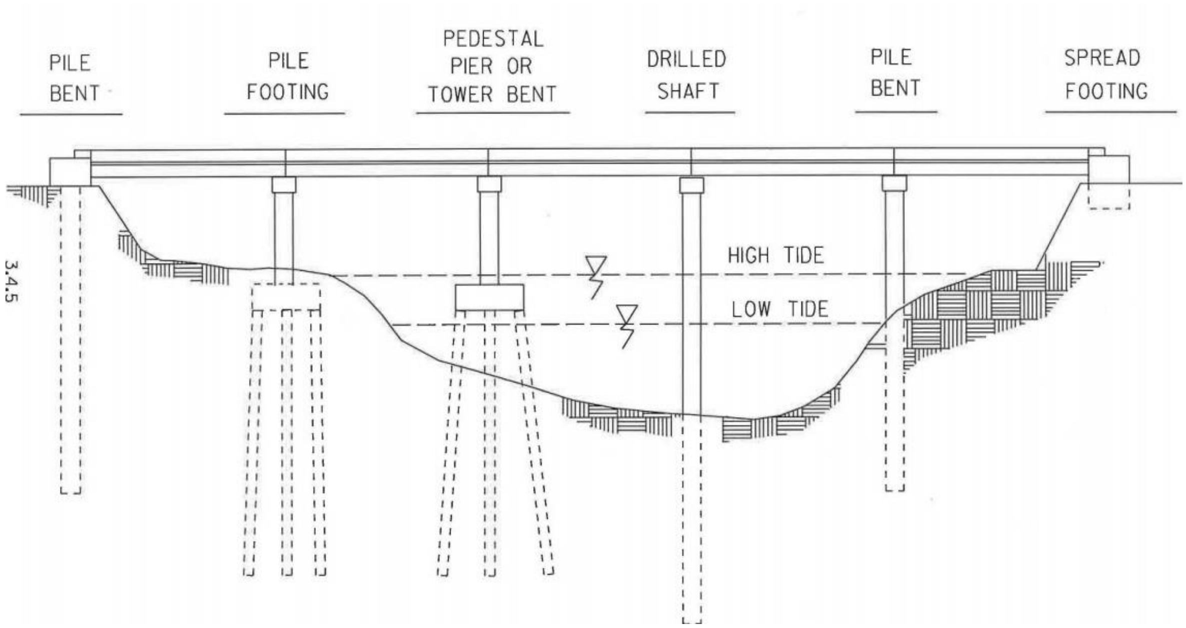


Figure 10. Illustration. Representative bridge foundation types (from GDOT Bridge Foundation Types 3.4.5, Bridge Foundation Investigation Guidelines).

Other geotechnical asset

Culverts and high mast towers are considered within the "other geotechnical assets" category, as discussed in the following. According to FHWA Managing Assets Beyond Pavements and Bridges - Case Study 7 some states consider culvert assets, and at least one agency manages high mast towers (FHWA, 2020).

Box Culvert Foundation

A culvert is a concrete or metal structure designed to channel water beneath a roadway or around an obstacle that is typically constructed to allow water to flow under roadways, railways, or embankments. Generally, a culvert is defined according to shape (circular, ellipse, box, or arch), size (typically ~3 feet to 12 feet), and usage (river flow, stormwater, sewage) (Table 11). Box culverts are used at sites having favorable floodplain conditions, with drainage areas of less than 20 square miles (GDOT, 2020c) (Figure 11). While the number of culverts in a transportation network is significantly higher than the number of bridges, culverts are not routinely inventoried or managed systematically, and inspection guidelines and systems have not been developed for culvert assets (Richie and Beaver, 2017). In recent years, several agencies, including the Minnesota, California, New Jersey, and Ohio DOTs, have developed manuals for culvert management or used bridge inspection manuals to manage culverts, with Ohio and Minnesota DOTs providing training and certification courses for culvert inspection (AASHTO, 2020).

Table 11. Typical Culvert Shape and Characteristics (AASHTO Culvert and Storm Drain System Inspection Guide, 2020)

Shape	Range of size	Common uses
Circular	12 to 144 in (reinforced) 6 to 10 in (nonreinforced)	Culverts, storm drains, and sewers
Pipe arch	15 to 72 in. equivalent diameter	Culverts, storm drains, and sewers. Used where fill depth is limited.
Horizontal ellipse	Span x Rise 18 to 144 in. equivalent diameter	Culverts, storm drains, and sewers. Used where fill depth is limited.
Vertical ellipse	Span x Rise 18 to 144 in. equivalent diameter	Culverts, storm drains, and sewers. Used where lateral clearance is limited.
Box	Span 3 ft to 12 ft	Culverts, storm drains, and sewers. Used for wide openings with limited head.
Arch	Span 15 ft to 102 ft	Culverts and storm drains. For low, wide waterway enclosures.

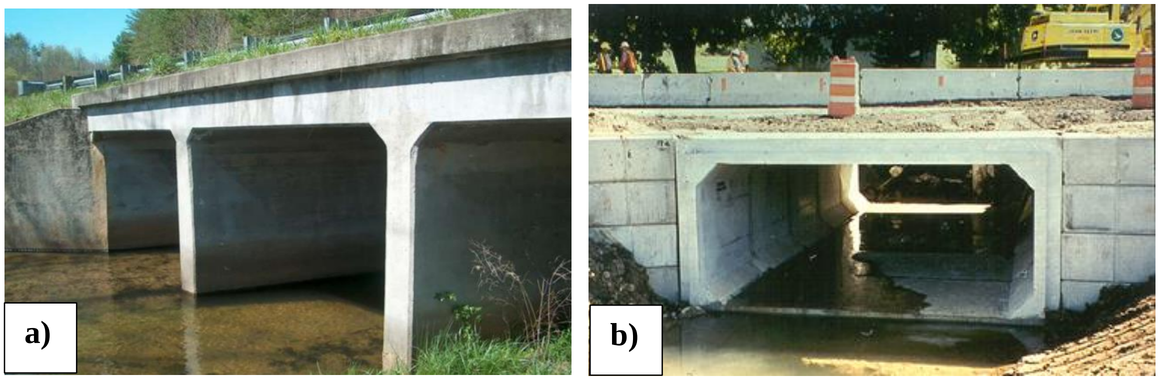


Figure 11. Photo. Examples of box culverts: a) triple barrel box culvert, b) single barrel box culvert. (https://www.dot.state.oh.us).

In the case of MnDOT, they have developed a system named TAMS HYDraulic INFRAstructure (TAMS HydInfra), which is focused on culvert asset management, including inventory, inspections, and maintenance activities. For inventory purposes, culverts are classified as either highway culverts (diameter less than 10 feet) or large culverts. For cases where the diameter is 10 feet or larger, the culvers are considered as bridge inventory. FHWA considers culverts that have 20 feet or larger spans as bridge inventory (MnDOT, 2019). Data collection for culverts is implemented at a frequency of 1 to 6 years for inspection, and inventory data include location, ownership, status, and roadway type. The location field typically includes route ID, GPS coordinates, a relative position from the centerline, and traffic direction. Status fields indicate if the assets are active or not. In the case of inactive status, the applicable conditions include: abandoned, removed, duplicate, or under review) (Figure 12). The roadway type field is the general location of the culvert asset and its impact on traffic flow when maintenance is implemented. For example, the location of highway culverts can include centerline, median, roundabout, ramp/loop, and collector/distributor, and centerline locations would result in highway traffic disruption when the culvert is maintained or replaced (MnDOT, 2021b).

Figure 12. Photo. Status of culvert assets (MnDOT, 2021b).

The inspection of culverts is recommended every 1 to 6 years, depending on the condition and level of risk (MnDOT, 2021b). During the inspection, an assessment of the condition rating is conducted in terms of structural issues, material issues, and service performance. The performance measure of culvert assets is recommended by the National Bridge Inventory (NBI) inspection standards and MnDOT requirements (MnDOT, 2019). Table 12 represents the performance measure and target of culvert assets by the Transportation Asset Management Plan of MnDOT (MnDOT, 2021b).

For field inspection, ArcGIS Collector applications are used, including Hydinfra Inspection, Hydinfra Inspection with Flow Arrows, Hydinfra Train, and Hydinfra Train with Flow Arrows. After inventory and inspection in terms of highway culverts are completed using ArcGIS Collector applications, processes to update records and produce reports are conducted with the Agile Asset application in the office (MnDOT, 2021b).

Table 12. Performance Measure and Target of Culvert Assets (MnDOT, 2019)

Asset Type	Performance Measure	Explanation	State Target
Highway Culverts	Share of culverts in poor condition	Highway culvert condition is assigned during inspections. Culverts in poor condition display cracks or joint separation, while those in very poor condition exhibit holes and more significant joint separation resulting in a loss of surrounding (roadbed) material.	≤ 10%

In the case of the California Department of Transportation (Caltrans), the Culvert Inspection Program (CIP) was established in 2005. The program has processes for locating, assessing, and inventorying culverts; however, there have been some limitations including incomplete inventorying of existing culverts, lack of condition assessment protocols, and lack of re-inspection date implementation (Caltrans, 2021). An action plan for CIP Improvements was conducted under the Road Repair and Accountability Act of 2017. The main objective of this project is to move 90% of culverts to good or fair condition by 2027. The improved results from the previous CIP include the following:

- Complete the inventory processes of undefined culverts to make a more accurate management system. Over 1.5 million linear feet were added to new culvert inventories between 2017 and 2019. According to the 2019 State Highway System Management Plan (SHSMP) and 2018/19 Performance Benchmark Report, 212,181 culverts with an estimated length of 20.98 million linear feet are now inventoried by Caltrans.
- A Caltrans culvert inspection manual was produced to establish health assessment protocols. According to the manual, the condition of culverts is evaluated based on five attributes, as shown in Table 13.
- For systematic re-inspection processes, a CIP Re-Inspection Manual and Guidelines were established in August 2020.

Table 13. Attributes for Condition Assessment of Culvert (Caltrans, 2021)

Attributes	Explanation
Waterway Adequacy	A measure of how much of the original design flow exists. This measure is based on percent blockage.
Joints	Degree of separation and evidence of soil infiltration or water exfiltration.
Material	The degree of deterioration or corrosion.
Shape	A measure of how much of the original design shape still exists.
Alignment	A measure of how much the original designed alignment still exists

High Mast Lighting Foundations

High-mast lighting structures consist of a drilled shaft foundation and a vertical pole with lighting at the top. The standard height of high mast lighting is variable according to different agencies. For example, MnDOT defines a high mast light tower as ranging from 100 to 140 feet in height (MnDOT, 2019), while in the NDOT, a high mast is defined as 120 ft to 140 ft (Sim et al., 2020). As shown in Figure 13, concrete foundations with anchor bolts are generally used to secure the high mast tower with drilled shaft foundations typically used for high mast lighting foundations (WisDOT, 2017; Sim et al., 2020). For high-mast lighting towers, failure issues typically occur because of high-cycle fatigue (Figure 14), and many studies have been conducted to determine the fatigue behavior of high-mast lighting towers (Connor et al., 2012; Thompson 2012). In terms of fatigue behavior, the failure investigations have focused on the bolts that connect the plate to the foundation. In contrast, few studies have found that the substructure was responsible for failure due to fatigue (Sim et al., 2020).

Figure 13. Photo. Examples of high mast lighting tower. (https://dot.nebraska.gov).

Figure 14. Photo. Failure of high mast lighting tower due to fatigue loading (Sim et al., 2020).

The MnDOT has implemented an asset management system for high-mast light towers throughout the state. While bridge and pavement assets have an established robust management system due to the MAP-21 transportation authorization bill, high-mast light towers have not been tracked in most DOTs. In the case of the MnDOT, asset data of high-mast light towers were partially inventoried in the initial stage, and inspections for condition assessment, development of deterioration models, and maintenance activities were not conducted appropriately during initial implementation (MnDOT, 2014). In more recent cycles, to improve the incomplete data inventory, data collection has been established on a five-year cycle by the Minnesota Bridge Office. The collected data are stored in the Automated Facilities Management System (AFMS). In 2019, a total of 478 high-mast light tower structures were inventoried in the system. Based on the construction year of the asset, the age profile was determined (MnDOT, 2014) , and most high-mast light tower structures are relatively new, with construction in the last

20 years. MnDOT (MnDOT, 2014) estimated a replacement value of approximately $19 million based on $40,000 per unit.

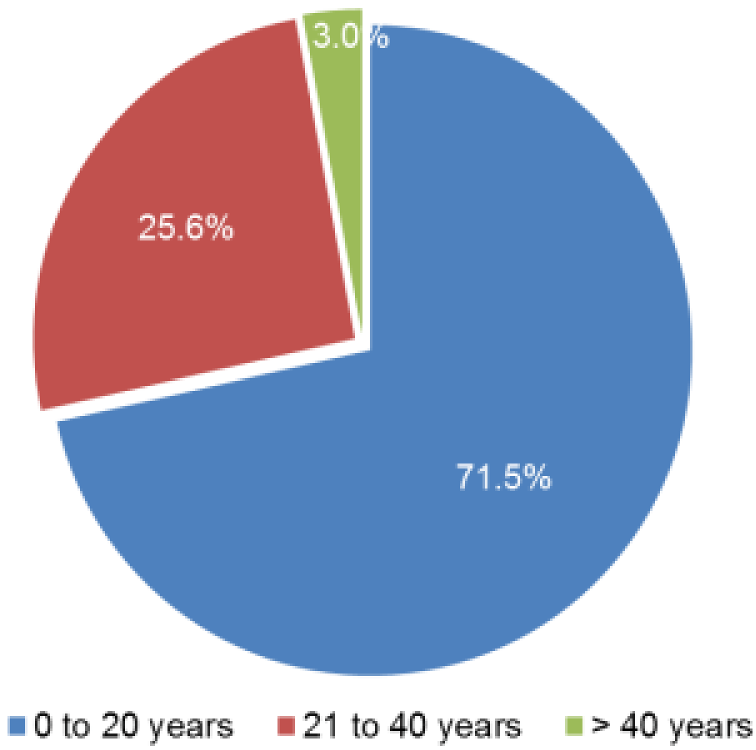


Figure 15. Graph. Age profile of statewide high-mast light towers in Minnesota (MnDOT, 2014).

Since 2001, inspection processes for high-mast light tower structures have been developed and implemented on a five-year cycle by the MnDOT. Condition assessments of high-mast light towers are based on the National Bridge Inventory (NBI) rating scale. MnDOT inspected several significant factors which can lead to failure problems, including fabrication and installation issues, wind-induced vibration, fatigue cracking of structural components, corrosion, traffic hits, and collapse of structural support systems (MnDOT, 2014).

Minimal maintenance has been performed on high-mast light towers because they have long service lives, and failures are rare when the structures are built to specification. Therefore, MnDOT has focused on preventing improper installation (MnDOT, 2014). MnDOT has established performance measures/targets for high-mast light tower structures (Table 14), which expanded treatment activities for performance improvement of high-mast light tower structures, including tightening and levelling nuts and removing debris and replacement of components that have performance issues (MnDOT, 2019).

Table 14. Performance Measure and Target of High Mast Light Tower (MnDOT, 2019)

Asset Type	Performance Measure	Explanation	State Target
High-Mast Light Towers	Share of high-mast light towers in poor condition	High-mast light tower condition is assigned by the Bridge Office on a five-year cycle. The assessment inspects the structure and tightens the nuts--among other general maintenance.	≤ 6%

GEOTECHNICAL ASSET MANAGEMENT IN THE STATE OF GEORGIA

GDOT has been managing transportation assets according to Georgia's Transportation Asset Management Plan (GDOT, 2019a; GDOT, 2022b), which is a federally mandated document and is normally updated every four years. The GDOT Transportation Asset

Management Plan report FY 2019 – 2028 (GDOT, 2019a) quantified 17,923 centerline miles of roadway and 6,239 bridge structures of the Georgia State Route System (SRS), and 7,241 miles of highways and 4,089 bridges from the Georgia National Highway System (NHS). Bridges and pavements are managed by their divisions, which are responsible for periodically assessing the assets' condition and establishing the best long-term life-cycle strategies considering critical assets and funding. Figure 16 shows a timeline of how transportation asset management has been evolving in the state of Georgia.

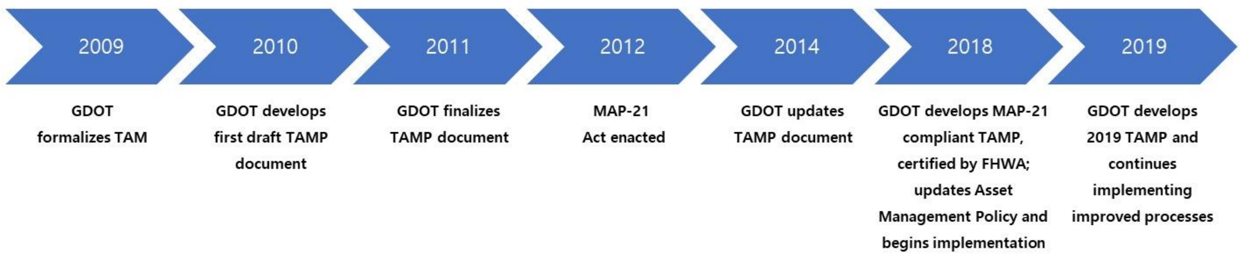


Figure 16. Illustration. Asset management history in GDOT (GDOT, 2019a).

As part of the TAMP plan, the GDOT also manages bridge assets (over 20 feet in span length), which are defined as structures supporting traffic loads, as well as large culverts. Approximately 14,750 state-owned and locally-owned bridge structures are managed in Georgia (GDOT, 2019b). The GDOT Investment Report (GDOT, 2019b; GDOT, 2022b) states that the GDOT has implemented Transportation Performance Management (TPM) to monitor and improve asset performance in terms of safety, asset condition, system reliability, and environmental sustainability. The collected information is used to make decisions on investment, policy, and maintenance. Finally, the Bridge Maintenance Program is implemented through regular periodic bridge inspections. Figure 17 provides statistics of targets for this program (GDOT, 2022d). The maintenance program considers the following activities:

- Inspection of bridges and bridge culverts within a two-year cycle.
- Underwater bridge inspection every five years.
- Determination of a bridge's ability to carry a load (load rating).
- Routing of permit loads (including superloads).
- Assisting counties with solutions to bridge and bridge culvert problems.
- Design and detail bridge repairs.

Figure 17. Illustration. Asset count and construction and maintenance costs resulting from the GDOT Bridge Maintenance Program (GDOT, 2019b, p. 47).

In terms of other efforts focused on assessing data collection practices, Mildner (2018) collected data from fifty-six Georgia cities and counties, which was documented in the Planning for Local Agency Transportation Asset Management report (Mildner, 2018). This report showed that city agencies employ a variety of software types for asset management, of which GIS-based systems are the most commonly used software for TAM. Importantly, it demonstrated that approximately fifty percent of county and city officials were concerned with the inventory and data collection practices within their divisions, suggesting the need to refine protocols in location, data sharing, managing, and inventorying.

Currently, the GDOT uses an ArcGIS-based interface named GeoPI to visualize information on the location, traffic records, safety issues, and previous and ongoing transportation projects throughout the state (Torres et al., 2022). This system has built-in search features to identify and locate project database and asset information by name or ID, including but not limited to the following: county, congressional districts, GDOT Districts, and geographical search. However, there is no record of a geotechnical asset inventory (e.g., slopes, earth structures, embankments, and bridge foundations). Figure 18 illustrates how GeoPI shows the location and information of all bridge projects within an area of interest. When any bridge from the GeoPI interface is selected, it can access photos and details of the bridge and its components and also links to available inspection reports. A Bridge Inspection Report retrieved from GeoPI usually includes details about the location, dimensions, and manual condition assessments of the main structure and relevant components.

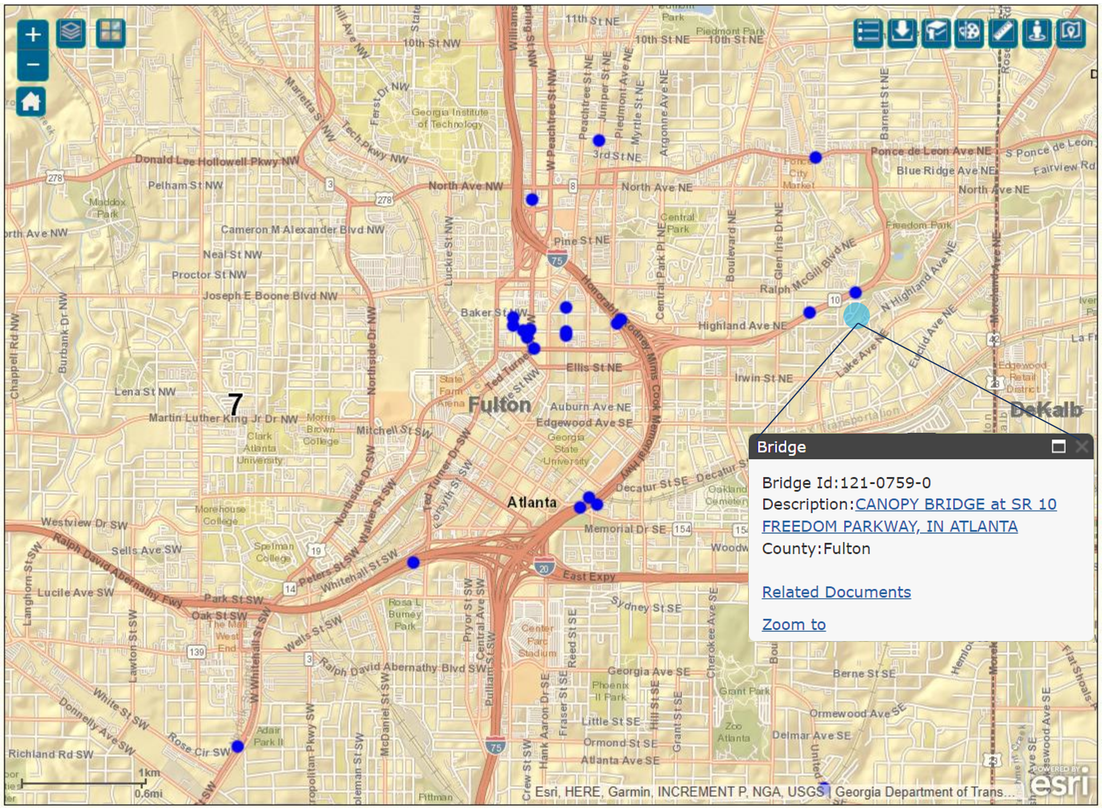


Figure 18. Map. Example of ArcGIS-based interface named GeoPI ([Torres et al., 2022](#)).

The GDOT has also used AgileAssets Inc. and Pathway Services Inc. for managing transportation assets in Georgia. The AgileAssets (www.agileassets.com) software is employed for the implementation of asset management processes state-wide, and the Pathway (www.pathwayservices.com) software is used for identifying, locating, collecting, and rating the condition of roadways in Georgia. The AgileAssets website states that the GDOT performs some essential asset management tasks through licensing software modules specially designed for maintenance, bridge analysis, bridge inspections, signal, and field data management. In comparison, the Pathway software can manage transportation assets such as concrete, composite, and paved roadways through a 3D pavement imaging system that allows the responsible agent to survey and automatically collect distressed areas and roadway defects from a customized vehicle while driving. At the end of each survey, the roadways can be identified and located, and the pavement condition can be calculated. Even though the aforementioned procedures have been successfully implemented for rating, identifying, and locating roadway assets within the Georgia transportation network, the desired long-term vision, according to NCHRP (2019), should be to extend the referred capabilities to locate and manage geotechnical assets.

CONDITION ASSESSMENT OF GEOTECHNICAL ASSETS

The condition assessment rates the physical condition of an asset and provides an index to represent the severity and extent of the existing damage in the asset. There are several structured frameworks in which the condition assessment of geotechnical assets could be considered including (1) the U.S. Army Corps' of Engineers Repair, Evaluation, Maintenance and Rehabilitation Condition Index (RMR), (2) the FHWA's National Bridge Inspection Condition Rating, (3) the U.S. Navy's Condition Rating in a Standard Base Report (BASEREP), and (4) the ASTM's Pavement Condition Index (PCI) (Stanley & Pierson, 2013).

The NCHRP-903 Report recommends focusing on developing simplified rating scales that can be easily implemented in the early stages of a GAM program (e.g., good, fair, poor). Although there are no specific guidelines for rating the condition and performance of each geotechnical asset based on quantitative methods, the NCHRP-903 provides a general framework to assess their condition based on visual inspections and the level of effort needed to maintain assets in a state of good repair. Figure 19 illustrates the five-level category of the operation and maintenance (O&M) condition decision tree used towards a mature GAM implementation.

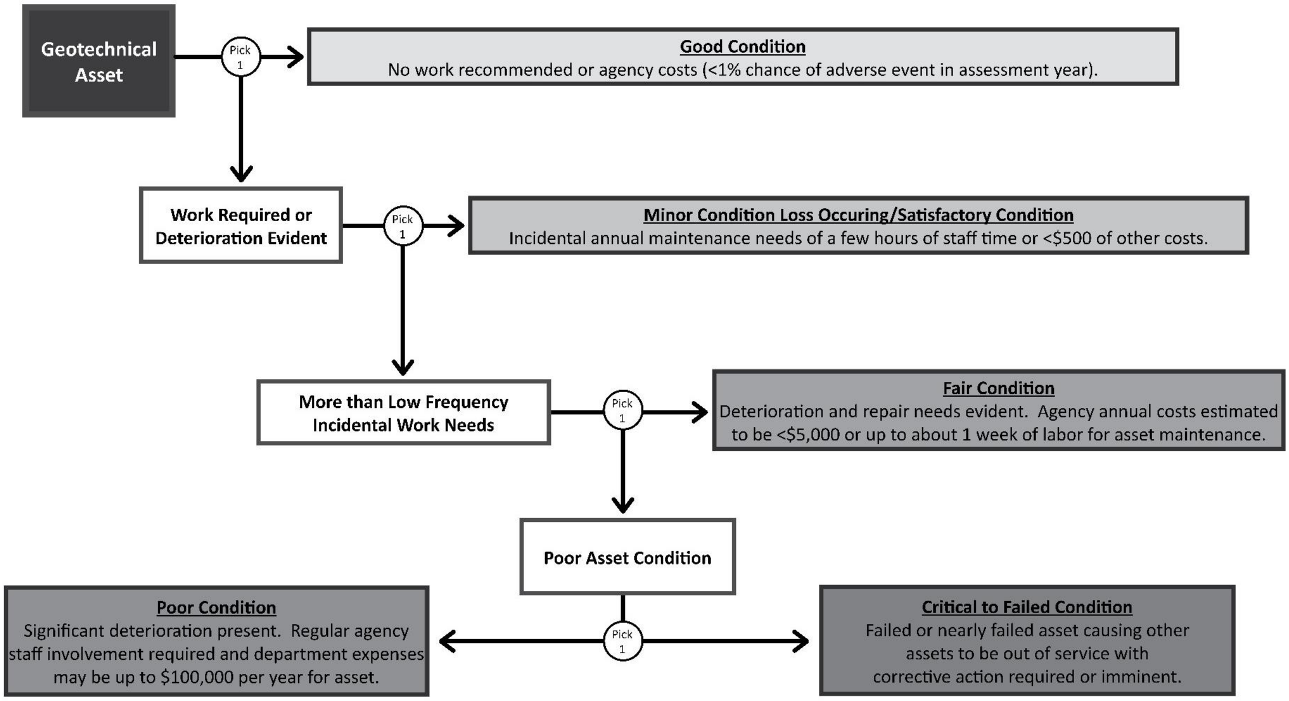


Figure 19. Illustration. Asset condition levels based on O&M criteria. (NCHRP, 2019).

Appendix D of the NCHRP-903 report (NCHRP, 2019) shows examples that relate scenarios of deteriorated geotechnical assets and condition level based on the distress observed and the time and funding needed to maintain, repair, rehabilitate or reconstruct the inspected asset. Similar assessment structures have been followed by several DOTs nationwide, some of which will be discussed further below.

Retaining walls

The Colorado DOT (Walters et al., 2016) considers condition ratings ranging from 0 to 9; the New York State DOT (NYSDOT, 2018), the Wisconsin DOT (WisDOT, 2017), and the Michigan DOT (Athanasopoulos-Zekkos et al., 2020) implemented four condition states to represent qualitative ratings such as good, fair, poor, and severe. The FHWA rating system for the National Park Service (FHWA-NPS) uses values from 1 to 10, which are associated with qualitative labels denoted as critical, poor, fair, good, and excellent (DeMarco et al., 2009) (Table 15).

Table 15. Retaining Wall Condition Rating Scales (DeMarco et al., 2009)

Element Condition Rating	Rating Definition
9-10 Excellent	No to very-low extent of very low distress. Any defects are minor and are within the normal range for newly constructed or fabricated elements. Defects may include those typically caused by fabrication or construction. Ratings of 9-10 are only given to conditions typically seen shortly after wall construction or substantial wall repairs.
7-8 Good	Low-to-moderate extent of low-severity distress. Distress present does not significantly compromise the element function, nor is there significant severe distress to major structural elements of an element. Ratings of 7-8 indicate highly functioning wall elements that are only beginning to show the first signs of distress or weathering.
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 and/or elevated risk of element failure in the near term. Ratings of 5-6 indicate functioning wall elements with specific distresses that need to be mitigated in the near-term to avoid significant repairs or element replacement in the longer term.
3-4 Poor	Medium-to-high extent of medium-to-high severity distress. Distress present threatens element function, and strength is compromised, and/or structural analysis is warranted. The element condition does not pose an immediate threat to wall stability, and closure is not necessary. Ratings of 3-4 indicate marginally functioning, severely distressed wall elements in jeopardy of failing without element repair or replacement in the near-term.
1-2 Critical	Medium-to-high extent of high-severity distress. Element is no longer serving its intended function. Element performance is threatening the overall stability of the wall at the time of inspection. Ratings of 1-2 indicate a wall that is no longer functioning as intended and is in danger of failing catastrophically at any time.

As an example of the value of a lean start approach for implementing a GAM program, the Ohio DOT recommends rating assets according to the ODOT Retaining Wall Inventory Manual (ODOT, 2018), focusing on evaluating the overall state of the retaining wall rather than a thorough examination component by component (e.g. backfill, structural, vertical, and horizontal elements, drainage system, foundation). This general assessment considers the wall drainage system's physical state, the surrounding soil's condition, and the wall's overall structural performance as one unit, and depending on the overall performance, the rating could be denoted as good, fair, or poor.

Slopes

The slope condition assessment provides a qualitative label or numerical value to represent the severity and extent of the existing damage, aging, or deformation on a slope. For example, the Alaska DOT and Public Facilities (AKDOT-PF) breaks down the condition assessment of soil slope assets into three categories, namely class A, B, or C (Table 17). The condition assessment for rock slopes follows a similar logic as soil slope assets, i.e., three categories are considered (Table 18). The AKDOT-PF report (Beckstrand et al., 2017c) provides several examples of slope systems being rated within the described categories (Figure 20 to Figure 22).

Table 16. Modified Soil Slope Condition Basic Rating Scales

(Beckstrand et al., 2017c)

Soil / Slope Class	Rating Definition
A	Soil slopes exhibit signs of instability that could affect public safety, require regular maintenance action, or threaten the functionality of the surrounding infrastructure in the event of a failure. In addition to the classic unstable slope failures that show clear signs of sunken or uneven grade, with or without evidence of patching or other maintenance activity, are treated as Class A soil slope sites.
B	Soil slopes are those that exhibit signs of minor instability but are relatively short (typically less than 10 feet tall) with a wide ditch, have required little or no unscheduled maintenance attention in the past, or are deemed unlikely to require maintenance attention or threaten the functionality of the surrounding infrastructure in the future. Slopes that can be reasonably assumed to be threatened by future erosion were also included in the Class B category.
C	Soil slopes exhibit no signs of instability and/or would not affect the roadway in the event of failure.

Table 17. Modified Rock Slope Condition Basic Rating Scales

(Beckstrand et al., 2017c)

Rock / Slope Class	Rating Definition
A	Capable of producing rockfall that reaches the roadway, has a history of doing so, requires regular unscheduled maintenance attention, or could have impacts beyond the right-of-way
B	Unlikely to produce rockfall that reaches the roadway, but has an infrequent history of producing rockfall or of requiring unscheduled maintenance attention
C	Highly unlikely to produce rockfall that will affect the roadway or private property

Figure 20. Photo. Class A soil slope, there is an active sloughing of saturated soil and vegetation. This unstable soil slope, due to its height and proximity to the roadway, warrants a detailed examination (Beckstrand et al., 2017c).

Figure 21. Photo. Class B soil-slope, this cut slope does not represent a safety risk, but the adjacent ditch is filled with debris, and it might require immediate minor intervention from the Operation & Maintenance Office. Roadside ditches should always be clean and obstruction-free to achieve proper drainage conditions. Moreover, a timely report accompanied by a proper condition assessment might prevent a slope from going from a fair condition to a poor one

(Beckstrand et al., 2017c).

Figure 22. Photo. Class C soil-slope, this geotechnical asset is a stable cut slope showing no signs of unstable performance. Depending on the judgment of the rater, this slope might be excluded from the inventory unless some degree of instability manifests (Beckstrand et al., 2017c).

Embankments

Similar to other assets, the condition assessment of embankments also provides a qualitative label or numerical value to represent the severity and extent of the existing damage, aging, or deformation on the embankment integrity (including the slopes, material condition, etc.). Several DOTs have also used a lean start to implement embankment condition assessment techniques. For example, the Alaska DOT (Beckstrand et al., 2017a) used a system similar to the one previously described for slopes where three categories (Class A, B, or C) are considered (Table 22). Some examples relating the condition and performance of embankments and the AKDOT's three-level condition framework are illustrated in Figure 23 to Figure 25

Since slopes and embankments share similar stability and deterioration concerns and are solely designed by geotechnical and geology engineers, most of the literature addressing the condition and performance of embankments are within slopes and landslides management programs, such as the WSDOT's Unstable Slope Management Program (WSDOT, 2018) and the Ohio DOT's Manual for Landslide Inventory (ODOT, 2013). Nevertheless, other useful references that discuss important aspects for assessing the performance and condition of embankments include Glendinning et al. (2009) and Bernhardt et al. (2003).

Table 18. Modified Embankment and Soil Slope Condition Basic Rating Scales (Beckstrand et al., 2017c)

Embankment / Slope Class	Rating Definition
A	Embankments exhibit signs of instability, impacting serviceability and public safety. These failures require immediate attention and regular maintenance action or threaten the functionality of the transportation network in the event of a sudden collapse. Every unstable embankment/slope failure that shows clear signs of sunken or uneven grade, with or without evidence of patching or other maintenance activity, should be treated as a Class A soil slope site.
B	Embankments relatively short (typically less than 10 feet tall) and with a wide side ditch exhibit signs of minor instability and pavement deformation. The road segment has required little or no unscheduled maintenance attention in the past, deemed unlikely to require maintenance attention, or threatening the surrounding infrastructure's functionality in the future. Downslopes that can be reasonably assumed to be threatened by future erosion were also included in the Class B category.
C	Embankments and downslopes exhibit no signs of instability and/or would not affect the roadway in the event of failure.

Figure 23. Photo. Example of a Class A embankment-slope: Active sloughing of non-saturated soil and vegetation. This unstable downslope due to its height and proximity to the roadways warrants a detailed examination. Most likely, the head scarp of the translational slide can be seen in the roadway as significant horizontal and vertical deformation. (ODOT, 2013).

Figure 24. Photo. Example of a Class B embankment-slope: Downslope does not represent a safety risk, but the dip in the roadway is perceived, affecting serviceability and demanding the intervention from the Operation & Maintenance Office. Roadside ditches should always be clean and obstruction-free to achieve flawless drainage conditions. Moreover, a timely report accompanied by a proper condition assessment might prevent the downslope from going from a fair condition to a poor one (ODOT, 2013).

Figure 25. Photo. Example of a Class C embankment-slope: Geotechnical asset with a stable engineered fill showing no signs of unstable performance. Depending on the judgment of the rater, this slope might be excluded from the inventory unless some degree of instability manifests. (No author, retrieved 2022).

Bridge Foundations

Bridge condition assessment is typically performed at least every other year (NBIS, 2004). In general, overall assessments of bridge condition are implemented through inspection of the major elements of bridge assets, including the deck, superstructure, and substructure, where condition assessment of bridge foundations is included in the substructure. Typically, condition ratings ranging from 0 to 9 are recommended to describe the condition (Table 19), with any element rated below 5 considered deficient and in need of major improvements.

Table 19. Condition Ratings of Bridge Assets (FHWA, 1995)

Element Condition Rating	Rating Definition
9	Excellent condition
8	Very good condition; no problems noted.
7	Good condition; some minor problems
6	Satisfactory Condition; Structural elements show some minor deterioration.
5	Fair Condition: all primary structural elements are sound but may have some minor section loss, cracking, spalling, or scour.
4	Poor condition; advanced section loss, deterioration, spalling, or scour
3	Serious condition: loss of section and deterioration, spalling or scour have seriously affected primary structural component. Local failures are possible.
2	Critical condition; Advanced deterioration of primary structural components. Close of the bridge might be necessary before corrective action.
1	Imminent failure condition; major deterioration and section loss in critical structural components. Close of the bridge is done for corrective action.

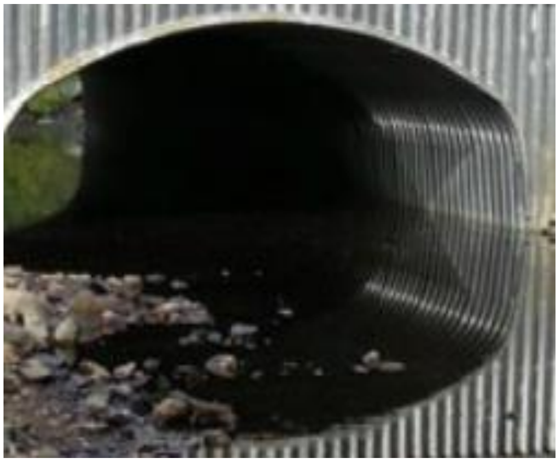
Other Geotechnical Assets

Box Culvert Foundation

For condition assessment of box culverts, aspects of both culvert stability and material durability should be inspected, including structural and material properties that could lead to significant issues in performance. For example, the condition inspection of a box culvert must include an assessment of degradation of concrete due to acidic drainage, sulfate formation, freeze-thaw, or corrosion of reinforcing bar, as well as box culvert performance. Additionally, details and descriptions of critical damage, such as cracking, spalling, deterioration, and settlement, should be provided. Based on the inspection results, condition ratings of box culvert assets will be determined. The size of spall, abrasion, crack, settlement, and other exposed damage determine condition ratings. As shown in Table 20, condition ratings ranging from 1 to 4 are recommended (AASHTO Culvert and Storm Drain System Inspection Guide, 2020). According to North Atlantic Aquatic Connectivity Collaborative (NAACC), for culvert footings, the condition rating is conducted through the assessment of cracking, delamination, spalling, joint deterioration by weathering, and settlement. Examples of each culvert footing condition are given in Figure 26 (note for FHWA highest numbers represent better conditions, but this differs for other agencies):

Table 20. Condition Ratings of Box Culvert
(AASHTO Culvert and Storm Drain System Inspection Guide, 2020)

Rating Scale	Rating Definition	Condition Details
1	**Good**	Like new (no deterioration, structural and functional problem); No problems
2	**Fair**	Some deterioration, but it has adequate structural and functional performance; Minor to Moderate problems (e.g., cracking, spalling, deterioration, settlement)
3	**Poor**	Significant deterioration. It has inadequate structural and functional performance; Extensive problems (e.g., cracking, spalling, deterioration, settlement)
4	**Critical**	Severe or critical issues in function or stability of box culvert; immediate action and analysis are required.



a) Good condition

b) Fair condition

c) Poor condition

d) Critical condition

Figure 26. Photo. Examples of culvert deterioration conditions according to NAACC condition ratings (https://streamcontinuity.org/naacc/assessments/documents) (NAACC, 2019).

Inspection frequency is determined by each state or agency based on the importance of the asset. According to National Bridge Inspection Standards (FHWA, 2004), culvert inspections are typically conducted every two years. For new culvert construction, inspection should be done within 30 days after installation. Also, recommended inspection frequency is different according to barrel span (AASHTO Culvert and Storm Drain System Inspection Guide, 2020), as detailed in Table 21.

Table 21. Culvert Inspection Frequency According to Barrel Size (AASHTO Culvert and Storm Drain System Inspection Guide, 2020)

Barrel Size(s)	Inspection Frequency
S < 4ft	Inspect during roadway maintenance.
4 ft ≤ S ≤ 10 ft	Every 10 years or prior to routine roadway maintenance activities, whichever is less
S > 10ft	Every 5 years or prior to routine roadway maintenance activities, whichever is less.

High Mast Lighting Foundations

For condition assessment of high mast lighting, several major elements, including the foundation, anchor bolts, steel base plates, and steel poles and splices, should be inspected in maintenance-related inspections, routine inspections, and in-depth inspections (WisDOT, 2017). The foundation inspection is considered a routine inspection, and the inspection should include all applicable elements and also evaluate defects, including cracking, spalls, delamination, and erosion around the foundation (Figure 27).

Figure 27. Photo. Spalled and exposed high mast lighting foundation (WisDOT, 2017).

Condition ratings ranging from 1 to 4 can be assigned based on the results of the inspected elements (Table 22). The condition states are as follows: 1) Good: no major defects; 2) Fair: minor cracks, spalls, exposed reinforcing steel, rust staining, while erosion can be present, but does not impact structural stability; 3) Poor: significant corrosion and loss of concrete exists, but does not lead to critical stability problems; and 4) Critical: immediate structural and elemental reinforcement are required due to problems in strength or serviceability.

Table 22. Condition Ratings of High Mast Lighting Foundation (WisDOT, 2017)

Condition State	Condition Details
Condition State 1	The element shows no deterioration.
Condition State 2	Minor cracks and spalls may be present in the foundation, but only minimal reinforcing steel is exposed. When efflorescence is present, it is minor, with no evidence of rust staining. Grout pad (if present) is in good condition. Minor erosion around the foundation may be present but does not affect structural capacity.
Condition State 3	Many Spalls are present. Corrosion of reinforcement and/or loss of concrete section is evident though not sufficient to warrant structural analysis. Grout Pad (if present) has moderate cracking, spalls, or delaminations. Erosion may be present that reduces the foundation embedment significantly but does not pose a threat to the stability of the structure.
Condition State 4	Condition State 4: The condition warrants a structural review to determine the effect on the strength or serviceability of the element, or a review has been completed, and it has been found that the defects impact strength or serviceability.

DECISION-MAKING AND RISK ASSESSMENT

Risk assessment

The Georgia Department of Transportation (GDOT) has been managing transportation assets according to Georgia's Transportation Asset Management Plan (TAMP), which is a federally mandated document normally updated every four years. Bridges and pavements are managed by their respective Divisions, which are responsible for periodically assessing the asset's condition and establishing the best long-term risk strategies considering critical assets and limited funding. Historically, geotechnical assets are managed by restoring the asset after failure rather than preventing failure. Therefore, aiming to develop a financially sustainable geotechnical asset management (GAM) system that transportation agencies (such as the GDOT) can use to enable more proactive infrastructure risk assessment is critical for strategic investment and long-term management of the transportation network (Wolf et al., 2015).

MAP-21 requires all state DOTs to develop risk-based transportation (including geotechnical assets) asset management plans, stating that "Agencies should manage potential risks by identifying, analyzing, evaluating, and addressing the risks to assets and system performance" (FHWA, 2012). Risk in infrastructure systems is defined as the potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences (FHWA, 2012). Furthermore, the risk is often represented as the positive or negative effect of uncertainty or variability based on Agency objectives (AASHTO, 2017). The NCHRP-903 (Volume 2) defines risk as "the product of the probability of a hazard event occurring and the consequences of the event occurring" (NCHRP, 2019). For instance, as the likelihood of slope failure (hazard) increases during storm events in North Georgia, the risk of damaging infrastructure (e.g., roads, parking lots, and sidewalks) increases. Thus, a robust risk assessment in any risk-based GAM program should at least consider hazards, likelihood, and consequences.

Hazard refers to any potential occurrence of a natural or human-induced physical event that may cause damage to property, infrastructure, population, service provision, and environmental resources (FHWA, 2017). According to NCHRP-903, hazards are considered as any potential events with negative consequences, including natural events and those due to deterioration (NCHRP, 2019). For example, as precipitation frequency and duration increase due to climate change, the increased frequency of inundation of roadways during a storm event is a potential hazard for low-lying coastal embankments.

From a risk perspective, consequences are the interpretation of adverse scenarios in financial terms or by quantifying a lack of performance. According to the NCHRP-903, consequences are "quantified or scaled values of impacts from asset performance incorporated into the determination of risk exposure" (NCHRP, 2019). For instance, the consequence of wall failure could be expressed in U.S. dollars and include impacts that are not strictly financial, such as affected populations, delays, opportunity costs, and injuries.

The risk-based GAM program recommended by the NCHRP-903 considers how the asset affects the performance of an agency by:

- Evaluating general consequences of having safety concerns (SC) due to failing geotechnical assets. Figure 28 shows the logic tree behind GAM safety consequences.

- Estimating the loss of mobility (MC) due to asset failure or harmful geotechnical events, namely landslides, rockfall, and rockslides. Figure 29 shows the logic tree behind GAM mobility consequences.

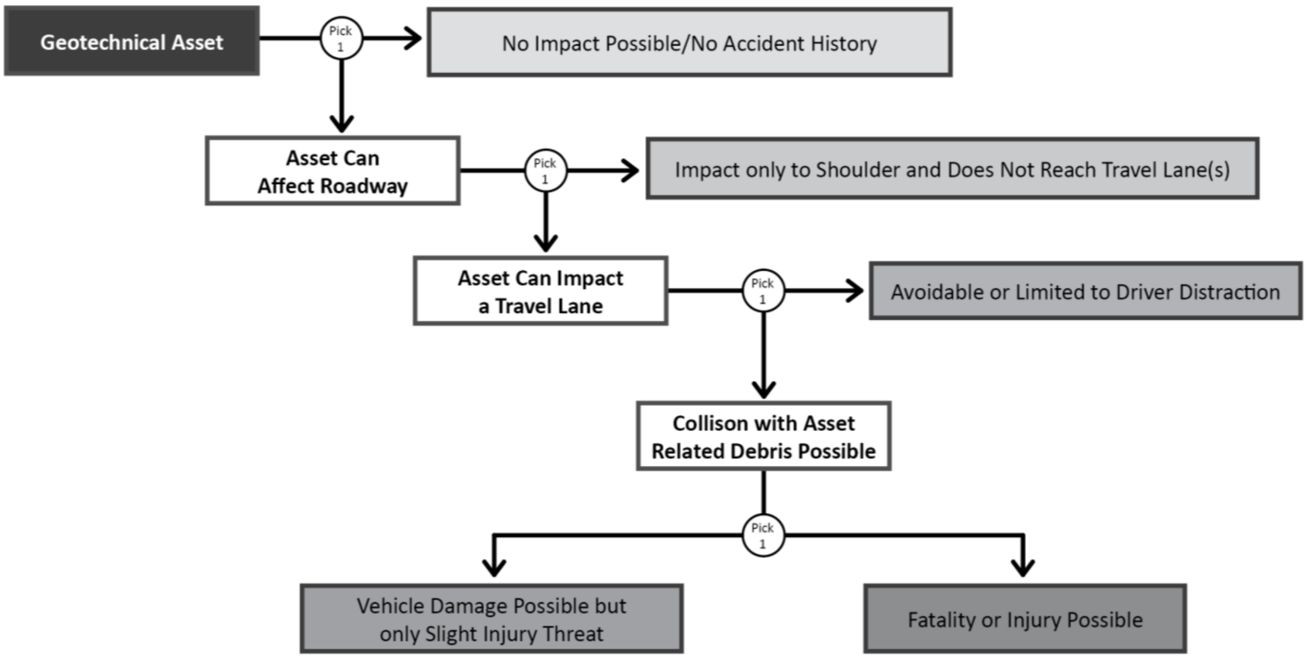


Figure 28. Illustration. Safety consequence tree (NCHRP, 2019).

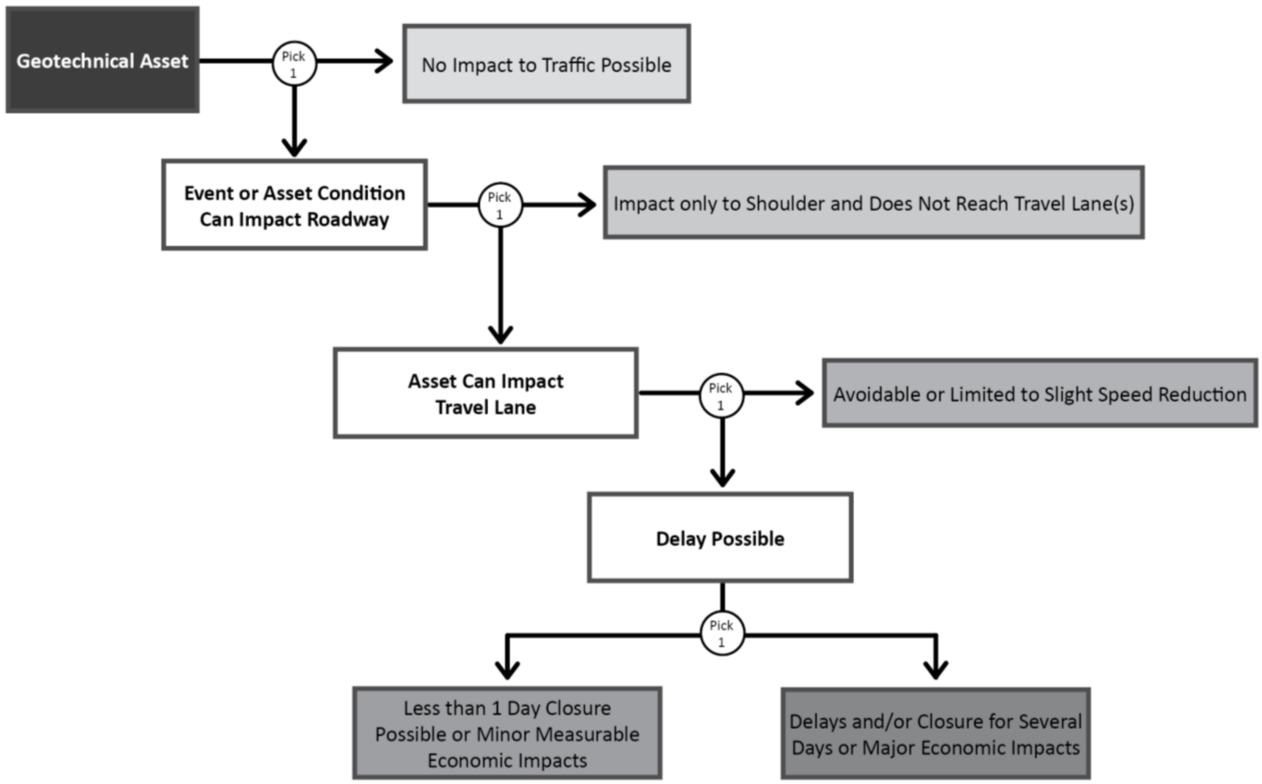


Figure 29. Illustration. Mobility consequence tree (NCHRP, 2019).

Defining vulnerability is essential because the consequences of a geotechnical asset failure would be aggravated by its vulnerability. Vulnerability encompasses a variety of concepts and elements, such as susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2014) or the latent weaknesses present during an asset's design, construction, or operation that can be susceptible to sustaining damage from hazards (FHWA, 2017; Choate et al., 2017). The NCHRP-903 expresses vulnerability as the conditional probability of particular consequences, given triggering events. For example, some walls, slopes, and embankments are more prone to failure based on saturation and have limited drainage capacity to adapt, therefore highly vulnerable during extreme precipitation events.

After the condition assessment is conducted and the most likely consequences after potential failure have been defined, a risk assessment is required to estimate the level of risk (LOR). Estimating risk from a quantitative approach can be done by multiplying the numeric values given to each level of consequence, in both safety and mobility, with the numeric values given to the asset condition.

Life cycle planning

Life cycle planning is the process to implement the most cost-effective asset management over the entire life of an asset, and the life cycle stages for asset management can be classified into planning, design, construction, operation and maintenance, decommissioning, and reconstruction phases (

Figure 30). Life cycle planning facilitates cost reduction in each stage of an asset's service, which can significantly enhance savings.

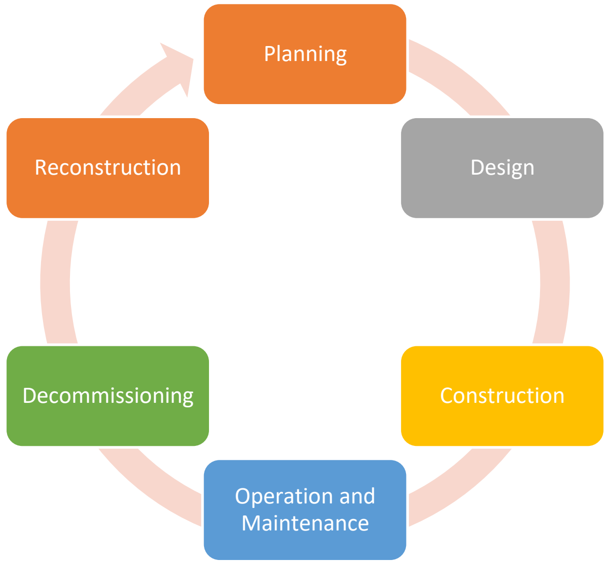


Figure 30. Illustration. Asset life cycle for asset management.

Most of the life cycle cost (up to 80%) is determined by preconstruction decisions. In contrast, for operation and maintenance processes, the cost escalates over the asset's entire life (Figure 31). Because deterioration occurs over the life cycle of constructed assets, and it can lead to severe damage in terms of human life and/or property. Consequently, treatment processes such as maintenance, repair, rehabilitation, and reconstruction are necessary to prevent failure and extend the lifetime of the geotechnical assets.

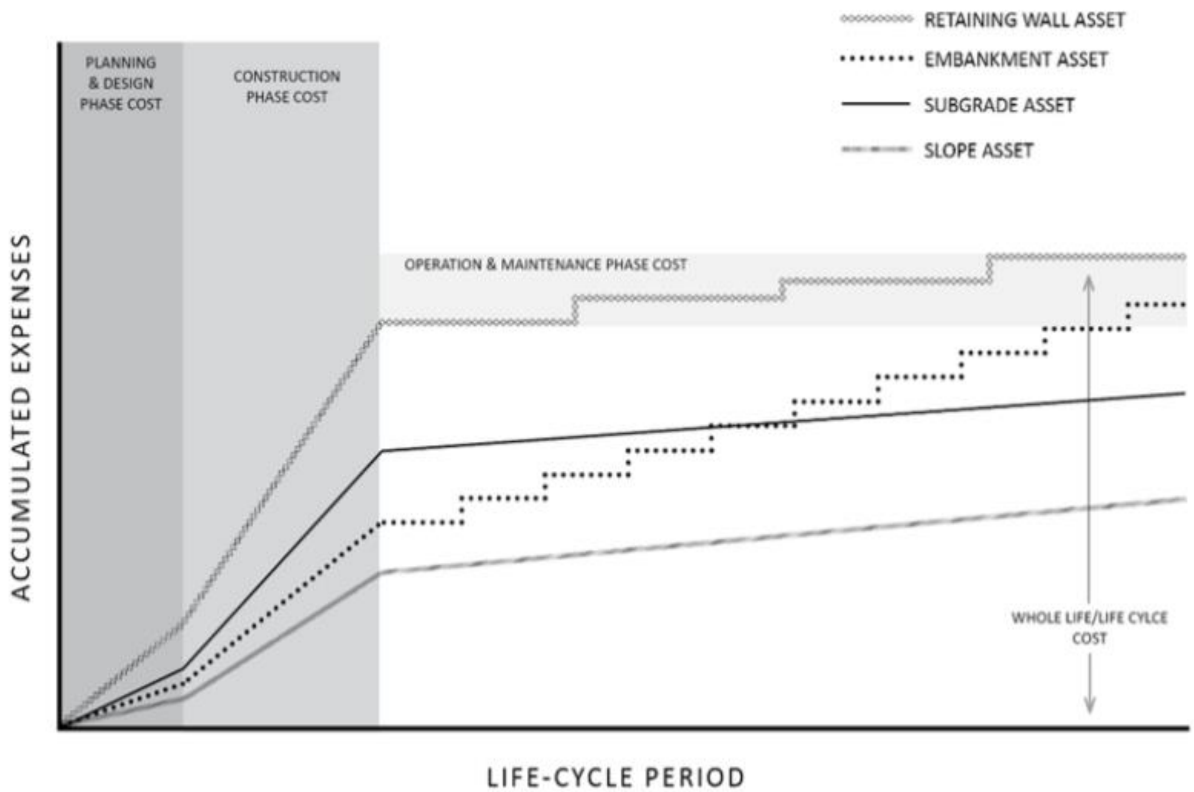


Figure 31. Graph. Life-cycle cost of geotechnical assets (NCHRP, 2019).

In addition, expected expenses vary according to the treatment method and timeline. Maintenance, repair, rehabilitation, and reconstruction are representative treatment types defined as follows:

- Maintenance: routine or cyclic activities to delay asset deterioration
- Repair: non-routine restoration of asset elements
- Rehabilitation: replacement of asset elements or section
- Reconstruction: reestablish asset

Many DOTs have developed life cycle plans to manage assets effectively. Examples from Alaska, Minnesota, Ohio, Tennessee, and FHWA are summarized.

Alaska Department of Transporttion and Public Facilities (AKDOT&PF)

AKDOT&PF conducts routine maintenance corrective action, including preservation, risk mitigation, and reconstruction to extend the lifespan of an asset. Also, they developed preliminary models of deterioration rates to determine cost-effective treatment actions. Figure 32 to Figure 34 shows the typical pattern of soil slope condition over time according to treatment action. In the case of corrective action (preservation) and reconstruction, they extended asset life span when compared to pure deterioration cases. In particular, research has shown that corrective action on soil slope led to a 15% return on investment. In the case of rock slope, retaining wall, and material site resulted in 38%, 148%, and 882% of return on investment, respectively (Thompson, 2017).

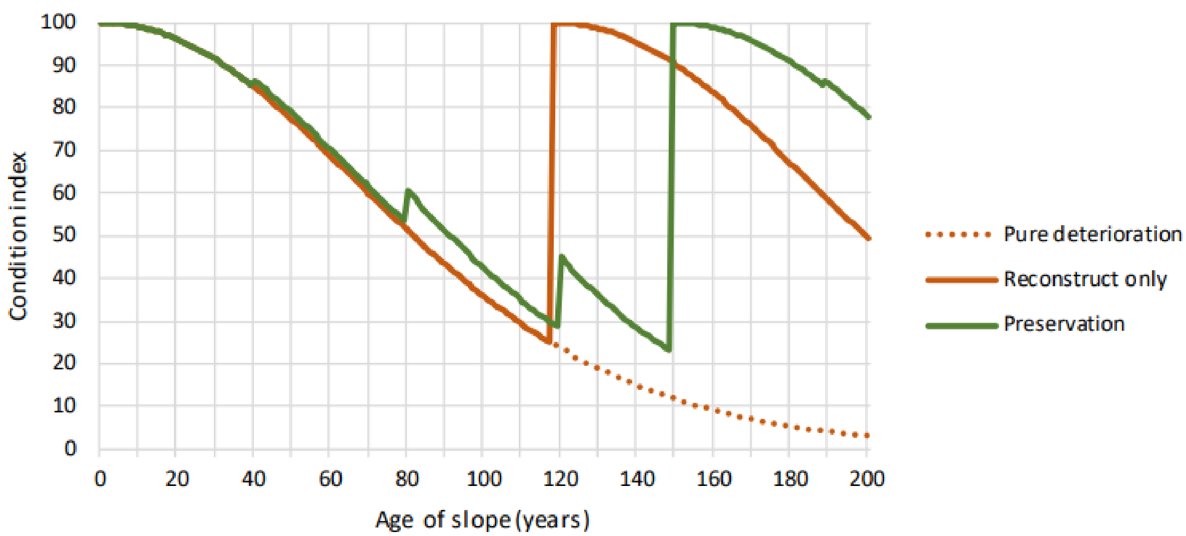


Figure 32. Graph. Typical pattern of soil slope condition (Thompson, 2017).

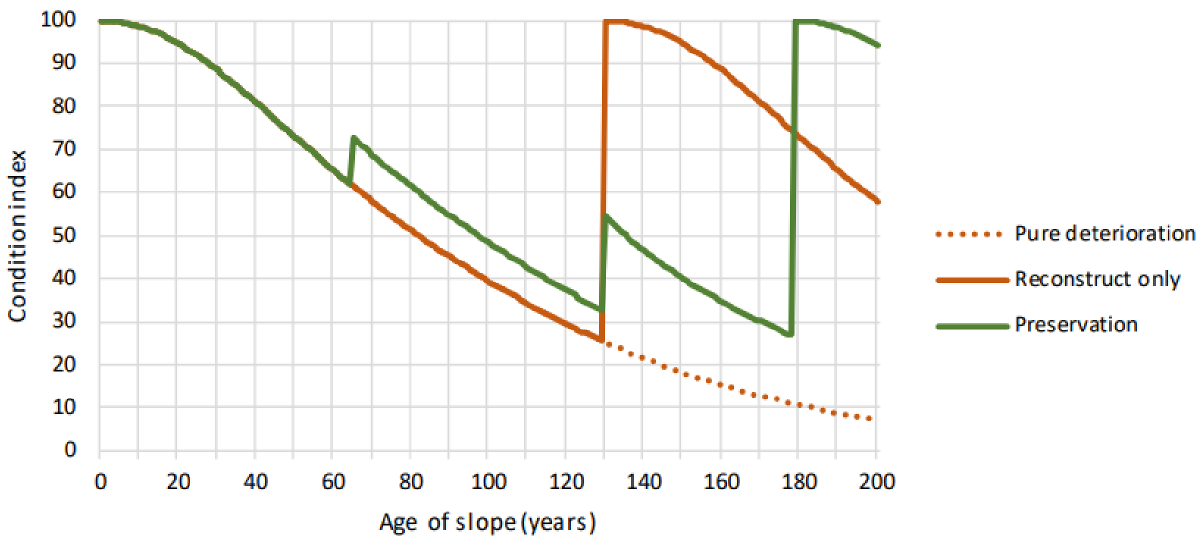


Figure 33. Graph. Typical pattern of rock slope condition ([Thompson, 2017]).

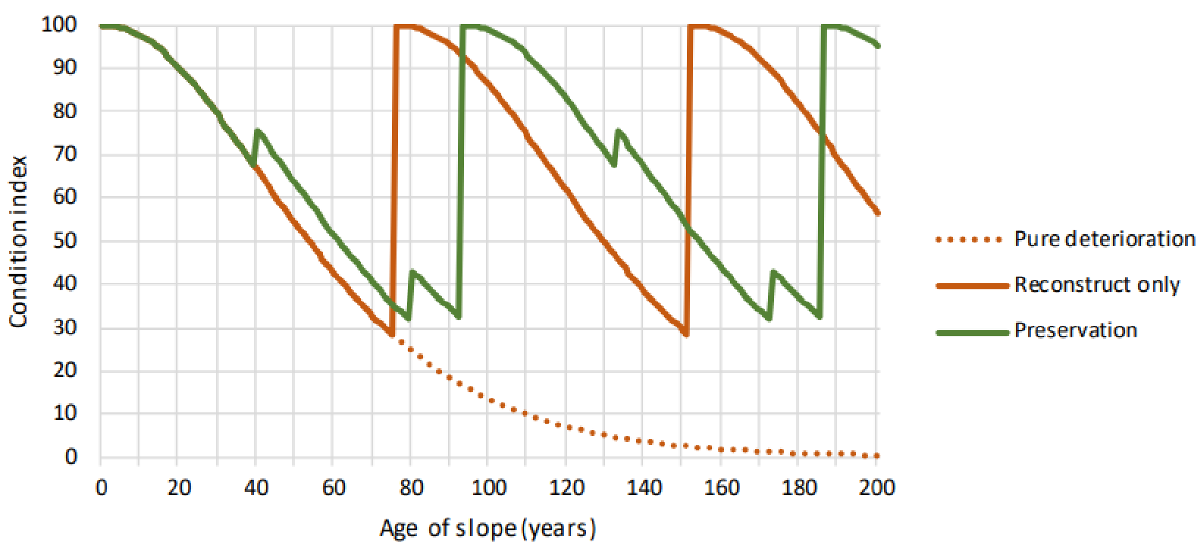


Figure 34. Graph. Typical pattern of retaining wall condition ([Thompson, 2017]).

Minnesota Department of Transportation (MnDOT)

In the case of MnDOT, they compared three improvement strategies to determine the most cost-effective treatment as a life-cycle analysis (MnDOT, 2014). The strategies are as follows:

- Typical strategy

This considers treatments that MnDOT can normally implement.

- Worst-first strategy

This conducts limited treatment for asset improvement and allows deterioration of asset until it needs replacement (poor condition state).

- Desired strategy

The desired strategy conducts treatment according to intervals that are defined in MnDOT's pavement design manual. This strategy is considered only for pavement assets. In the case of other assets, there is not enough data for implementation.

Table 23 summarizes the different strategies for a variety of assets, as indicated by the MnDOT (MnDOT, 2014).

Table 23. Strategies of Each Asset for Life Cycle Cost Analysis (MnDOT, 2014)

Asset	Typical Strategy	Worst-first Strategy	Desired Strategy
Pavements	Delay the need for reconstruction by applying a combination of surface treatments, crack sealing, and mill and overlays, depending on the pavement condition and the available budget.	Reconstruct a pavement as it deteriorates to Poor condition without routine preservation activities.	Apply a major rehabilitation and/or reconstruction activity at year 50 once the pavement has undergone a few preservation cycles and minor rehabilitation events.
Bridges and Large Culverts	Perform repair and preventive maintenance on approximately two percent of bridges and large culverts; wash	Replace the entire bridge or large culvert structure as it deteriorates to a Poor condition without	Insufficient data

Asset	Typical Strategy	Worst-first Strategy	Desired Strategy
	about 75 percent of bridges annually. Perform limited repair actions based on funding availability and judgment of inspectors and district bridge engineers.	any preventive maintenance or repairs.	
Highway Culverts	Perform various maintenance actions on approximately two percent of culverts annually; flush each culvert once every 10 years. · Maintenance work performed based on the judgment of inspectors	Replace a culvert as it deteriorates to a Poor condition without any preventive maintenance or repairs.	Insufficient data
Overhead Sign Structures and High Mast Tower Lights	Perform routine inspections after initial construction to determine maintenance needs. Perform routine maintenance and major structural rehabilitation on an as-needed basis, as identified through inspections.	Perform routine inspections after initial construction, but perform no maintenance. Replace structure in a 40-year cycle (assuming deterioration to a condition when maintenance and rehabilitation are not expected to be effective).	Insufficient data

Figure 35 shows an example of the cost estimation for different strategies by life cycle analysis. In the case of the worst-first strategy, it had a relatively much higher life cycle cost. On the other hand, the typical and desired strategy showed approximately 60 percent of life cycle cost savings when compared to the worst-first strategy.

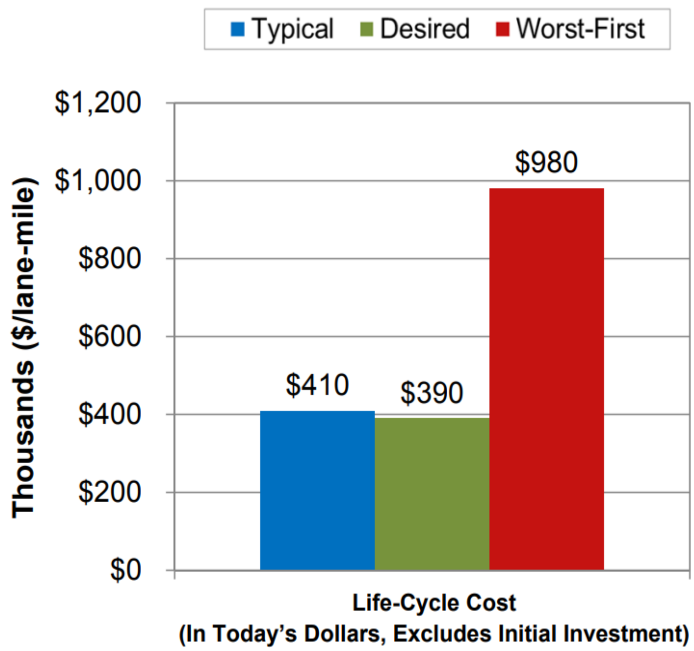


Figure 35. Graph. Example of life cycle cost analysis (MnDOT, 2014).

ODOT

ODOT also focused on reducing life cycle costs in terms of pavements, bridges, and conduits. They found that timely preservation can lead to reducing life cycle costs by extending the life span and delaying the reconstruction process. For example, in the case of bridges and conduits, preservation activities, including bridge cleaning, deck sealing, and deck sweeping, can prevent severe strength problems by corrosion and crack. For effective treatment, they have monitored the condition of assets through routine inspection over time and developed mathematical models for deterioration rate.

Figure 36 shows the differences between past and current strategies for managing assets. In the case of the past strategy, it manages assets with only routine maintenance ($2,500 per bridge per year) and implements only replacement activities. On the other hand, the current strategy conducts not only preservation treatment but also replacement activities. However, the current strategy needs fewer replacement activities and leads to extending the life span of bridge assets. In addition, it reduced life cycle costs compared to past strategies by implementing appropriate and timely treatment.

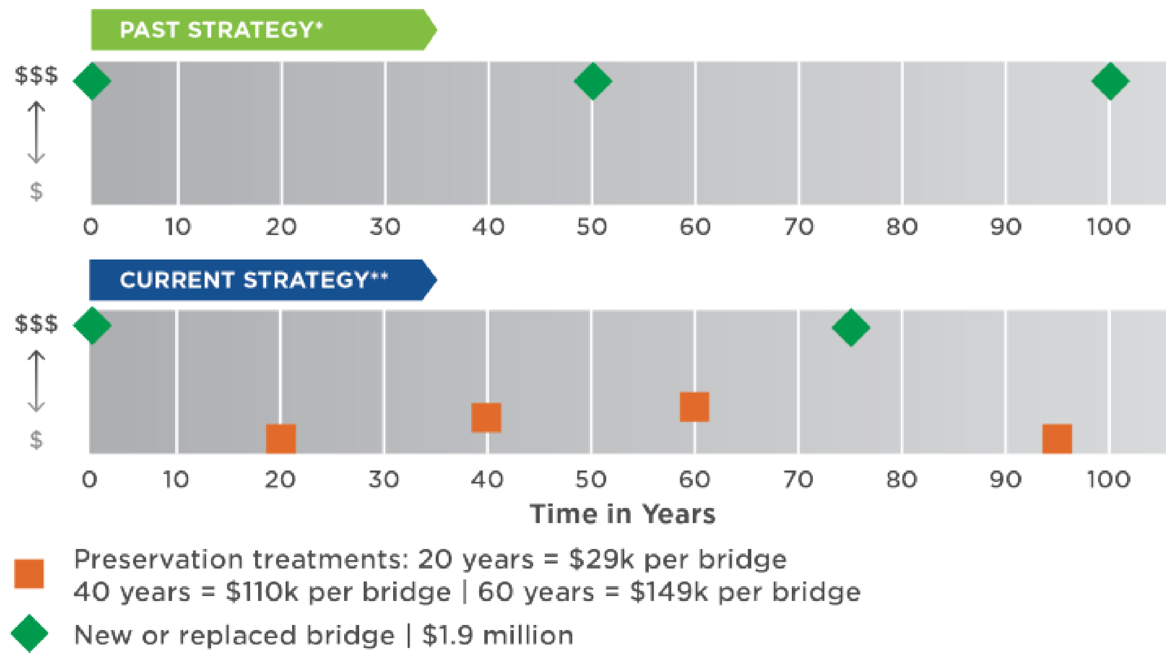


Figure 36. Graph. Example of bridge preservation strategies (ODOT, 2019).

Tennessee Department of Transportation (TDOT)

The TDOT has developed life cycle cost analyses for pavement and bridge assets. Only a few assets (pavement: less than 5% of interstate lane miles and less than 1% of state routes, bridge: less than 3 % of bridges on the NHS) are not considered for life cycle cost analysis. The TDOT implemented an investment strategy which is based on four types of works (e.g., preventive maintenance, preservation, rehabilitation, reconstruction) to manage pavement and bridge assets effectively. These treatment types are key factors for life cycle cost analysis. Thus, the identification of work types based on condition state, target, and cost, and the selection of proper timing is important. Table 24 - Table 25 represent treatment types and unit costs according to work type.

Table 24. Treatment Type and Unit Cost in terms of Pavement Assets (TDOT, 2019)

Work Types	Treatments	Unit Cost Per Lane mile
Preventive Maintenance	Shallow patching	Asphalt: $110/ton to 376/ton Concrete: $442/CY
	Skin Patching	
	Partial-depth patching	
	Repair concrete corner breaks	
	Concrete Joint Repair	
	Other thin patching	
Preservation	Thin asphalt overlay (≤1.5”)	State Routes: $21,100 to $122,300 Interstate: $164,100 to $168,000
	Microsurfacing	
	Chip seals	
	Cape seals	
	Crack sealing	
	Concrete joint sealing	
	Mill and fill asphalt overlays (≤1.5”)	
Rehabilitation	Full-depth patching	$248,100
	Repair/replacing concrete slabs	
Reconstruction	Rubblization and overlay of concrete pavement	$622,200 to $1,554,700
	Full-depth replacement of asphalt pavement	

Table 25. Treatment Type and Unit Cost in terms of Bridge Assets (TDOT, 2019)

Work Types	Treatments	Average Unit Cost Per Sq. Ft.
Preventive Maintenance	Filling potholes in deck	$20
	Minor structure repair	
	Major structure repair	
	Cleaning structure	
Preservation	Repainting structural steel	$70
	Sweeping	
	Deck repairs	
	Deck waterproofing	
	Deck epoxy overlay	
	Polymer modified concrete deck overlay	
	Cleaning and resealing expansion joints	
Rehabilitation	Replacement of expansion joints	$140
	Concrete spall repairs	
	Structural steel repairs	
	Scour prevention	
	Bearing replacement	
Reconstruction	Replace entire bridge	$165

FHWA

Table 26 includes examples of expected treatment costs in terms of retaining walls, which show significant variation and demonstrate the need to implement maintenance activities to prevent costly deterioration and reconstruction.

Table 26. Expected Cost According to Treatment Cost (FHWA, 2009)

Treatment Type	Treatment Cost
Maintenance	The average cost is about $4,000 per wall.
Rehabilitation	Average costs range from $25,000 to $35,000.
Reconstruction	Total costs for wall replacement average about $150,000.

Examples of a variety of treatment alternatives for geotechnical assets, including slopes, walls, embankments, and subgrades, are summarized in Table 27. For effective implementation of geotechnical asset management, life cycle analysis can be used to compare complex treatment alternatives to identify the optimal solution given the existing constraints, which can then be evaluated based on risk and economic aspects.

Table 27. Treatments for Risk Mitigation of Geotechnical Assets (NCHRP, 2019)

Geotechnical Asset	Treatment Category	Asset Specific Alternatives	Investment and Risk Considerations
Slopes	Maintenance	Periodic scaling and debris removal	Each alternative will present a different threat to traveler safety and the level of effort for maintenance staff
		Frequent ditch cleaning	
	Rehabilitation	Draped mesh	While lower initial cost, barrier or draped mesh alternatives may have a high threat to safety when compared to anchored mesh
		Anchored mesh	
		Barriers	
	Reconstruction	Flatten slope inclination	One alternative may impact environmental resources or require property acquisition,

Geotechnical Asset	Treatment Category	Asset Specific Alternatives	Investment and Risk Considerations
		Retaining wall	while the other adds a more complex asset to the network
Walls	Maintenance	Cleaning inspection of drainage elements	Cleaning and rinsing action require annual investment and resources but can slow deterioration rates. I&M has a lower cost and provides early warning of problems but will not slow deterioration.
		Rinsing of elements	
		Instrumentation and monitoring (I&M)	
	Rehabilitation	Add structural reinforcement	Each alternative should consider the service life of the rehabilitation method relative to the required remaining service life of the wall asset
		Repair/replace deteriorated facing systems	
	Reconstruction	Rebuild the wall to the current design standard	Select wall type based on required service life and lowest life-cycle cost
Embankments	Rehabilitation	Install reinforcements	Each alternative will have a different design reliability that results in different impacts on future maintenance needs
		Partial re-construction	
		Install groundwater drainage	
		Add buttress fill	

CHAPTER 3. DEVELOPMENT OF A GEOTECHNICAL ASSET MANAGEMENT FRAMEWORK FOR THE STATE OF GEORGIA

This chapter details the development of the framework for a GAM system in the State of Georgia. As previously discussed, the management of geotechnical assets in the state of Georgia is in its early stages; hence, consistent with the NCHRP (2019), a lean start that prioritizes simplicity is developed. Moreover, the major emphasis is put on retaining walls, which, based on discussions with the GDOT, are the geotechnical assets with the highest priority.

DEFINITION OF GEOTECHNICAL ASSETS IN THE STATE OF GEORGIA

In general, there is no standardized definition of what constitutes a geotechnical asset, and different agencies define geotechnical assets differently. According to the NCHRP (2019) report, geotechnical assets include embankments, slopes, retaining walls, and constructed subgrades within the right of way (ROW) that contribute to the continuous operation of the transportation network (Anderson et al., 2016). International programs such as Highways England and Network Rail in the UK define geotechnical assets as cut slopes (cuttings) and embankments within the agency boundary (Network Rail, 2021). In the U.S., the Alaska Department of Transportation and Public Facilities (Alaska DOT&PF) defines geotechnical assets as rock and soil slopes, embankments, retaining walls, and material sites (Thompson, 2017). In the Colorado DOT GAM program, only retaining walls are considered a geotechnical asset, while slopes, embankments, and subgrades fall within the geohazards category (Anderson et al., 2017).

Georgia Tech conducted several meetings with the GDOT OMAT office, defining the geotechnical assets of interest for the state of Georgia as retaining walls, slopes, embankments, and bridge foundations. In addition, a secondary list of other assets was also defined, which included culverts and high mast lighting foundations. The considered assets are shown in Figure 37, in a modified version of the GAM taxonomy defined in the NCHRP (2019) report.

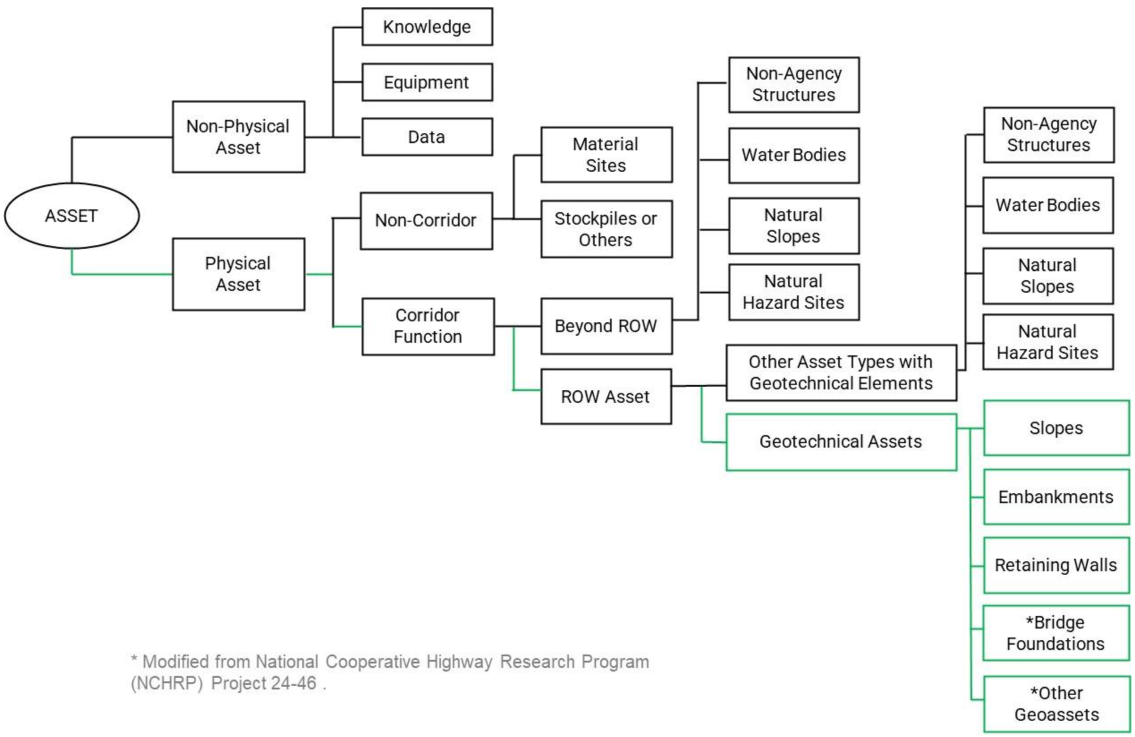


Figure 37. Illustration. Adopted definition of geotechnical assets for the state of Georgia in the context of the NCHRP 903 (NCHRP, 2019) GAM taxonomy.

The geotechnical assets defined in the asset management program include the following (Torres et al., 2022):

Retaining walls: Under a geotechnical management framework, retaining walls are structures higher than 4 feet and with an inclination greater than 70 degrees that restrain or retain all kinds of natural or engineered materials to prevent slope instability of the retained material onto a roadway or other assets. Retaining walls may also be called earth-retaining structures. Some retaining walls can also be found beneath sound barriers; nevertheless, if the primary function is to retain or impede materials from falling into the highway, they should be tracked as retaining walls.

In some instances, it is challenging to differentiate earth retaining systems from bridge walls due to their physical similarities; consequently, the NCHRP (2019) report recommends collecting them under different management programs when the distinction can be made. Indeed, the NCHRP (2019) manual states that "if a wall also functions as a bridge abutment that is integral with the bridge structure, the wall should be considered to be part of the department's bridge inspection and asset management program and should not be inventoried and assessed as an independent asset". Similarly, the Ohio DOT (ODOT, 2018) considers that walls within 50 feet of the bridge should be assessed as a structure's support. A clear distinction between a bridge wall and a retaining wall is given by Colorado DOT (Walters et al., 2016), which states that “Bridge walls are associated with Roadway Bridges, Railroad Bridges, Pedestrian Bridges and any other type of bridge where a wall is used to retain fill that supports the bridge. If a wall does not contribute to the structural stability of a bridge, it should be inventoried as a retaining wall, not a bridge wall”. When differentiating retaining walls from bridge walls, Colorado DOT recommends three possible scenarios as follows:

- Scenario 01 (Figure 38): If the beginning and the end of one or multiple retaining structures are within the effective zone (defined as the area between the frontal abutment wall and a 200-foot mark perpendicularly away from it), all walls should be considered bridge walls (Walters et al., 2016). This procedure avoids fracturing a unique retaining system into multiple smaller wall assets.

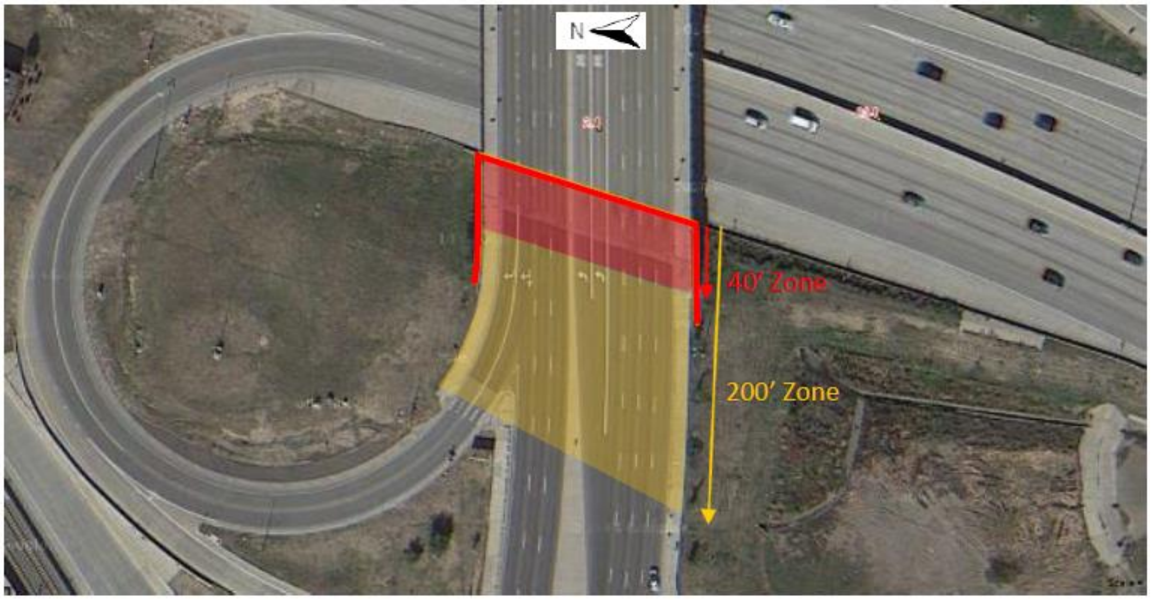


Figure 38. Photo. Bridge wall zone, scenario 01 (Walters et al., 2016).

- Scenario 02 (Figure 39): Any wall asset constructed between two different bridges whose abutments are 200-feet or less apart from each other (effective bridge zone between two bridges) (Walters et al., 2016). Similar to scenario 01, these definitions seek to simplify the inventorying process, avoiding the creation of multiple assets and preventing a double count.

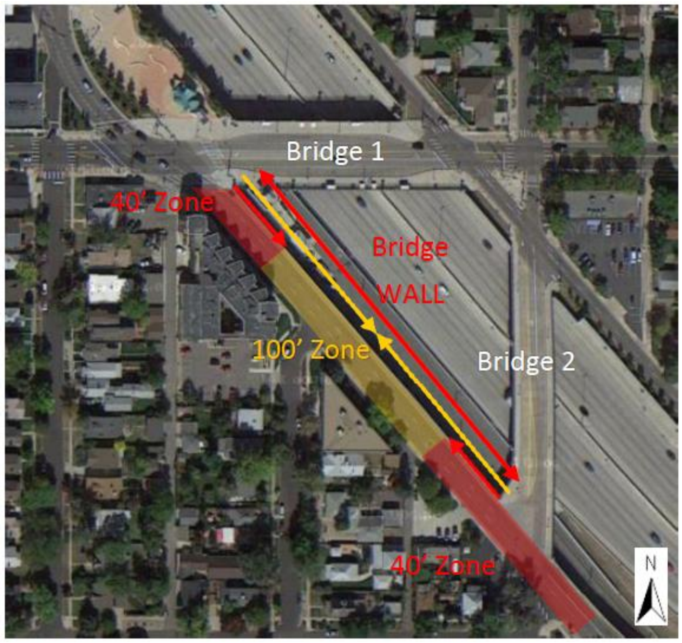


Figure 39. Photo. Bridge wall zone, scenario 02 (Walters et al., 2016).

- Scenario 03 (Figure 40): Delineates a conceptual threshold between a retaining wall and a bridge wall at a 40-foot bridge zone mark when the wall extends 200 feet beyond the frontal face of the abutment. Additionally, Walters et al., (2016) recommend verifying if the inventoried wall is monolithic with the bridge abutment (e.g., wing wall); if it is, it should be excluded from the wall inventory program.

Figure 40. Photo. Bridge wall zone, scenario 03 (Walters et al., 2016).

Slopes: These are the sides of an excavation or natural geologic formation composed of soil, rock, or a mixture of both. There are two different aspects in the definition of slopes: excavated slopes and beyond-the-ROW geologic hazards. Excavated slopes are defined as the sides or boundaries of excavation in which roadways have to be done as a part of the transportation network. On the other hand, beyond-the-ROW natural geologic slopes, even though we are not directly affected by the construction process of an asset (e.g., road, highway), they represent a potential hazard to its safe and reliable operation. The latter also includes natural rockfalls, landslides far from ROW, and natural or man-made debris flows that could affect any asset inside the transportation network. It is recommended to track slopes with heights greater than 10-feet cut and all slopes that could represent a potential hazard to users and assets (NCHRP, 2019).

Embankments: Embankments are designed, and constructed earth fills composed of rock, soil, or any other geomaterial that provides the necessary support for a roadway to operate above natural or engineered surfaces safely. The embankment concept also applies to improved earth fills, assets that support roadways, and the lower slope of a roadway. Additionally, according to the GAM Implementation Manual (NCHRP, 2019), embankments should be tracked when they are 10 feet (3 meters) above the finished grade, while shorter assets can be defined as a minor earthwork. For instance, according to GDOT Design Policy Manual, an embankment is also defined as an earthwork structure that raises the roadway higher than the surrounding terrain.

Bridge Foundation: These assets act to transfer loads between the bridge (superstructure) and the ground (bearing soil) and prevent the bridge from tilting or experiencing excessive settlement. Usually, bridge foundations are made of reinforced concrete and/or steel and may interact with surrounding soil at shallow or deep depths, depending on site conditions and foundation type. The GDOT will inventory piles, tower bents, spread footings, pedestal footings, caisson, micro piles, and drilled shafts.

Culverts: A culvert is a structure made of concrete, reinforced concrete, or metal that is designed to channel water beneath a roadway or past an obstacle. Culverts are commonly installed on shallow foundations and are designed to limit roadway settlement or deflection while providing an unimpeded path for water drainage. The GDOT will inventory large box culverts.

High Mast Lighting Foundations: High mast lighting structures consist of a drilled shaft foundation connected to a tall (~60 – 100 feet) vertical pole with lighting at the top. A drilled shaft foundation with embedded anchor bolts connects the high mast tower to the foundation, and the high mast lighting structure interacts with the soil through the drilled shaft under lateral and cyclic loading. The GDOT will inventory high mast lighting foundations.

GAM FRAMEWORK FOR THE STATE OF GEORGIA

The framework proposed for the state of Georgia follows the NCHRP (2019) guidelines. Figure 41 shows the different stages suggested by the NCHRP (2019) for an ongoing GAM, highlighting the value of starting simply, which has been one of the drivers for this study, and Figure 42 shows the proposed framework schematically. The first step is to identify the geotechnical assets of interest and define them (Chapter 3); in this study, retaining walls were identified as the assets with the highest priority. The next step is the definition of the phases of a GAM (Chapter 3), followed by the definition of an inventory system, which requires the selection of the asset features to be collected during the different phases of GAM (Chapter 3).

Once the inventory system is conceptualized, inspection protocols also need to be defined. The protocols include an initial inspection of existing assets as well as periodic recurrent inspections. Given the value of a lean start recommended by NCHRP (2019), simplicity is prioritized in defining the inspection protocols. The proposed protocols, consistent with NCHRP (2019), include 1) a ranking of the operation and maintenance conditions at a site and 2) a ranking of the mobility and safety risks. By combining these rankings, an initial risk score can be defined. It is important to note that precision is not required at this stage, consistent with a lean start. The next stage considers defining minimum, maintenance, rehabilitation, and reconstruction costs, which can be estimated in the initial stages and refined over time. With the inputs defined, the estimated resources to be allocated and the overall risk score of an asset portfolio can be defined using the NCHRP (2019) guidelines (discussed in Chapter 2). The collected information can then be used to communicate assessment outcomes, inform key stakeholders, confirm targets, and set performance goals. Importantly, the collected feedback from stakeholders and the updated performance goals can be used to continue the inventory and assessment of the assets of interest.

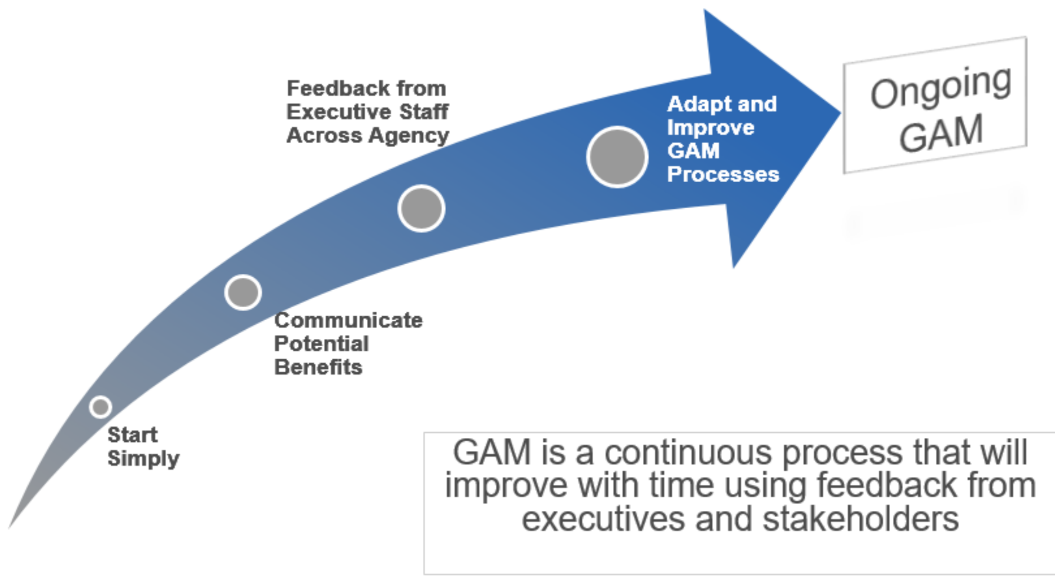


Figure 41. Illustration. Life cycle for starting the GAM program.

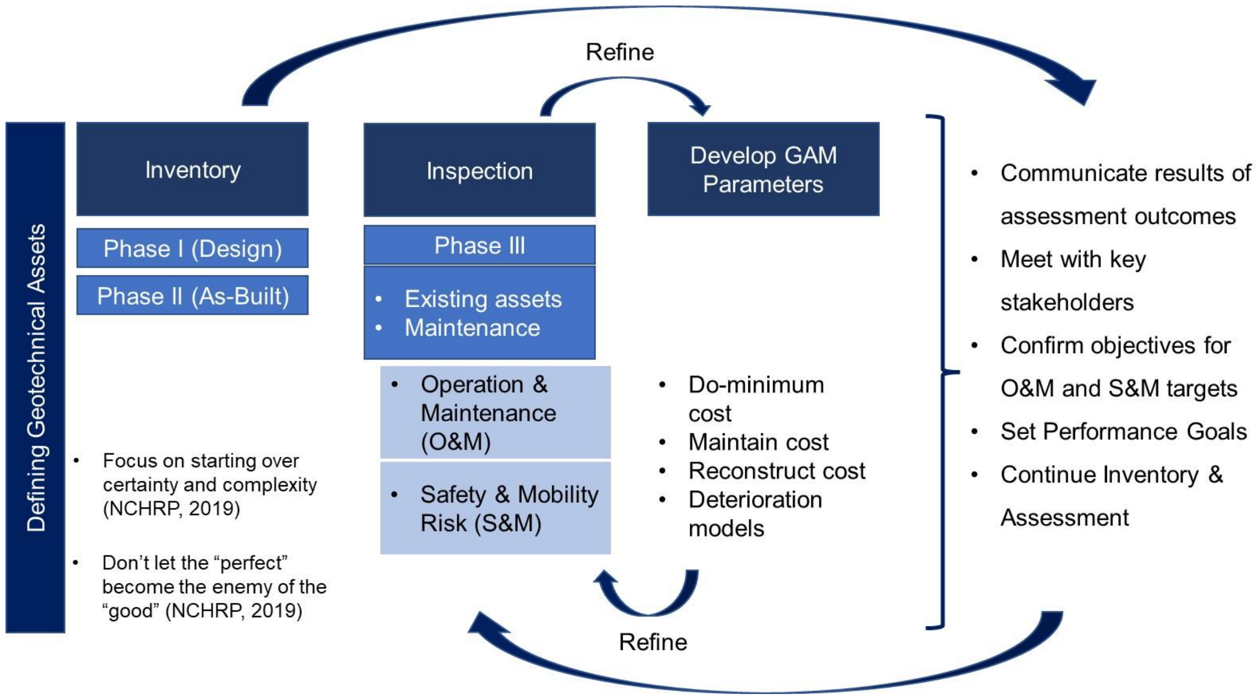


Figure 42. Illustration. Schematic GAM framework for the state of Georgia.

For inventory and assessment during the lifetime of an asset, the following phases have been defined: 1) inventory during design, 2) as-built inventory, and 3) maintenance inspection (Figure 43). Given the current state of GAM practices (no previous efforts in the state of Georgia), this study prioritizes phases (1) and (2).

Inventory during design: This phase includes the inventory of geotechnical assets in upcoming projects at the GDOT using features defined in Chapter 3. This phase will create the asset identity for the geotechnical components, which will be later used in the other two phases to track the state of a given asset. The computational tools can then be used to incorporate the information required by this phase.

As-built inventory: This phase considers the inventory of assets after construction and also the inventory of existing assets; features for the inventory (mandatory and non-mandatory) are defined subsequently in Chapter 3. In the case of existing assets that have not been inventoried in the design phase, the unique identity of an asset is defined at this stage. The computational tools in Chapter 3 can be used in this phase.

Maintenance inspection: This phase considers the periodic inspection of previously inventoried assets. In the case of existing assets, an initial inspection should be conducted, creating the initial asset condition, which will be subsequently tracked and updated. Chapter 3 provides inspection guidelines for the geotechnical assets considered in this study, with the exception of bridge foundations, where the current focus is on inventory.

DEFINING FEATURES FOR INVENTORY

This section documents the defined features for inventory purposes after iterations with the GDOT. The following features were defined for each asset:

- **Attributes (this field considers the asset ID and other identifying information)**
- **Location**
- **Classification**
- **Geometry**
- **Condition and Inspection Routine**
- **Engineering details**

Details on these features are provided in the following for the different assets considered in this study. Table 28-Table 32 provide the features defined as part of the attributes, location, classification, geometry, and condition/inspection categories. Table 33-

Table 38 provides the features defined as part of engineering details in terms of each geotechnical asset.

Table 28. Inventories of Each Geotechnical Asset for Asset Attributes

	Retaining wall	Slope	Embankment	Bridge Foundation	Other Geotechnical Asset
Asset ID	√	√	√	√	√
GIS Object ID	√	√	√	√	√
PI Number	√	√	√	√	√
Description	√	√	√	√	√
Construction Year	√	√	√	√	√
Plans	√	√	√	√	√
Approved Shop Drawings	√	√	√	√	√
Others	√	√	√	√	√
Wall No.	√				
Bridge No.				√	

Table 29. Inventories of Each Geotechnical Asset for Asset Location

	Retaining wall	Slope	Embankment	Bridge Foundation	Other Geotechnical Asset
County	√	√	√	√	√
GDOT District	√	√	√	√	√
District Area	√	√	√	√	√
Route Type	√	√	√	√	√
Route Number	√	√	√	√	√
Nearest Milepost	√	√	√	√	√
Asset Begin Coordinate	√	√	√	√	√
Asset End Coordinate	√	√	√	√	√
Asset Position1	√	√	√		
Asset Position2	√	√			
ROW Status	√	√		√	√
ROW Distance	√	√	√	√	√
Asset Begin Station	√		√	√	
Asset End Station	√		√	√	
Embankment Downslopes			√		

Table 30. Inventories of Each Geotechnical Asset for Asset Classification

	Retaining wall	Slope	Embankment	Bridge Foundation	Other Geotechnical Asset
Function	√				
Type	√	√	√	√	√
Trademark	√				
Purpose of Wall	√				
Natural Soil Foundation	√	√	√		
Site Classification				√	

Table 31. Inventories of Each Geotechnical Asset for Geometry

	Retaining wall	Slope	Embankment	Bridge Foundation	Other Geotechnical Asset
Total Length	√	√			
Total Height	√	√	√		
Min. Exposed Height	√		√		
Max. Exposed Height	√	√	√		
Design Slope Grade		√			
As-Built Slope Grade		√			
Number of Berms			√		
Elevation of Berms			√		
Berm Station			√		
Number of Bents				√	
Number of Barrels					√
Tower Number					√

Table 32. Inventories of Each Geotechnical Asset for Condition/Inspection Routine

	Retaining wall	Slope	Embankment	Bridge Foundation	Other Geotechnical Asset
Asset Condition	√	√	√	√	√
Inspection Frequency	√	√	√	√	√
Last Asset Inspector	√	√	√	√	√
Last Inspection Date	√	√	√	√	√
Last Special Problems	√	√	√	√	√
Inspection History	√	√	√	√	√
Movement Occurred		√	√		

Table 33. Design and Relevant Parameters to be Inventoried (Retaining Wall)

	MSE	Rigid	Soldier Pile	Tie-Back	Soil Nail	GDOT Standard	Others
Min. Bearing Pressure	√	√					
Max. Bearing Pressure	√	√					√
Max. Allow. Bearing Pressure				√	√	√	
Min. Base Width		√					
Max. Base Width		√				√	
Min. Strap Length	√						
Max. Strap Length	√						
Estimated Anchor/Nail Length					√		
Estimated Bond Length			√	√	√		
Require Anchor/Tie-Back Force			√	√	√		
Design Minimum Tip Elevation / Pile Embedment			√				
As-built Minimum Tip Elevation / Pile Embedment			√				

	MSE	Rigid	Soldier Pile	Tie-Back	Soil Nail	GDOT Standard	Others
Min. Bearing Pressure	√	√					
Max. Bearing Pressure	√	√					√
Max. Allow. Bearing Pressure				√	√	√	
Soil Class(es) within retained and foundation soil			√	√	√		
Soil Class(es) below the bottom of the wall (within 10 ft.)	√	√				√	√
Max. Bearing Resistance (Nominal)	√	√					
Max. Bearing Resistance (Factored)	√	√					
Slip Joint Recommended	√	√					
Shotcrete Facing					√		
Ground Improvement	√	√					
Max. Design Settlement	√	√					
Average Settlement	√	√					
Settlement Monitoring	√						

	MSE	Rigid	Soldier Pile	Tie-Back	Soil Nail	GDOT Standard	Others
Min. Bearing Pressure	√	√					
Max. Bearing Pressure	√	√					√
Max. Allow. Bearing Pressure				√	√	√	
Sett. Monitoring Frequency	√						
Settl. Monitoring History	√						
Global Stability Analysis	√	√	√	√	√	√	√
Other Parameters							√

Table 34. Design and Relevant Parameters to be Inventoried (Slope)

	Soil	**Rock**
Design Slope Grade	√	√
As-built Slope Grade	√	√
Slope Stability Analysis	√	√
Rock/Soil Type	√	√
Rock/Soil Description	√	√
Design Reinforcement Type (Geotextile, Geogrid, soil nail, tieback, rock bolds, ground anchors, no reinforcement, other-data entry)	√	√
As-built Reinforcement Type (Geotextile, Geogrid, soil nail, tieback, rock bolds, ground anchors, no reinforcement, other-data entry)	√	√
Design Reinforcement Length	√	√
As-built Reinforcement Length	√	√
Design Slope Drainage	√	
As-built Slope Drainage	√	

Table 35. Design and Relevant Parameters to be Inventoried (Embankment)

	Soil	Rock
Soil Class(es) below the bottom of the embankment (within 10 ft.)	√	√
Slope Stability Analysis	√	√
Rock/Soil Type	√	√
Rock/Soil Description	√	√
Design Reinforcement Type (Geotextile, geogrid, soil nails, tiebacks, ground anchors, no reinforcement, other-data entry)	√	
As-built Reinforcement Type	√	
Design Reinforcement Length	√	
As-built Reinforcement Length	√	
Design Slope Drainage	√	
As-built Slope Drainage	√	

Table 36. Design and Relevant Parameters to be Inventoried (Bridge Foundation)

	Steel H-pile	PSC pile	Metal Shell Pile	Micropile	End Bearing Drilled shaft	Skin Friction Drilled shaft	Concrete Spread Footing
Steel Grade	√						
Concrete Strength		√					
Max. Factored Strength Limit State Load	√	√	√	√	√	√	
Max. Factored Service Limit State Load	√	√	√	√	√	√	
Factored Extreme Event I Limit State Load	√	√	√	√	√	√	
Down Drag Load	√	√	√	√	√	√	
Scour Load	√	√	√				
Resistance Factor	√	√	√	√	√	√	√
Geotechnical/Driving Resistance	√	√	√				

	Steel H-pile	PSC pile	Metal Shell Pile	Micropile	End Bearing Drilled shaft	Skin Friction Drilled shaft	Concrete Spread Footing
Nominal Side Resistance				√		√	
Factored Side Resistance				√		√	
Factored Axial Resistance				√	√		
Nominal Tip Resistance					√		
Factored Tip Resistance					√		
Pile Size	√	√					
Pile Diameter			√				
Wall Thickness			√				
Diameter of Shaft				√	√	√	
Gross Footing Size							√
Effective Footing Size							√
Min. Tip Elevation	√	√	√				
Est. Tip Elevation	√	√	√				
As-Built Tip Elevation	√	√	√				
Pile Embedment below Scour	√	√	√				
Design Pilot Hole Rock Socket	√	√	√				
As-Built Pilot Hole Rock Socket	√	√	√				
Circumstance of Shaft				√		√	
Permanent Casing Elevation				√	√	√	
Design Min. Rock Socket/ Bond Length				√	√		
As-Built Rock Socket/ Bond Length				√	√		
Base Area of Shaft					√		
Total settlement							√

	Steel H-pile	PSC pile	Metal Shell Pile	Micropile	End Bearing Drilled shaft	Skin Friction Drilled shaft	Concrete Spread Footing
As-Built Footing Embedment							√
Bottom of Spread Footing							√

Table 37. Design and Relevant Parameters to be Inventoried (Box Culvert Foundation)

	Box Culvert Foundation
Box Culvert Dimensions	√
Box Culvert Material	√
Box Culvert Type	√
Soil Classes within 10 feet below Bottom of Culvert	√
Design Ground Improvement Type	√
As-Built Ground Improvement Type	√
Design Depth of Ground Improvement	√
As-Built Depth of Ground Improvement	√
Load Transfer Details	√
Changes to Design on Construction	√

Table 38. Design and Relevant Parameters to be Inventoried (High Mast Lighting Foundation)

	High Mast Lighting Foundation
Design Foundation Dimensions	√
As-Built Foundation Dimensions	√
Design Foundation Depth	√
As-Built Foundation Depth	√
Material type the foundation is bearing on	√
Shaft Construction Method	√
Soil Classes foundation is bearing in/on	√
Rock Type	√
Design Rock Socket Depth	√
As-Built Rock Socket Depth	√
Foundation Type	√

The definition of every feature and how they are collected in the field using the computational platform is explained in Appendix B and Appendix C.

INVENTORY AND INSPECTION PROTOCOLS

This section provides general guidelines for the inventory and inspection of geotechnical assets in Georgia. The inventory task is the process of collecting geotechnical assets, including the type, dimensions, particular attributes, and engineering details to create robust records starting from the design, construction, or operation phase within the life cycle of the asset. The inspection task is the process of evaluating the performance of the asset focusing on basic dimensions and visual inspection of flaws, distress, or imperfections of the asset and its surroundings that could potentially undermine the level of service (LOS) and the Department goals. The inventory should be performed first to ensure the creation of the structure ID, which will provide a unique identifier within the GAM program. Thereafter, the inspection will follow with the unique asset ID as input before gathering distress, and providing a condition assessment. Figure 43 shows the GAM system workflow and the list of geotechnical assets considered in the inventory and inspection process.

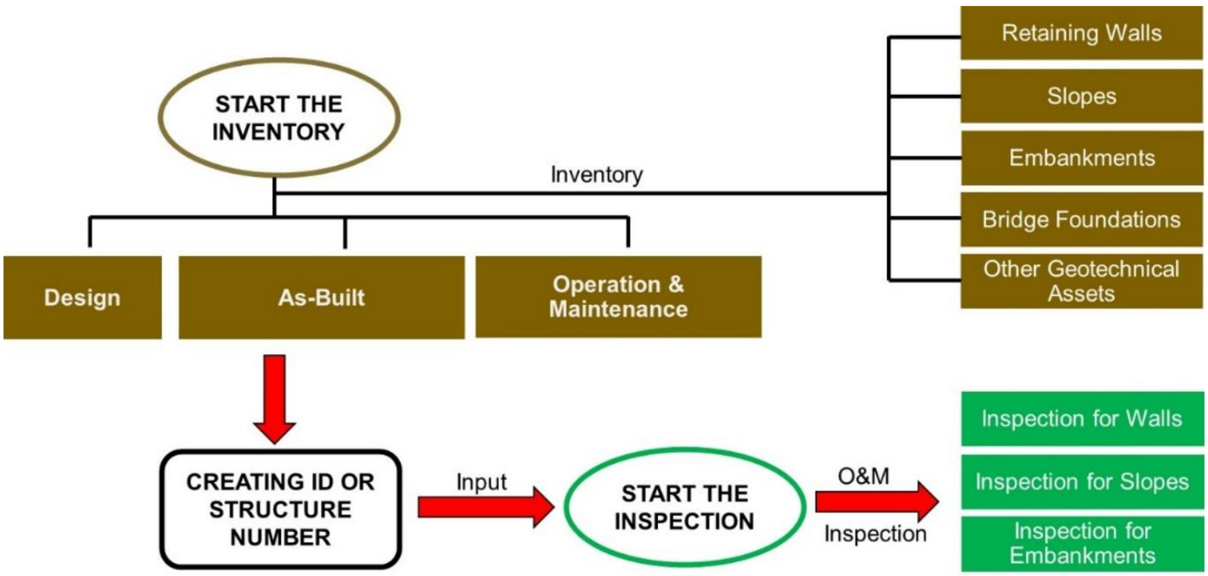


Figure 43. Illustration. GAM System workflow

The steps include: (1) Identify and locate the geotechnical assets; (2) collect features and parameters of interest; (3) estimate asset Operation and Maintenance (O&M) conditions; and (4) assess risk based on potential consequences if the asset fails.

Identify and locate geotechnical assets

Following the definitions and criteria adopted for inventorying geotechnical assets, the literature recommends starting the inventory by giving preference "to assets located in heavily trafficked highways or corridors whose closure would result in significant freight detours" (NCHRP, 2019). Because Georgia consists of 159 counties, organized in 7 GDOT Districts, the inventory process could begin in the major transportation corridors and then propagate to every district simultaneously. Locating the geotechnical assets should be done using mobile devices with built-in GPS systems (e.g., smartphones, tablets) during the inventory and inspection process.

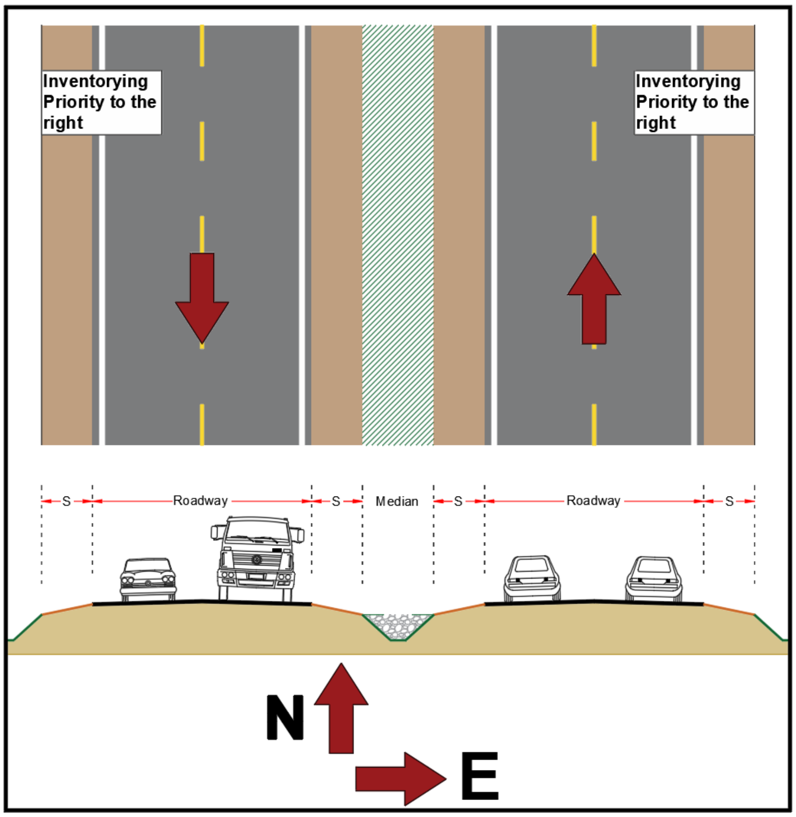


Figure 44. Illustration. Recommended directions to prioritize data collection.

Figure 44 shows the Right-Of-Way (ROW) of a typical highway cross-section comprised of roadways, shoulders, median, and margins. Consistently with the current TAM practices in the state, it is recommended that data collection proceeds as follows (GDOT, 2020b):

- From south to north
- From west to east

- Right-hand traffic should prioritize assets on the right, next to the roadway or shoulders.

The recommendations provided in this section can be applied when: (1) prioritizing data collection; (2) setting the georeferenced location of any geotechnical asset when inventoried as a point feature class; and (3) the start and the end of the inspected structure.

Collect features and parameters of interest.

After the inventory process is finished, the next step is to identify distress on the geotechnical asset of interest and detect potential hazards that could accelerate the deterioration of the components over time, reducing its performance and expected lifetime.

Table 39 (Gabr et al., 2018; Butler et al., 2016) shows the deterioration signs or distress to be noted during a geotechnical asset inspection of a retaining wall as an example. Every detected sign of distress should be recorded, including pictures to support the operation and maintenance (O&M) state assessment of a wall. Furthermore, all pictures taken should facilitate the estimation of the damage/distress extent and expedite its location when further corrective actions can be taken.

Table 39 summarizes the distress and deterioration signs to be noted during inspections.

Table 39. Geotechnical Asset Evaluation Criteria

Distresses and Deterioration Signs	Description
Undesired surcharges	Undesired material adds loads on top of the wall. Surcharges from rockfall, landslides, and others.
Tilting	Visually out of plumb, wall inclination beyond intended
Cracking	Tension cracks in the backfill, slopes, embankments, cracks in the wall structure, or broken elements
Spalling	Concrete deterioration is shown as flaking or peeling
Local bulges	Local distortions or lateral deformations in a slope, embankment, or wall facing
Missing panels	Missing blocks, bricks, lagging, tilts, or other face elements
Staining	Watermarks, graffiti, evidence of rust or corrosion
Erosion	Evidence of eroded materials within or around the geotechnical asset
Settlement	Vertical deformation or deflection of a wall, visible wall elements, embankments, or slopes
Misaligned joints	Joints between face elements or retaining structures are misaligned
Scour	Evidence of scour in the drainage system, in slopes, or in front or back of the wall
Blocked drains	Runoff is impeded to run away properly due to clogging or drainage obstruction
Root penetration	Root penetration between joints or within face elements
Vegetation	Growth of undesired vegetation in the geotechnical asset, including drainage obstruction.

Estimate asset O&M conditions

Table 40 to Table 42 summarize the proposed criteria for assessing the Operation and Maintenance (O&M) **Condition of the geotechnical assets considered in the inspection system.**

Table 40. Wall Condition Assessment Criteria

Condition		Rating Criteria	O & M Criteria
Good	1	**Brand new wall** with no signs of significant distress**.**	**No maintenance needed**
Good	2	**Low severity damage.** Highly functional wall showing minor cracks, mild spalling or misalignments in the joint zones, panels or elements, stains, and graffiti.	**Few hours**
Fair	3	**Greater maintenance is needed** due to the large extent of low-severity distresses and/or low extent of high-severity distresses. Most common scenarios are the **high extent** of **minor cracks** or spalls, **partially disrupted** drainage outlets, extra loading in the backfill, large extent of missing elements, misalignments or root penetration in joints and panels, and evidence of erosion or scour.	**About 1 week**
Poor	4	**Significant deterioration observed.** Medium-to-high severity distresses observed, and some wall elements might be compromised. Some examples are **regular** rockfall, **collapsed** drainage systems, **significant** areas with exposed steel reinforcement, visible **mild** settlements, local bulges, tilting, or deformations.	**Periodic or regular**
Poor	5	**Failed asset, no longer performing as intended**, and **is affecting nearby structures** or regular transit.	**Replacement or rehabilitation**

Table 41. Slope Condition Assessment Criteria

Condition		Rating Criteria	O&M Criteria
Good	1	**Brand new slope** with no signs of significant distress**.**	**No maintenance needed**
Good	2	**Low severity distresses,** such as ditch cleaning and trimming excessive vegetation. **Highly functional slope** that is showing minor signs of erosion, scour, or weathering. If there were minor soil or rock detachments, these **rarely hit the road or other assets.**	**Few hours**
Fair	3	Greater maintenance is needed due to occasional soil or rock particles reaching the road. **Functional slope with minor-to-medium presence of low-extent erosion, scour, or rockfall,** in which **specific maintenance actions** should be taken **to avoid compromising** the asset performance and safety **in the near future**.	**About 1 week**
Poor	4	The slope is **impaired, but functioning** and isolated damaged elements should be replaced or rehabilitated in the near-term to avoid future collapse. Beyond "Fair", the slope might also exhibit a **partially collapsed** drainage system; and, visible local bulges or deformations. **Rockfall occurs constantly**, and maintenance is needed more than once a year.	**Periodic or regular**
Poor	5	**Failed or nearly failed asset,** does not meet service level needs and **is affecting nearby structures** or regular transit.	**Replacement or rehabilitation**

Table 42. Embankment Condition Assessment Criteria

Condition		Rating Criteria	O&M Criteria
Good	1	**Brand new embankment** with no signs of significant distress.	**No maintenance needed**
Good	2	**Low severity distresses and highly functional embankment** that is showing minor signs of erosion, or deterioration. If there were **minor soil or rock detachments** from the downslope**, these do not affect road traffic safety**.	**Few hours**
Fair	3	**Greater maintenance is needed** due to occasional cracks or minor settlements near the downslope. **Functional embankment** with minor-to-medium **presence of low-extent** erosion, and scarps, in which specific maintenance actions should be taken to avoid compromising the asset performance and safety in the near future. Among the recommended actions to take in this category are placing patches, clearing drainages and ditches, removing scour, and installation of warning signs.	**About 1 week**
Poor	4	**Significant deterioration observed**, which demands the regular involvement of GDOT staff. The embankment is impaired but functioning. There are visible local ground movements or deformations. **A stability analysis is warranted**, and isolated damaged sectors should be replaced or rehabilitated in the near term to avoid future collapse.	**Regular, more than once a year**
Poor	5	**Failed or nearly failed asset** that does not meet service level needs and is affecting nearby structures or regular transit. **One or more lanes are closed,** and maintenance is needed regularly.	**Replacement or rehabilitation**

Assess risk based on potential consequences if the asset fails

According to Chapter 2, the NCHRP-903 recommends estimating the level of risk (LOR) per asset, considering the safety and mobility risks associated with possible negative impacts due to the asset failure. Figure 45 illustrates the process behind the risk assessment of geotechnical assets in different conditions and potential consequences. The different parameters involved in the GAM LOR calculation are:

- Maintenance Condition (AC) with values ranging from 1 to 5 (see Chapter 2).
- Safety Consequence (SC) with values ranging from 1 to 5 (see Chapter 2).
- Mobility Consequence (MC) with values ranging from 1 to 5 (see Chapter 2).
- Safety Risk Score, obtained by multiplying AC times SC. Range from 1 to 25.
- Mobility Risk Score, obtained by multiplying AC times MC. Range from 1 to 25.
- GAM Level of Risk (LOS), is obtained by adding Safety and Mobility Risk Scores. Range from 2 to 50
- Figure 45 also shows how to relate GAM Grading (A, B, C, D, F) to the GAM LOR.

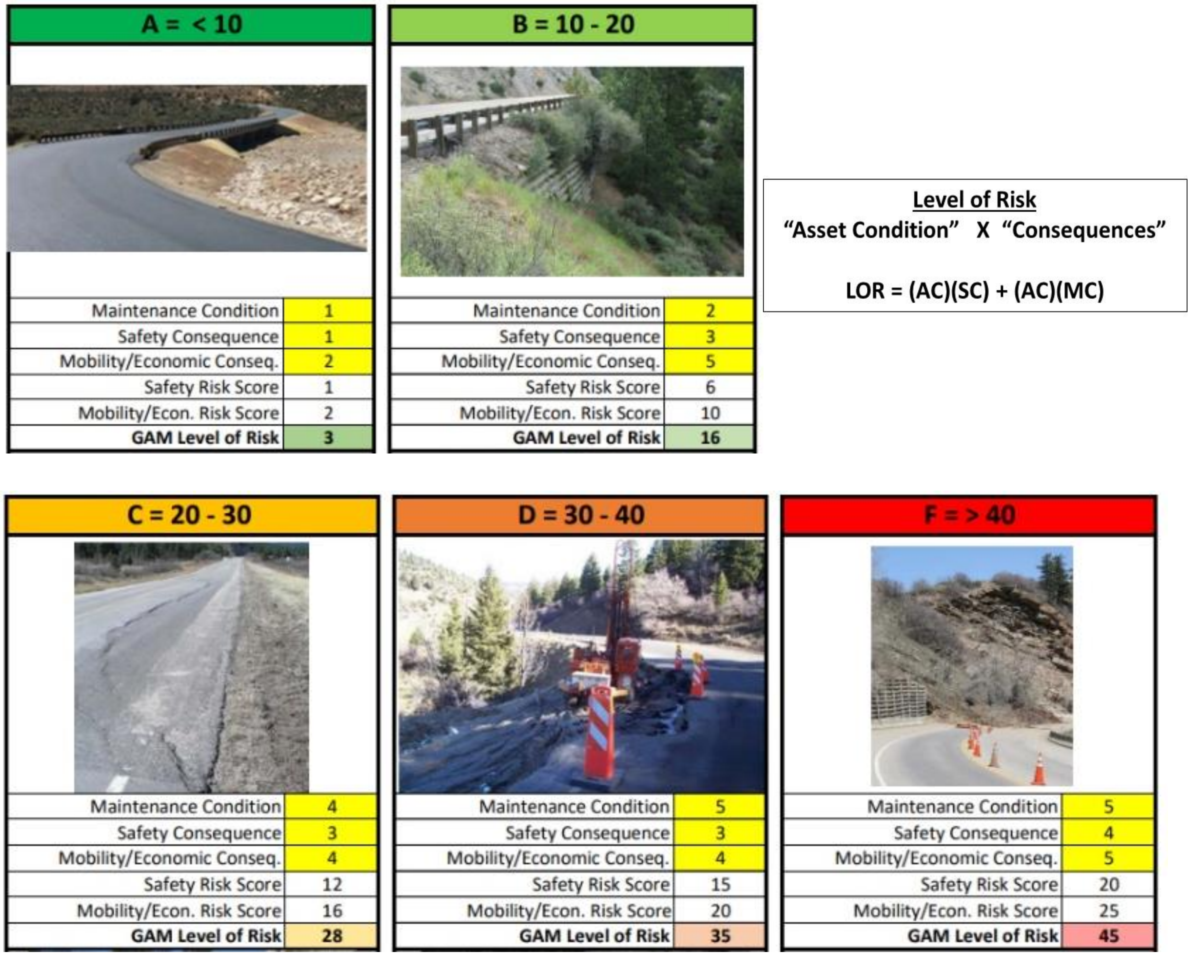


Figure 45. Illustration. Example of risk assessment (NCHRP, 2019).

IMPLEMENTATION OF A GAM SYSTEM

In this study, a computational system named as Georgia geotechnical asset management system (G-GAMS) V1.00.00 is proposed as a significant component within the GAM system. G-GAMS enables users to document, manage, and understand GDOT's multiple types of geotechnical assets, including retaining walls, soil slopes, embankments, and bridge foundations. The purpose of the application is to create a streamlined digital process that will allow the following:

- Document new and existing geotechnical assets
- Capture various data elements for each asset
- Calculate an overall risk score for each asset
- Derive additional products from each survey, including but not limited to scheduling future inspections, generating inspection reports, and automatically alerting shareholders when certain conditions are met.

System overview

The proposed G-GAMS system consists of eight separate Esri ArcGIS Online (AGOL) feature layers. While these feature layers and applications were developed within Georgia Tech's AGOL services, all developed applications and datasets can be migrated into GDOT's ArcGIS Server Enterprise (aka ArcGIS Portal). Each asset (retaining walls, slopes, embankments, and foundations) will have one feature layer dedicated to performing inventory and an additional and separate feature layer for inspection. These modular feature layers can feed customized AGOL apps, dashboards, and web map views. The elements in these feature layers will be populated through various collector applications such as AGOL Survey123 and Field maps, as well as manual data entry and QA/QC within the ArcGIS Desktop/Pro environment. Additional data entry or data delivery methods can be added utilizing webhooks as required in future developments. The following AGOL tools are used in the system:

- Esri Survey 123 is a commercial off-the-shelf (COTS) solution, highly configurable and commonly used where a survey structure is needed. The collection is done via desktop web or mobile devices, even when working offline or out of network coverage.

- Esri Field Maps is a COTS solution capable of helping mobile workers inventory and locate assets, edit records, and explore field information in real-time using data-driven maps.
- Esri ArcGIS Dashboards is an app designed to display predefined information. Datasets created from Field Maps and Survey123 will be displayed in customized ArcGIS dashboards.

Survey123 (survey123.arcgis.com) and Field Maps (arcgis.com/apps/fieldmaps) apps can be used to collect assets, store attachments, and manage questions to ease the inventory process. However, combining them to potentiate inventory and inspect processes will provide functionalities beyond standard data entry offered in individual AGOL environments. Figure 46 shows a schematic view of the interaction between apps to create a risk-based inspected inventory of geotechnical assets. The interaction between apps takes place as follows:

Once the geoasset is located and identified as an asset of interest for the GAM program, Field Maps allows users to collect a predefined list of parameters and features during the design, post-construction, and operation phases. The data collection in every one of the five assets is organized by sections focused on: (1) photos, attachments, and location; (2) data related to the GDOT project where it belongs; (3) the function and type of asset; (4) essential geometry; (5) collector details; and (6) engineering parameters valuable during design and post-construction phases. After the Field Maps form is submitted, and the inventory process is finished, the app creates a Structure Number (Asset ID) for the geotechnical asset to make it unique among current and future structures.

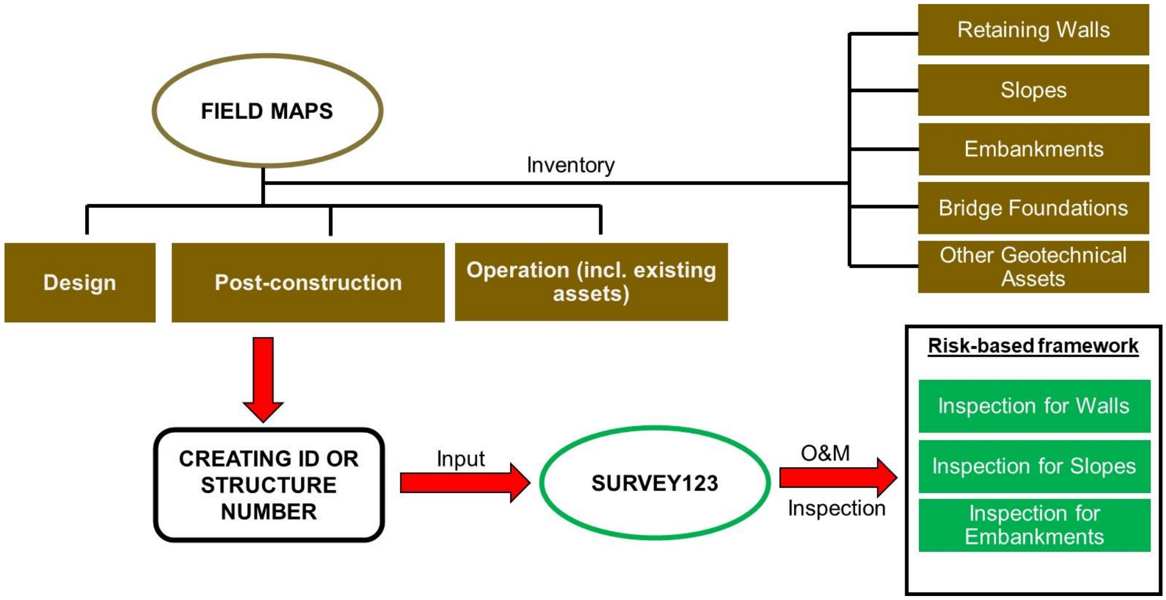


Figure 46. Illustration. Schematic illustration of the interaction between different ESRI applications to populate AGOL database.

The Asset ID will be used as input for performing inspections and as a potential common field for relating inventory and inspection databases if needed. Every inspection will be carried out using Survey123, which has been designed to assist raters in the condition assessment of retaining walls, slopes, and embankments. The inspection form also integrates the risk assessment framework recommended by the NCHRP-903 and discussed in Chapter 3. Figure 47 shows the interaction between Field Maps, Survey123, and secondary ArcGIS products to allow the management of inventory and inspection records, including their visualization through customized ESRI Dashboards and Web Maps. For more details, please refer to Appendix D.

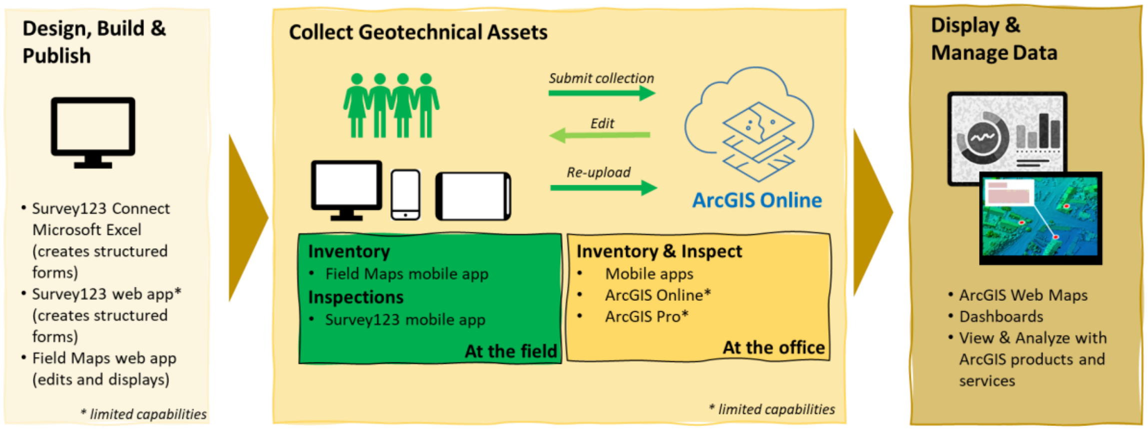


Figure 47. Illustration. Computational System workflow, including tools for displaying information.

Anticipated users

Internal Users:

GDOT can provide access to data viewers, editors, collectors, and managers based on the different user types, roles, and privileges offered in AGOL (ESRI, 2022), which should be decided by the GDOT after migrating the implemented tools. The data collectors are responsible for documenting the data in the field using various field tools and engineering judgment. Data managers would be required to do the quality assessment and control the collected data. Additional features are summarized below. The respective Architectural Design Document (ADD) provides additional details on the computational platform. Appendix B and Appendix C provide guidelines for using the Field Maps and Survey123 for the inventory and inspection processes, respectively.

- Predefined internal GDOT AGOL accounts can monitor the condition of each asset from within customized ArcGIS dashboards and apps.
- The implemented tools will collect information on new assets with properties defined during the design and construction stages.

- The implemented tools will present the current condition of historically collected geotechnical assets and show these assets spatially, with filterable tables.
- Based on the observed asset conditions and unique asset variables, these tools will store the inspection records, the inspection frequency, and further recommended actions.
- Predefined internal GDOT AGOL accounts can collect data for Geotechnical assets.
- The inventory and inspecting process can be done whether connected to the internet or offline.
- Data collectors can generate survey reports from within AGOL, providing valuable documentation on each survey. These reports can be customized per GDOT's requirements.

CHAPTER 4. GAM TECHNOLOGY

INTRODUCTION

Historically, transportation agencies in the U.S. started monitoring and inventorying transportation and geotechnical assets, heavily relying on manual operations and engineering judgment. Slope and Geohazard programs developed in DOTs from Alaska, Colorado, and Ohio (Beckstrand et al., 2017a; Walters et al., 2019; ODOT, 1993) started their programs locating geotechnical assets based on a milepost system, assessing the condition and asset performance based on in-situ observations, manual measurements, and engineering judgment. GAM practices have improved over time by implementing geographic information systems, remote sensing, and image-based technologies. This transition was observed in the Ohio DOT, which started in the early 90s, inventorying and assessing the rockfall hazards without using GPS or image-based technologies (ODOT, 1993). Nowadays, they are planning to collect geotechnical assets and monitor geohazard asset information using LiDAR technologies and automated data processing. In Georgia, an analogy with TAM programs can be made, where the GDOT inventoried and assessed the condition of pavements manually by following a distress protocol named PACES to indicate how to survey and compute ratings (Tsai et al., 2008). Since 1998, a computerized version of PACES (COPACES) was developed, in which GIS-based technologies and a computational system improved distress identification, location accuracy, and data entry management. This natural transition is acknowledged in the NCHRP-903, which states that it is possible to improve inventory procedures and data complexity as the asset management plan matures over time and aligns with state and federal mandates (NCHRP, 2019).

GAM managers should understand the types of data involved in their programs so that they can choose technologies that will make them more efficient and robust. Table 43 shows common data types used in asset management programs, including descriptions and some examples (NCHRP, 2019).

Table 43. Common Data Types Used in Asset Management (NCHRP, 2019)

Data type	Description	Examples
Inventory	Static data related to physical asset location, geometric extents, design and construction details, and material and physical characteristics	Asset location relative to milepost, size of the asset, type of asset, asset value, and traffic volume at asset location
Condition	Data that describe the condition of the asset (or specific elements of the asset) at a given point in time	Good, fair, or poor condition of the entire asset or asset elements
Performance	Data that indicate how an asset is performing in the context of a performance objective, such as technical performance or user perspectives	Asset impacts on other assets, mobility of traffic, financial and economic measures, or staff resources
Work Activity	Data that provide information about repairs, routine maintenance work, and rehabilitation actions	Maintenance work orders, SME support requests
Temporal	Data that capture changes in asset condition with time	Recurring inspection data, deterioration rates for an asset, or asset elements

Depending on the data collection type, Soga et al. (2019) have examined technologies that track and record features associated with movement and displacement in geotechnical assets of interest. Table 44 lists established and emerging technologies focused on assessing the condition and monitoring asset performance.

Table 44. Equipment and Technologies Capable of Monitoring Assets (Soga et al., 2019)

Parameter	Established Tech	Emerging Tech
Movement and displacement	• Total station (robotic) • Acoustic emission sensing • Electro-level sensors • Linear variable differential transformer (LVDT)	• Distributed Fiber Optic Sensing • Differential Global Positioning System • Interferometric synthetic-aperture radar (InSAR) • Light Detection and Ranging (LiDAR) • Computer vision coupled with structure-from-motion (SfM)

REMOTE SENSING IN GAM

Remote sensing is the technique of acquiring pertinent data (e.g., inventory, condition, performance) without direct contact with the object of interest. A remote sensing method is defined according to its sensor, platform, and technology. Sensors are devices used to collect data remotely at specific wavelengths in the electromagnetic spectrum; platforms are the structures responsible for holding one or multiple sensors, and the technology is the engineering behind processing and modeling the data gathered by the sensors. As interest grows in inventorying assets and attributes and assessing the condition of geotechnical assets, the following remote sensing methods are gaining popularity: (1) LiDAR, (2) InSAR, and (3) Structure-from-Motion (SfM) and photogrammetry. The application of remote and image-based technologies in managing geotechnical assets, whether by monitoring, inspecting, evaluating conditions, or assessing performance (Wolf et al., 2015; Rathje and Franke, 2016; Soga et al., 2019; Stark et al., 2021) is addressed in the following section.

REVIEW OF DIFFERENT REMOTE SENSING TECHNOLOGIES

LiDAR technology

Light Detection and Ranging (LiDAR) systems are active remote sensing techniques that use a laser source to illuminate the ground and map it through the collection of reflected and backscattered light. The operation of the system relies on a laser beam that scans back and forth, repeatedly firing pulses of light that hit in-range surfaces. Based on the reflectivity of the scanned asset, these pulses scatter a portion of the light back toward the sensor. The round-trip time for each laser pulse is computed to measure the distance between the source and scanned points. When the position and orientation of the laser pulses are known, a group of 3-axis coordinates can be processed, and subsequently, a digital elevation model (DEM) is generated. LiDAR systems come in all sorts of presentations, sizes, and shapes, including lightweight, smaller ones that can be mounted on a variety of platforms that carry the sensors. The most common platforms are terrestrial vehicles, cranes, telescopic rods, drones, and unmanned aerial vehicles (UAVs). Besides the typical components found in terrestrial systems, mobile or aerial LiDAR systems rely on differential GPS navigation systems and an inertial measuring unit (IMU), which is used to verify the sensor's position and orientation. Whether a survey is conducted by land or air, Figure 48 illustrates the different elements involved in mobile scanning.

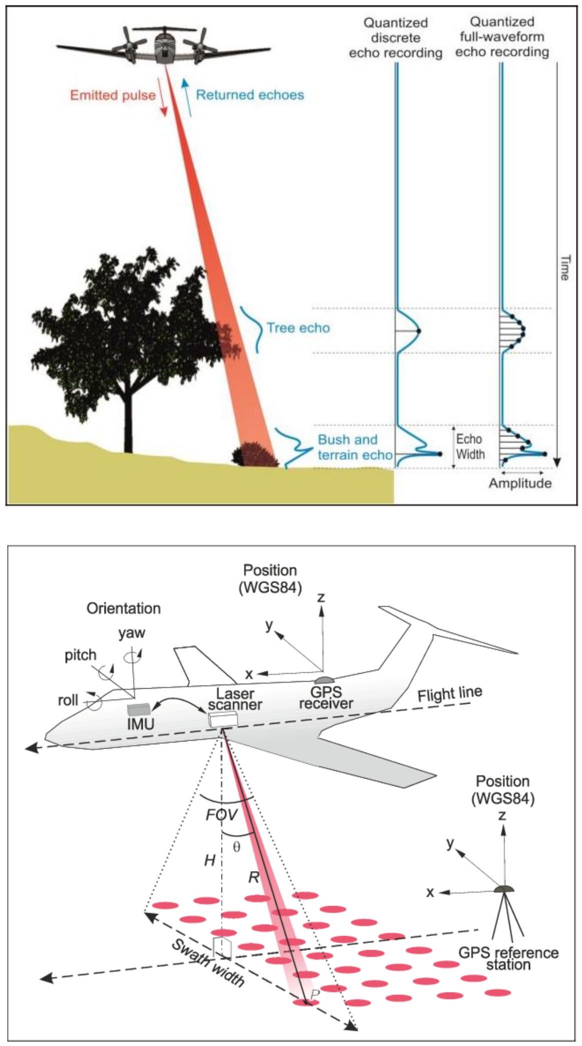


Figure 48. Illustration. Elements involved during Airborne LiDAR Scanning (Gallay, 2013).

LiDAR systems are versatile, so technically, they can collect data regardless of the range and vertical view limitations during the scanning process. Moreover, they can cover a wide range of scenarios, from underground facilities to vast open spaces. Light detection and ranging systems have been introduced for long-term high-resolution measurements as an alternative to conventional systems. LiDAR works by emitting and sensing laser signals at regular space intervals to collect three-dimensional (3D) coordinates of the surrounding environment, which are referred to as point clouds (Ackerman, 1999). One of the most challenging tasks when collecting data from different devices simultaneously (e.g., LiDAR sensors, IMU, and GPS) is the synchronization of their independent timelines. When it comes to airborne LIDAR data, the main sources of error include timing errors with the laser, IMU malfunction, GPS positioning errors, and data stream integration (Rathje et al., 2006). It is recommended that ALS scan areas from different orientations to overcome the presence of shadows during the scanning and acquire a high-quality representation of desired assets or failed zones.

InSAR technology

InSAR is a remote sensing system based on Radio wave Detection And Ranging (RADAR). InSAR stands for Interferometric Synthetic Aperture Radar. Radar-based images are created from the interaction between emitted and received pulses of radar energy from satellites (Figure 49). The received signal is scattered from the Earth's surface and reflected back to the satellite with two types of information: amplitude and phase. As the return signal is affected by the physical properties of the surface, the amplitude will represent the strength of the signal. The distance between a satellite and the ground (back and forth distance) is measured in units of radar wavelength. Changes in the distance between two radar images are reflected in the phase difference. The process of combining two radar images taken in different instances is known as interfering because the waves either reinforce or cancel each other out (Soga et al., 2019). Based on radar technology, synthetic aperture radars (SARs) can produce high-resolution images of the Earth's surface and cover up to 10,000 km^2 when scanned from a satellite. Because SAR uses the microwave band in the broadband radio spectrum, the image resolution tends to maintain quality, regardless of weather conditions or cloudy environments (Soga et al., 2019).

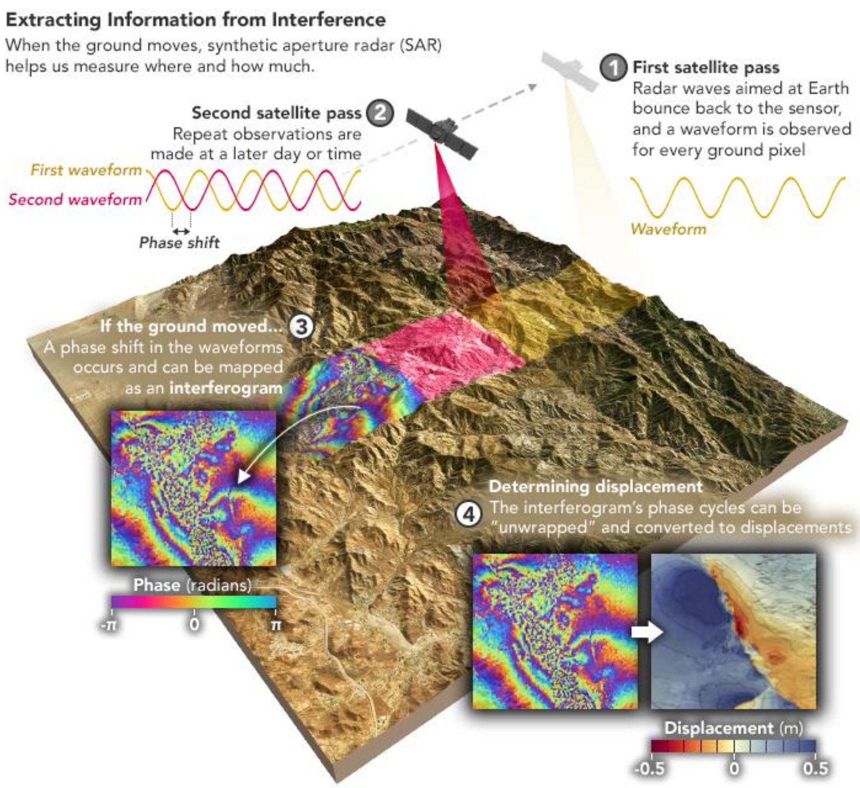


Figure 49. Illustration. Collecting SAR data of the same region at different dates (Source: NASA).

Currently, the most common sensors used on satellite-based InSAR consider three bands with different resolutions, namely X (approximately 3 cm), C (around 5 to 6 cm), and L (about 23 to 25 cm). For instance, the TerraSAR-X satellite from the German Space Agency captures and delivers 1 to 3-meter pixels with a 3 mm measuring precision. In contrast, the Sentinel-1 satellite from the European Space Agency captures 5 to 20-meter pixels with a 5 mm measuring accuracy. According to Stark et al. (2021), X-band SAR is recommended when monitoring critical structures that are sensitive to small movements and require high-resolution images. A C-band SAR survey is more suitable when monitoring large slopes with vegetation due to its better penetration and performance when affected by temporal decorrelation.

Structure-from-motion and photogrammetry

The process of taking, measuring, and interpreting photographs and patterns of recorded radiant electromagnetic energy and other phenomena is known as photogrammetry, a technique for obtaining reliable information about physical objects and their environments (Wolf and Dewitt, 2000). As a field of study, photogrammetry applies methods to measure and analyze objects and features from 2D images. Images may be captured via digital cameras or electronic scanners from fixed positions, vehicles, drones, or spacecraft.

In general, cameras are classified based on their frames per second (fps), bandwidth, pixels, and image stabilization. Nowadays, there are a variety of camera-based techniques available, going from digital image correlation techniques (DIC) to motion magnifying techniques (MM). Vision-based methods for inventorying and inspecting assets include the following steps: calibrating the camera, acquiring the image, rectifying, measuring the displacement field, and detecting the damage. Although the DIC is very popular, low levels of movement resulting from high-frequency excitation remain a challenge. It is evident that low-cost vision and sensing technology is increasingly available. With the aid of video and image analysis, the quality of condition assessment of structures can be greatly enhanced

Photogrammetry has a wide range of applications useful to enhance data collection from geotechnical assets, including estimating coordinates, extracting dimensions, developing orthophotos and topographic models, and producing plain digital elevation models (DEMs). For instance, Figure 3 shows a failed earth structure picture taken by a drone and a 3D high-density point cloud model of the same scenario used to extract dimensions and perform stability analysis (Zekkos et al., 2016)

Figure 50. Photo. 3D model rendered from photogrammetry (Zekkos et al., 2016).

Structure-from-Motion (SfM) photogrammetry is a method for computing 3D models of assets from moving positions that relies on the same principles as stereophotogrammetry (or stereoscopy). In stereophotogrammetry, objects are represented by clouds of three-dimensional points created by combining multiple photographs taken from different positions that overlap significantly. Traditionally, photogrammetric methods use the camera sensor's position and orientation to reconstruct the three-dimensional geometry of the target. On the other hand, SfM can be implemented even if the orientation and positions of the sensor (camera) are unknown. An iterative process and highly redundant algorithms are used to identify common features from overlapping images to solve sensor position and orientation at the same time.

USES IN GAM FOCUSING ON MONITORING AND CONDITION ASSESSMENT

This section discusses the application of remote sensing and image-based technologies in the management of geotechnical assets, from creating accurate digital elevation models (DEM) to monitoring and understanding their performance before and after failure.

Table 45 summarizes relevant literature focused on how technology has been implemented in monitoring, surveying, or assessing the condition and performance of geotechnical assets.

Table 45. Relevant Studies of Remote and Image-based Technologies Applied to GAM

Geotechnical Assets	Type of application	Literature on GAM technologies
Slopes & Embankments	□ Landslides □ Rockfall □ Erosion □ Rock identification □ Monitoring soil & rock earth structures	Stumpf et al., 2013; Greenwood et al., 2016; Gonzalez-Jorge et al., 2016; Zekkos et al., (2016, 2017, 2018); Rathje and Franke, 2016; Hamshaw et al., 2017; Saroglou et al., (2017, 2018); Carlá, 2018; Lato et al., 2019
Retaining Walls	□ Monitoring wall performance □ Wall condition assessment	Romo & Keaton, 2013; Oskouie, 2014; Palmer et al., 2015; McGuire et al., 2017; Aldosari et al., 2020; Hain and Zaghi, 2020.
Foundations	□ Displaced bridge piers □ Surface displacements	Zekkos et al., 2016; Milillo et al., 2018

To better understand the potential implementations and adaptations of remote and image-based technologies in future endeavors within the GDOT GAM program, the following subsections discuss the literature in

Table 45, focusing on LiDAR, In-SAR, and Photogrammetry.

LiDAR applications

In structural and geotechnical engineering, LiDAR has been used as a tool to build three-dimensional structural models (Cabaleiro et al., 2014) for maintenance and operation purposes; to monitor and measure deflections in bridge structural elements (Lee et al., 2019), to assess the condition of retaining walls based on dense 3D point clouds (Oskouie, 2014), and to analyze and monitor slopes through airborne LiDAR scannings (ALS) (Lato et al., 2019).

LiDAR can be incorporated into a GAM system after assessing the advantages and disadvantages of the sensor location, the platform used, and the class of data gathered with it. Lee et al. (2019) reported that permanently deployed terrestrial LiDAR equipment is vulnerable to weather and external agents that could cause small deformations to the equipment components and affect measurement accuracy. When scanning assets from a solely ground-based position, LiDAR systems cannot scan objects outside the field of view (FoV). Therefore, moving the equipment from its fixed position to other key locations is mandatory to obtain thorough surveys. Researchers (Rathje and Franke, 2016) emphasized the importance of acquiring data from multiple positions, especially when monitoring assets and slope failures (Figure 51).

Figure 51. Photo. Terrestrial LiDAR system, including the merge of scans from different positions to accomplish a thorough survey of the failure zone (Rathje et al., 2016).

A GAM program can also benefit from vehicle airborne and high-speed mobile LiDAR systems that are used in slope assets and landslide management. Lato et al. (2019) reported that every aerial LiDAR survey should collect ALS data at different time intervals to facilitate mapping landslide activity, which is well-known as a precursor of landslide failure. Additionally, ALS data can be used to locate and identify terrain stability slope assets, runout distances for debris and landslides, and relative landslide age. Moreover, once landslides have been identified along with their severity based on runout distances and deformation through time, they can be combined with available road data (lanes, AADT, AADTT), population density, and assets within the ROW to develop comprehensive risk maps in the GAM program.

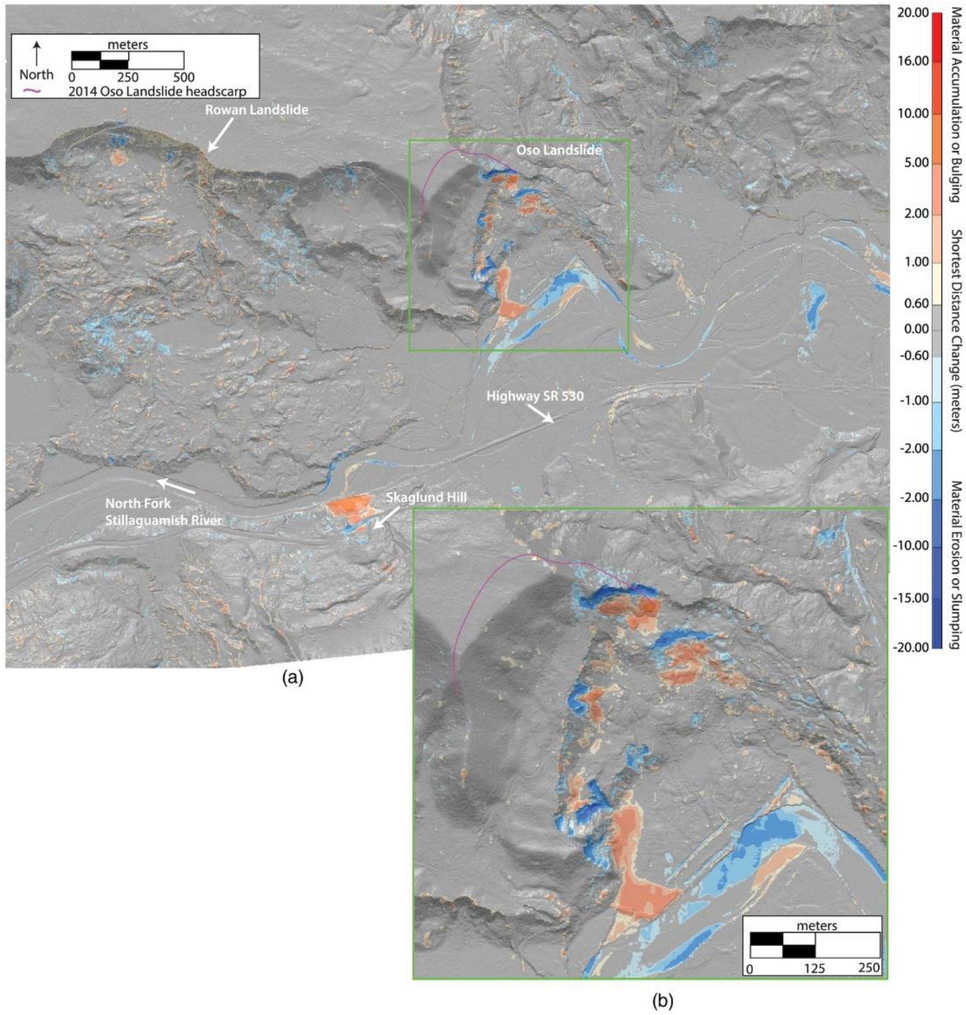


Figure 52. Illustration. ALS change detection analysis between 2006 - 2013 (pre-2014 Oso landslide) (Lato et al., 2019).

LiDAR and remote sensing technologies are also excellent tools for monitoring and reducing risk, providing warnings at underperformance levels, devising remedial actions to fix problems, satisfy regulators, and reducing the litigations associated with claims, liabilities, and failure (Marr, 2007). LiDAR has also been used to document slope failures in embankments in the 2010 Maule earthquake (Rathje and Franke, 2016), the Oso landslide (Lato et al., 2019), and to monitor MSE walls in Indiana (Aldosari et al., 2020). For instance, even though the Oso landslide could not be prevented, Figure 52 (a and b) shows detected deformation and movement before a massive failure. Hence, implementing LiDAR technologies for inventorying and monitoring "moving assets", has the potential to reduce landslide risks and expand understanding of the deterioration of geotechnical assets.

In-SAR applications

The U.S. Geological Survey (USGS) employs InSAR technology to map the Earth's surface using radar signals and images collected from orbiting satellites to determine ground deformation. The USGS has successfully tracked ground deformation, even during storms and at night, which is strongly desirable for monitoring vulnerable geo-assets.

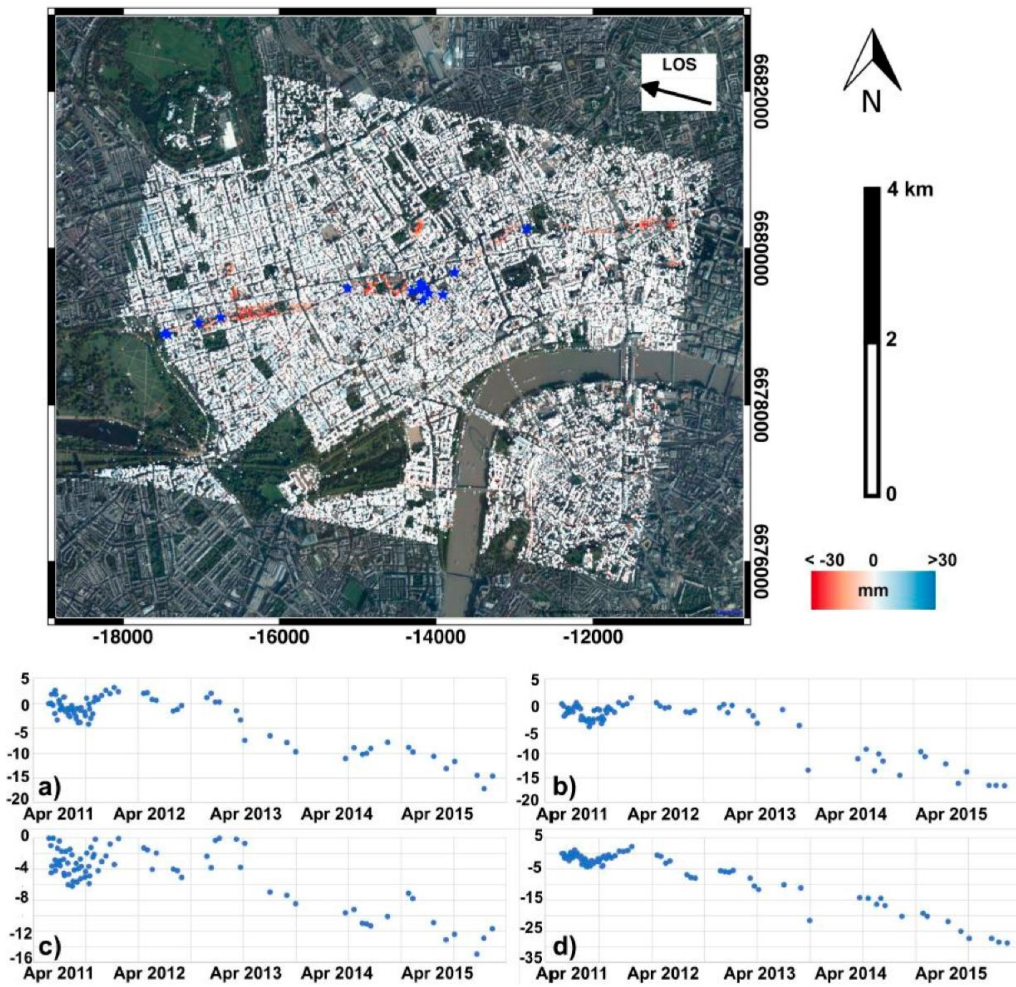


Figure 53. Illustration. Cumulative surface displacements at London Crossrail (Milillo et al., 2018).

One of the latest studies using InSAR was developed by Milillo et al. (2018) for the London Crossrail twin tunnel. A time series of cumulative deformation analyses were performed using InSAR time-series data acquired from April 2011 to December 2015. Figure 53 illustrates the contrast of millimetric settlements in London along a tunnel below downtown, which is of the order of 30 mm. Therefore, InSAR should be considered an effective technology for monitoring and extracting measurements of cumulative surface displacements in slope assets with millimetric accuracy. Carlá (2018) integrated satellite

InSAR and ground-based radar measurements to identify progressive deformation and evaluate the slope instability process before failure, evidencing the value of assessing the condition of geotechnical assets over time. In order to predict failure, Carlá (2018) considered cumulative displacement (Figure 54), velocity, and inverse velocity factors extracted from multitemporal datasets.

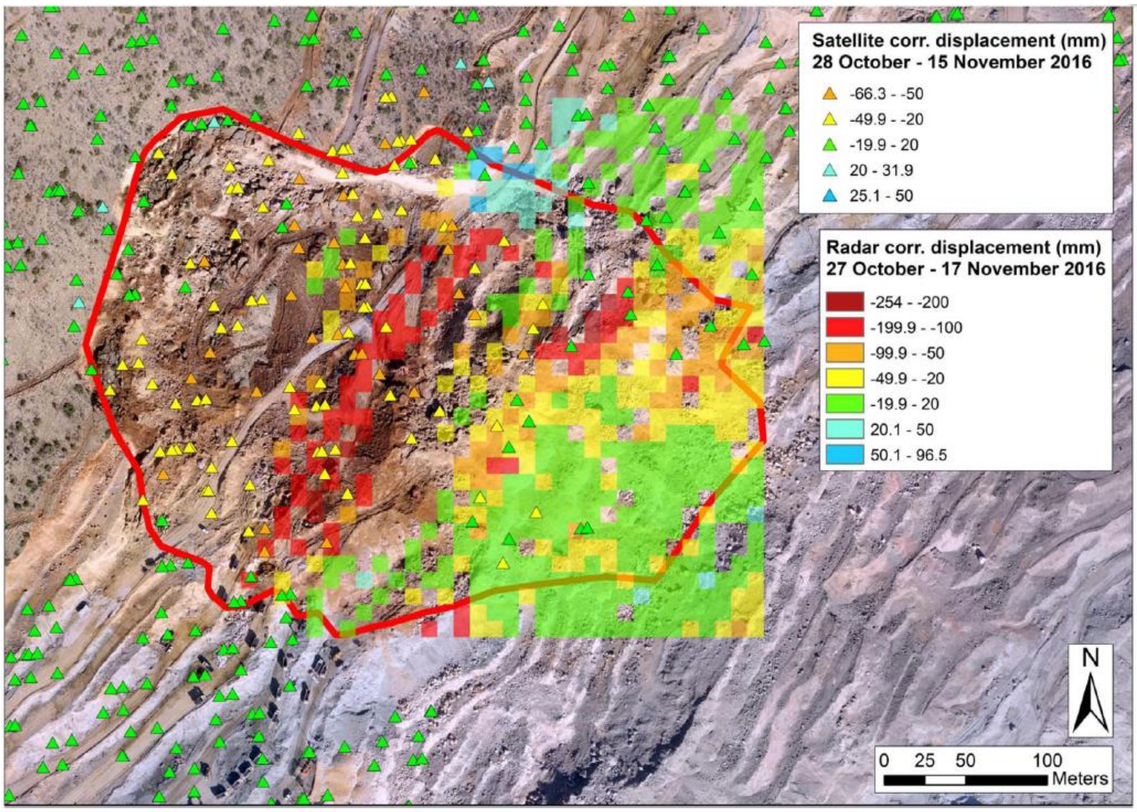


Figure 54. Illustration. Comparing Radar data and satellite InSAR to evaluate displacement (Carlá, 2018).

Photogrammetry and SfM applications

One of the main advantages of photogrammetry is the ease of detecting change, making it convenient for inspecting the condition of retaining structures (e.g., reinforced concrete, MSE walls, and masonry). Moreover, photogrammetry and SfM facilitate the characterization of rock types and potential rock slides (Greenwood et al., 2016); the development of 3D models from UAV explorations to assess the condition of rock embankments and port piers (Zekkos et al., 2016); and the identification of relevant features from failed assets covering large areas (Zekkos et al., 2018). Hain and Zaghi (2020) monitored and inspected an actively deforming masonry wall through 2D image processing. The overall process consisted of field trials, data management, and post-processing. For reference, making a 3D model of 150 square meters of masonry wall required around 850 images taken from different angles. After cleaning and processing the data, models were created by point clouds, easing the process of extracting sections, detecting change over time, and allowing VR visualizations.

Figure 55. Photo. 3D model rendered from photogrammetry (Hain and Zaghi, 2020).

In addition to digital cameras, a variety of recent low-cost and high-resolution video cameras have found useful applications in monitoring and inspecting assets. For example, Feng and Feng (2015) evaluated multipoint displacement for a reinforced concrete structure by utilizing two advanced template matching methods: unsampled cross-correlation and orientation code matching. The results were compared using a single camera, laser displacement sensors, and accelerometers. Vision sensors captured displacements as accurately as traditional technologies. Chen et al. (2015) used high-speed cameras running at a frame rate of 5000 fps to visualize and quantify the mode shapes of structures. It should be noted that the major disadvantages of using high-speed cameras are the susceptibility to weather conditions (e.g., wind, rain, sun, snow, fog), the surrounding vibrations, and the accuracy of camera-based measurements under small-amplitude motions.

Despite the potential value of technologies such as photogrammetry and SfM in inventorying and assessing geotechnical assets that are difficult to access, their advantages and disadvantages should be further analyzed if the GDOT decides to implement such technologies within the GAM framework.

COSTS AND COVERAGE OF REMOTE SENSING TECHNOLOGIES

As explored in previous sections, the considered technologies have unique features that can be applied to different projects depending on specific requirements. Table 46**Error! Reference source not found.** compares generic implementation cost ranges and coverage of three remote sensing technologies (e.g., LiDAR, InSAR, and Photogrammetry), including the components considered in the implementation. Considering the reference values in Table 46, the GDOT could preliminarily compare and evaluate different technologies on a project-to-project basis. It is worthwhile to note that the costs and coverage outlined in this table are based on typical industry averages and can vary depending on the specific project, location, and other factors (e.g., spatial resolution, flight altitude, and the density of data points).

Table 46. Referential Costs and Coverage of Remote Sensing Technologies

Technologies	Application	Components	Coverage (Ha)	Estimated Costs (USD)
LiDAR Systems	Specific Assets Local Level	Classic multi-rotor drone Sensors (laser, cameras) Software	up to 1,000	35,000 - 100,000
	Regional Level	Fixed wing drone Sensors (laser, cameras) Software	up to 100,000	250,000 - 1,000,000
InSAR	Regional Level	Satellite Radar Sensor Software	up to 6.0 E06	free - 5,000 (per scene)
SfM & Photogrammetry	Specific Assets	Cameras Software	Specific Assets	1,000 - 10,000
	Local Level	Classic multi-rotor drone Sensors (cameras) Software	Up to 200	5,000 - 35,000

Note: (1) "Specific assets" refers to one geotechnical asset, specific failure zones, or multiple assets in a limited area; (2) "Local Level" refers to several dozens of transportation corridors; and (3) "Regional Level" refers to a county and state network corridor level.

PILOT STUDY ON THE USE OF IMAGE-BASED TECHNIQUES FOR GAM

Deep learning-based study of pattern recognition in retaining walls (proof of concept).

Geotechnical asset management (GAM) requires efficient and expedient information collection of geotechnical assets. The collection process is often conducted manually through visual inspection with mobile devices and measuring tools to create an inventory that documents the location and condition of geotechnical assets. However, this approach could become labor-intensive and time-consuming at the intermediate or advanced stages of GAM. With the rapid development of machine learning and artificial intelligence and their success in various engineering applications, it is promising to apply these technologies to geotechnical asset management. In this section, the potential of applying deep learning to efficiently identify characteristic features (i.e., patterns) in retaining walls is explored. As a proof of concept, a deep learning model - a convolutional neural network – has been developed that can identify patterns in retaining walls, showcasing the potential power of using deep learning in the asset management of retaining walls. Specifically, in this proof-of-concept effort, the patterns of different panel types collected through retaining wall images from a metro Atlanta area are considered. The end of this section discusses potential future applications based on this proof-of-concept effort.

Convolutional neural networks

Convolutional neural networks (CNNs) (Lecun et al., 2015) are a type of artificial neural network widely used in computer vision problems such as image recognition. The architecture of a CNN consists of an input layer, hidden layers, and an output layer (Albawi et al., 2017). In a CNN, the hidden layers include layers that perform convolutions.

Typically, this includes a layer that performs a dot product of the convolution kernel with the layer's input matrix. As the convolution kernel slides along the input matrix for the layer, the convolution operation generates a feature map, which in turn contributes to the input of the next layer. This is followed by other layers, such as pooling layers, fully connected layers, and normalization layers. Figure 56 shows a schematic illustration of the architecture of a CNN.

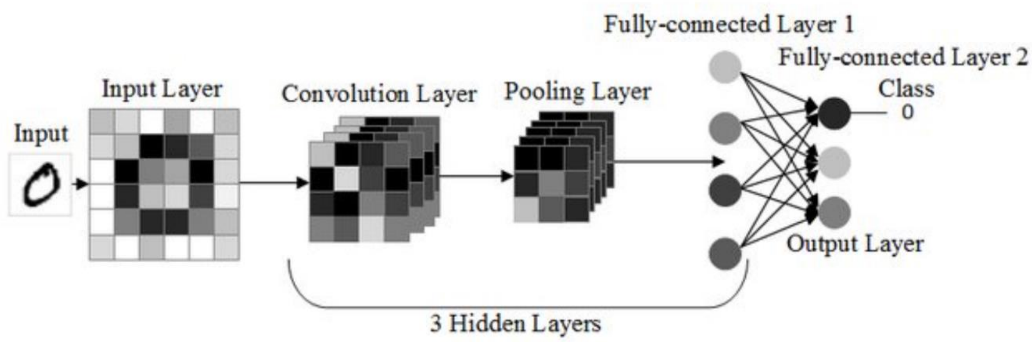


Figure 56. Illustration. A schematic illustration of a CNN used for hand-written digit classification.

The architecture shown in Figure 57 contains an input layer, a convolutional layer, a pooling layer, and multiple fully connected layers. The input layer represents the matrix digitized from an input image. The convolutional layer convolves the input matrix and passes its result to the next layer. The pooling layer reduces the dimensions of data by combining the outputs at the previous layer into a single neuron in the next layer. Finally, the fully connected layers connect every neuron in the previous layer to every neuron in the next layer (Shapiro and Stockman 2001; O'Shea and Nash 2015). The flattened matrix goes through a fully connected layer to classify the images. In this study, a CNN with a similar architecture as the one shown in Figure 56 is developed.

The CNN contains an input layer representing the retaining wall images in the database, three convolutional layers, each followed by a pooling layer, and three fully connected layers to classify the images.

Data collection

The Filio software, a visual asset management platform, is used for automatic image-based classification. The Filio application effectively collects image data at a site and manages the data in the office (Figure 57).

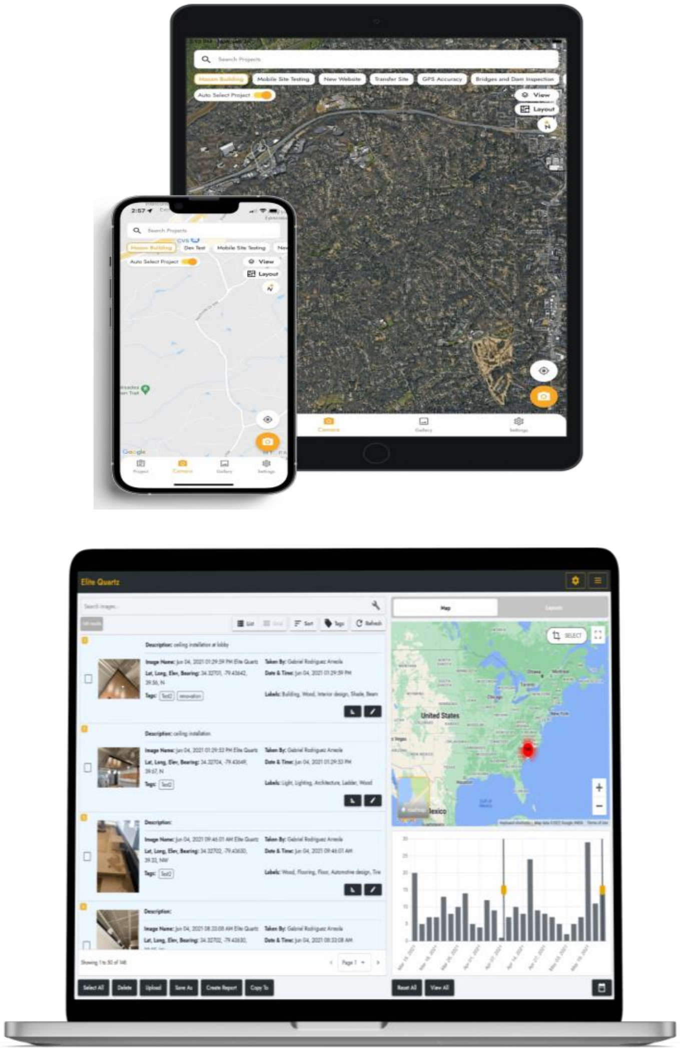


Figure 57. Illustration. Mobile and desktop Filio app (www.filio.io).

In this project, images of retaining wall-facing panels were collected to generate a database of retaining wall patterns for developing automatic image-based classification models. The following summarizes the data collection and management process that were performed using Filio software. Images of retaining walls in the metro Atlanta region (Interstate 75 and Interstate 85) were collected using a camera and a vehicle between March 2022 through May 2022 (Figure 58). Detailed geographical location and direction (e.g., latitude, longitude, elevation, bearing) for each retaining wall image can be determined by reading the metadata through Filio. During the pilot study, a total of 8,678 photos were taken using camera phones and organized manually based on predefined tag labels. The wall frontal panels considered in this proof of concept were the square, rectangle, cruciform, and Georgia cruciform (Figure 59).

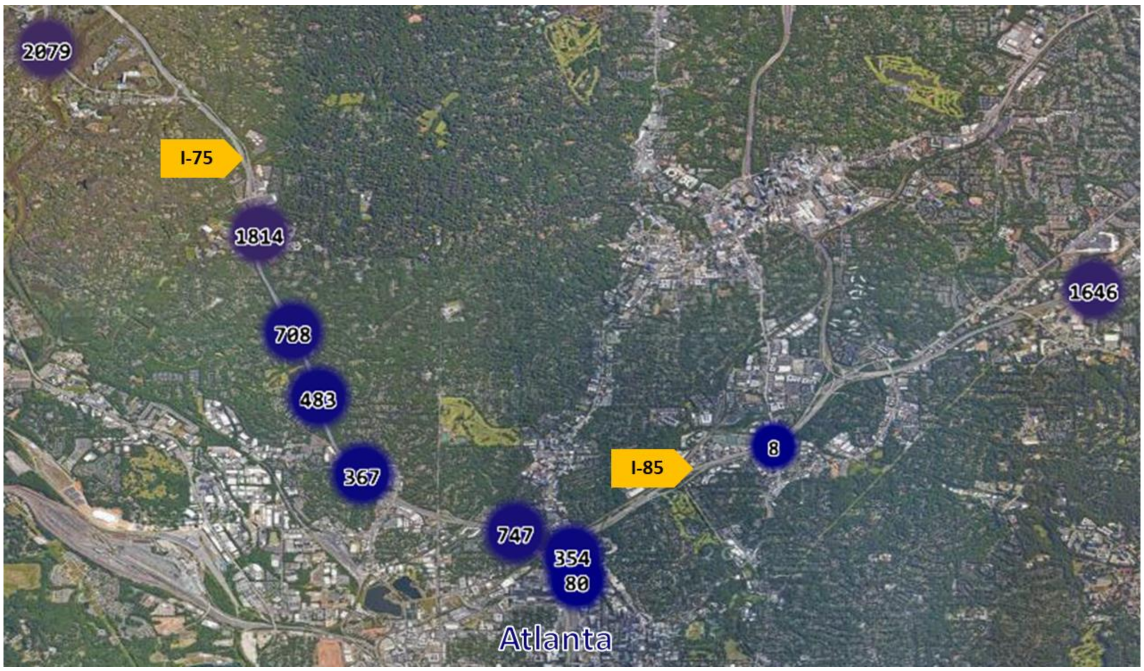


Figure 58. Illustration. Clusters showing the location and number of pictures taken in metro Atlanta region.

Figure 59. Photo. Examples of four types of retaining wall panels (from left: square, rectangle, cruciform, and Georgia-cruciform).

Given the large volume of images collected during the multiple mobile surveys, inadequate/inappropriate pictures were also collected in some instances (Figure 60). Images with potential issues were not considered in the deep learning training. More specifically, the issues in the data collection included blurry photos due to improper focus of the wall, insufficient wall area covered, high contrast lighting near bridges or sources of shadow, windshield reflectance, and capturing “close-ups” of the wall front panels affecting a fair pattern recognition outcome.

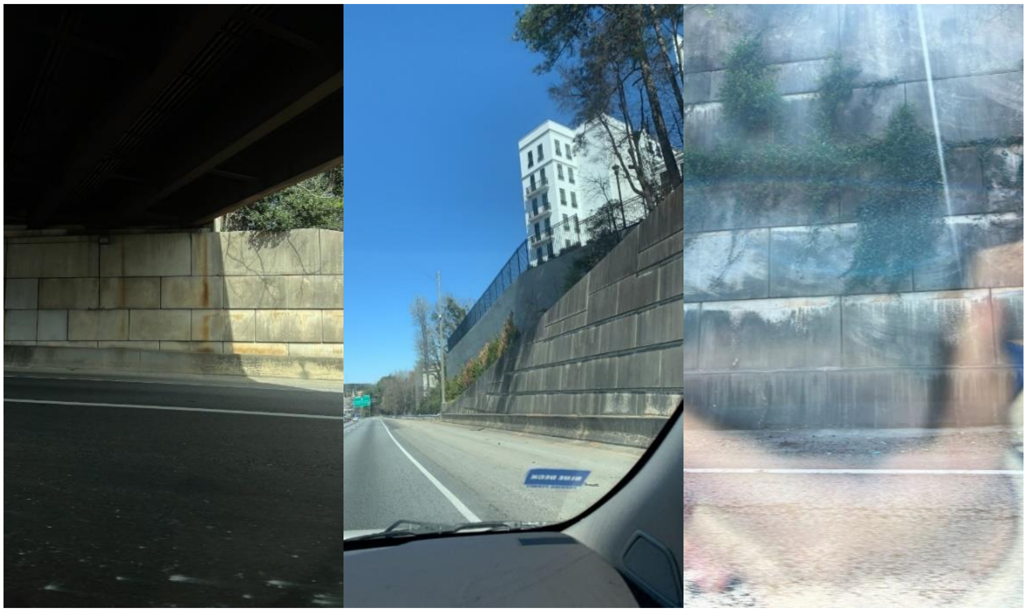


Figure 60. Photo. Examples of inappropriate photo data for the image-based classification model.

After ending the collection of wall images, the Filio desktop web app allows users to filter the database, as shown in Figure 61. The three filters organize the images by general information, tags, or geo-information. After refining the inquiries, users can also edit the image description, image name, and inspector name. Furthermore, if a collector incorrectly tagged a photo or forgot to assign a proper tag to the collected wall and panel shape, tags can be added or edited after collection. The geo-information section allows users to obtain the geographical location and orientation of where and how the images were taken. Lastly, if needed, the size of wall front panels can be measured directly using the Filio mobile app (Figure 62).

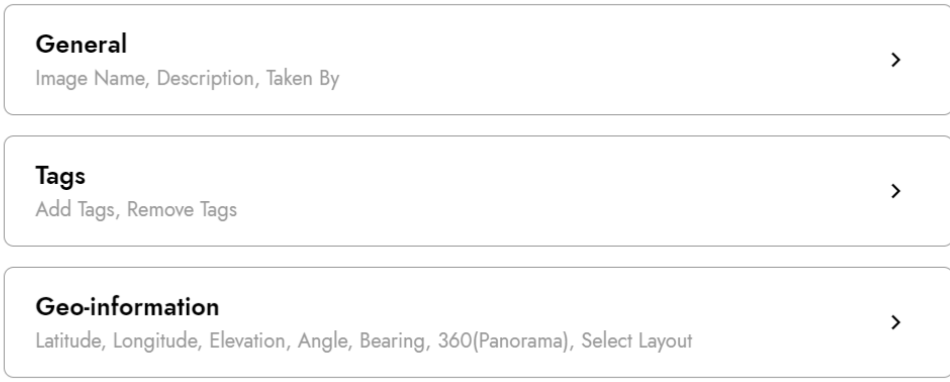


Figure 61. Illustration. Management platform for collected data in Filio.

Figure 62. Photo. Displaying measurements using Filio.

Database training

The model was developed from the database of 8,678 images of different retaining walls. The panel types of these images were manually labeled (a.k.a. tagged) through visual inspection. As mentioned before, four types of panel shapes were considered:

square, rectangle, cruciform, and Georgia-cruciform, and each retaining wall type contained a similar number of images in the database. The retaining wall database was split into a training set (70%) and a test set (30%). The training set was used to train the CNN model and tune the hyperparameters of the model, and the test set was used to evaluate the performance of the model.

Results and discussion

The retaining wall database was split into a training set (70%) and a test set (30%). The training set was used to train the CNN model and tune the hyperparameters of the model, and the test set was used to evaluate the performance of the model. The performance of the developed CNN model in the training and testing sets is evaluated in this section using two methods: classification accuracy and confusion matrix. The classification accuracy measures the number of correct predictions divided by the total number of predictions, as defined below:

$$accuracy = \frac{\sum_{i=1}^{n} y_i = f_i}{n}$$

Where n is the total number of images, y_i is the panel type of the i_{th} retaining wall image, and f_i is the corresponding predicted panel type for that image. The classification accuracy is an intuitive measure of the performance of a classification model. However, it does not provide useful information on the accuracy of the model on individual panel types; consequently, the confusion matrix was adopted to explore the model performance on different panel types.

The developed CNN model showed a high classification accuracy of 99.1% on the training set, with its confusion matrix shown in Table 47. The confusion matrix measured the percentage of classification and misclassification for each panel type in the database. It can be seen from the confusion matrix that the model perfectly classified retaining walls with square panels (100% of the square panels were correctly classified). For the other panel types, the model also achieved good performance with more than 97% accuracy. Interestingly, there were 2.5% of cruciform panels misclassified as Georgia-cruciform. This is because the cruciform and Georgia-cruciform panels are very similar in their shapes, as shown in Figure 59. This misclassification may have resulted from the shooting angle distortion of the retaining wall images, which made it difficult to distinguish between the two-panel shapes. However, the percentage of misclassified images was significantly small (2.5%).

Table 47. Confusion Matrix of the Developed CNN Model for the Training Set

Prediction percentage		**Precited panel type**			
		Cruciform	**Square**	**Rectangular**	**Georgia-cruciform**
True panel type	Cruciform	97.5%			2.5%
	Square		100%		
	Rectangular	0.2%		98.8%	1.0%
	Georgia-cruciform	0.3%		0.3%	99.4%

The performance of the CNN model on the test set showed an accuracy of 99.3%, which is as high as the accuracy for the training set. Table 48 shows the corresponding confusion matrix for the test set. The model on the test perfectly predicted the retaining walls with square panels and correctly predicted more than 98% of the retaining walls with other types of panels. Similarly, it was observed that a small fraction (1.65%) of cruciform panels were misclassified as Georgia cruciform panels for the same reasons explained previously.

Table 48. Confusion Matrix of the Developed CNN Model for the Test Set

Prediction percentage		**Precited panel type**			
		Cruciform	**Square**	**Rectangular**	**Georgia-cruciform**
True panel type	Cruciform	98.3%			1.65%
	Square		100%		
	Rectangular			99.2%	0.76%
	Georgia-cruciform	0.34%		0.68%	98.98%

In summary, the developed CNN model for retaining wall panel classification showed a high classification accuracy for each type of panel on both the training and test sets. Moreover, deep learning proved to be useful in identifying retaining wall patterns as judged by the high classification rate of panel features. This is promising for potential future implementation on identifying patterns for retaining wall distresses that can be incorporated into inspection protocols in future stages of the GAM program for the state of Georgia. Towards this end, a database of different types of distresses would need to be collected, and technologies similar to the one showcased in this section can be applied.

Image-based Automatic Retaining Wall Detection (proof of concept)

This section presents a proof-of-concept for a network-level retaining wall inventory using low-cost image-based automatic wall detection technologies. The roadway images on I-75 within metro Atlanta were collected using the Georgia Tech Sensing Vehicle (GTSV) and were used to evaluate the feasibility of inventorying network retaining walls. The tasks included data collection and evaluation of an artificial intelligence (AI) based retaining wall detection method with details in (Tsai and Wang, 2013; 2016). The following presents 1) data for testing, 2) a proposed automatic retaining wall detection and tracking method, 3) GIS mapping of the detected retaining walls, 4) test outcomes and analyses of the automatic retaining wall detection and tracking method, 5) an image-based retaining wall height measurement and 6) a summary.

Data for testing

Figure 63 shows the Georgia Tech Sensing Vehicle (GTSV) that was integrated through the research project used in the proof of concept. The GTSV is a mobile system that has been used in collecting 2D and 3D roadway data (e.g., 2D roadway, 2D/3D pavement images, and 3D Lidar data). Built on a Ford E350 cargo van model and equipped with a high-accuracy global navigation satellite system (GNSS), an inertial navigation system (INS), and 3D laser sensors (crack measurement system, LCMS), the GTSV serves as a comprehensive data acquisition platform to collect georeferenced, high-resolution, high-accuracy pavement and roadway data. The GTSV was used to collect high-resolution 2D roadway images for the proof of concept study.

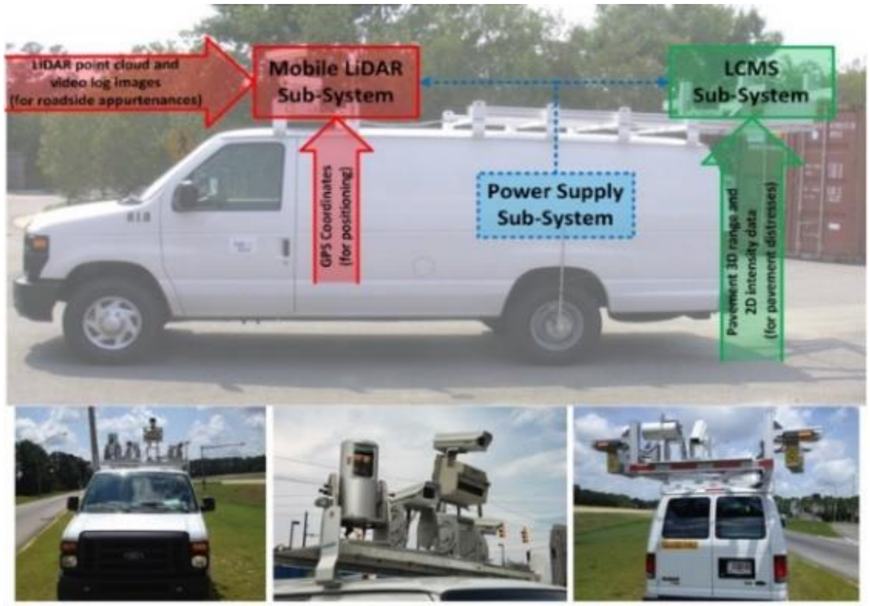


Figure 63. Photo. Georgia Tech Sensing Vehicle (GTSV).

Figure 64 shows the selected test sections on I-75. The roadway images with the corresponding GPS coordinates were collected at a fixed interval (5 meters). The image resolution was 2448 * 2048 pixels. The roadway images were collected on I-75 by Georgia Tech from Midtown Atlanta to the interchange of I-285 and I-75. Data was collected over 18.6 survey lane miles in the north and south directions. Three thousand images in the northbound direction and 2936 images in the southbound direction were taken, for a total of 5,936 images.

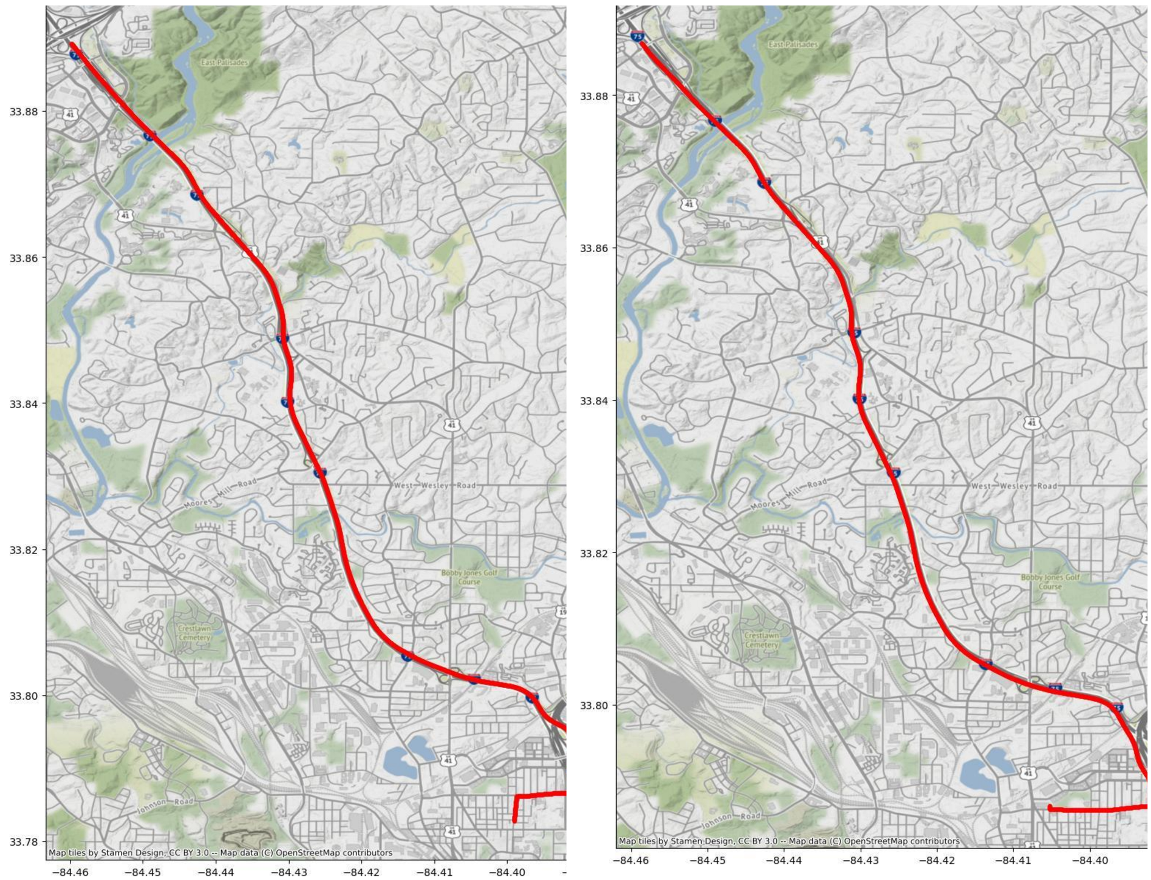


Figure 64. Map. Selected test section on I-75.

As an example, Figure 65 shows three roadway images (left, center, and right views) taken simultaneously using three cameras mounted on the GTSV. The right camera captures images on the right side of the roadway, which can better preserve the details of the objects on the roadside (where the retaining walls are detected and located). Consequently, our model mainly depends on the right-side roadway images to detect retaining walls. Center images are also utilized in this demo because they capture the lanes more clearly and can also maintain the height information of the retaining walls, which makes them more suitable for measurement.

Figure 65. Photo. Three roadway images collected using the GTSV.

Retaining wall detection and tracking method

The proposed method is composed of two major steps: first, use a detection model based on deep learning, similar to the one discussed in the previous proof-of-concept study (Chapter 4), to detect retaining walls in the selected images, and second, with the detection result, use a tracking algorithm to associate/cluster the detected retaining walls across different images and assign a unique ID to them.

(a) Detection step

In the detection step, a deep-learning-based model, similar to the one discussed in the previous section, was used for detection. The collected data was used to train and fine-tune the model so that it could detect the objects of interest (retaining walls in this study). The entire model has over 30 million trainable parameters, making it robust under different circumstances. Specifically, it can detect multiple objects at the same time; it has bounding boxes as the outcome. In practice, it can eliminate the detection with a lower confidence score.

(b) Tracking step

In the tracking step, a tracking algorithm was used for associating the same object detected by the detection model across different images. It considers the retaining wall-to-the-camera position and location and determines if the new detection shares the same object with the previous detection. After using the tracking algorithm, the model was able to count the number of retaining walls and the correspondence between the detected retaining walls and image frames in the video log by assigning unique IDs to the retaining walls. Figure 65 below shows an example of this step.

Figure 66. Photo. Tracking to cluster the same retaining walls at different roadway images.

Mapping of the detected retaining walls

The correspondence between the retaining walls from the proposed detection and tracking algorithms can be determined as discussed before, and image frames can be used to create an arc presenting each retaining wall. Consequently, the coordinates can be mapped on a map and joined into a line/arc parallel to the road. Figure 67 shows an example of a linear retaining wall that has been identified and mapped.

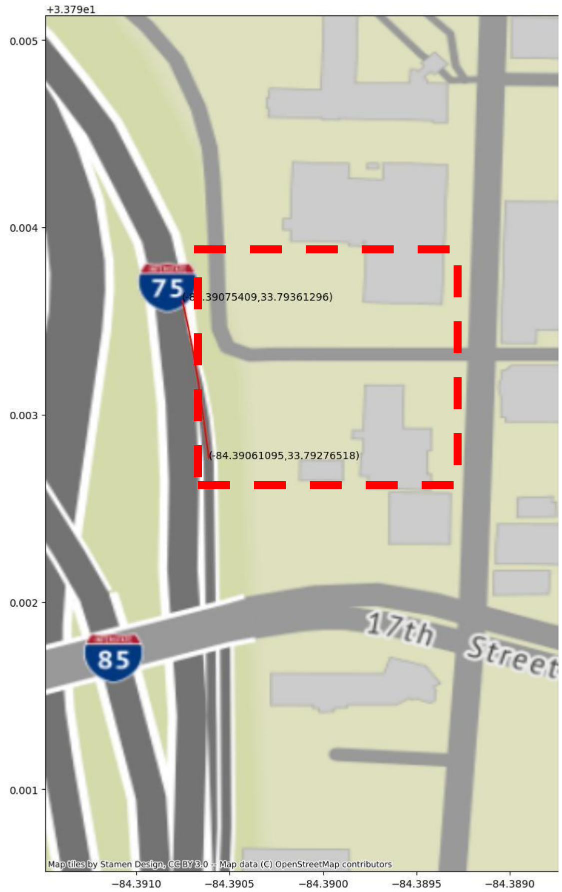


Figure 67. Illustration. Example of a linear retaining wall identified and mapped.

Test outcomes and analyses of the automatic retaining wall detection and tracking method

Based on the application of the automatic retaining wall detection and tracking on the selected test section on I-75, a total of 40 retaining walls were detected, 22 in the northbound and 18 in the southbound lanes. Figure 67 shows a map with the detected retaining wall locations. Red and blue lines represent the retaining walls in the southbound and the northbound lanes (shown in Figure 67 and listed in Table 1).

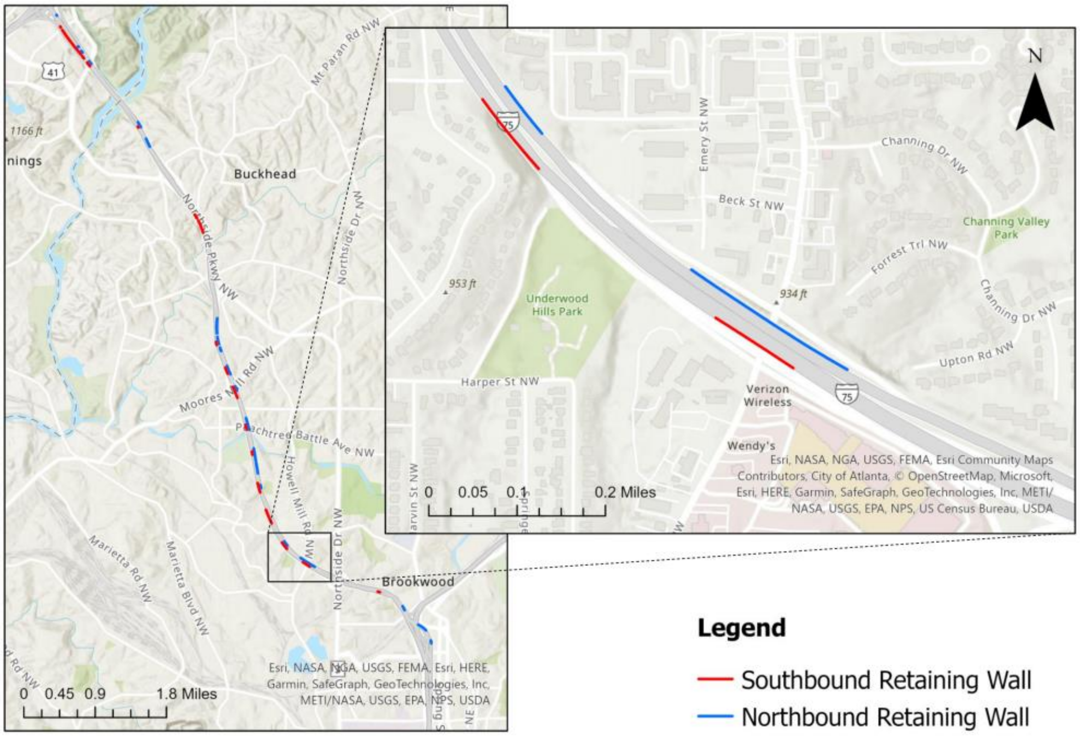


Figure 68. Map. Map of retaining walls in the test section on I-75.

Table 49 lists detailed information of the 40 retaining walls, including the beginning and end points and the estimated length of each retaining wall.

Table 49. Automatically Detected Retaining Walls

No	Direction (N/S)	RW_ID	Begin_x	Begin_y	End_x	End_y	Est. length (m)	GEE Length (m)
1	N	1	-84.391	33.793	-84.391	33.794	50	58
2	N	2	-84.392	33.795	-84.393	33.796	165	178
3	N	3	-84.396	33.798	-84.396	33.799	75	N/A
4	N	8	-84.412	33.805	-84.415	33.806	280	280
5	N	10	-84.417	33.808	-84.418	33.809	90	77
6	N	13	-84.422	33.817	-84.422	33.817	55	56.6
7	N	15	-84.422	33.819	-84.422	33.819	50	50
8	N	16	-84.422	33.820	-84.423	33.821	120	127
9	N	17	-84.423	33.821	-84.423	33.823	215	239
10	N	18	-84.424	33.826	-84.425	33.827	210	208

No	Direction (N/S)	RW_ID	Begin_x	Begin_y	End_x	End_y	Est. length (m)	GEE Length (m)
11	N	19	-84.426	33.832	-84.427	33.832	80	91.5
12	N	20	-84.427	33.834	-84.428	33.834	55	54
13	N	21	-84.428	33.835	-84.428	33.835	60	69
14	N	22	-84.429	33.837	-84.429	33.838	60	67.5
15	N	23	-84.430	33.839	-84.430	33.840	120	130
16	N	24	-84.430	33.840	-84.430	33.842	255	263
17	N	25	-84.442	33.868	-84.443	33.870	150	158
18	N	26/27	-84.444	33.871	-84.444	33.872	100	108.7
19	N	28	-84.453	33.881	-84.453	33.881	60	73
20	N	29	-84.454	33.883	-84.455	33.883	35	61
21	N	30	-84.455	33.884	-84.455	33.884	15	N/A
22	N	31	-84.459	33.888	-84.459	33.888	15	40
23	S	1	-84.458	33.887	-84.458	33.886	20	110
24	S	2/3/2004	-84.458	33.886	-84.456	33.884	255	374
25	S	5	-84.456	33.884	-84.455	33.882	230	255
26	S	6	-84.454	33.882	-84.454	33.882	50	N/A
27	S	7	-84.454	33.881	-84.453	33.881	80	90
28	S	9	-84.444	33.871	-84.444	33.871	20	120
29	S	10	-84.434	33.858	-84.433	33.858	75	100
30	S	11	-84.433	33.857	-84.432	33.855	215	265
31	S	12	-84.430	33.839	-84.430	33.838	55	65.5
32	S	13	-84.428	33.835	-84.428	33.834	110	128
33	S	14/15	-84.427	33.832	-84.426	33.830	200	214
34	S	16	-84.425	33.826	-84.424	33.826	80	110.5
35	S	17	-84.423	33.822	-84.423	33.822	55	77.5
36	S	18	-84.422	33.818	-84.422	33.816	165	176.5
37	S	19	-84.421	33.813	-84.420	33.811	250	262
38	S	20	-84.418	33.808	-84.417	33.808	135	142
39	S	21/22	-84.414	33.806	-84.413	33.805	140	190
40	S	23	-84.401	33.801	-84.400	33.801	40	357

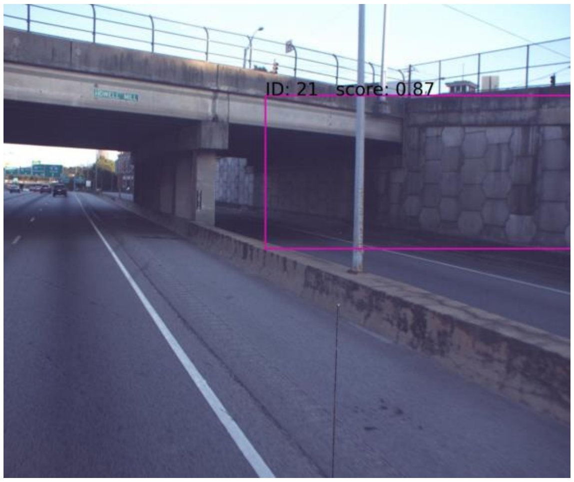
Overall, the outcomes are promising suggesting that a deep-learning based technology can be used for automating the inventory of retaining walls. As expected with any deep learning based technology, there are also false negatives (FN) and false positives (FP). One FN case was observed in this proof-of-concept study (Figure 69). The missing retaining wall is located between RW-02 and RW-03, and might not be a bridge/abutment wall, but is in between two bridge walls. It is likely caused by uncommon retaining wall texture and pattern. Potential future implementations should inspect these aspects in more details.

Figure 69. Photo. FN Case, missing retaining wall between RW-02 and RW-03.

In addition, there are 9 false positives (FPs), including 8 northbound FPs and 1 southbound FP. The main reason for the FPs is that some noise barriers have visual features that are very similar to typical retaining walls. If a misdetection occurs continuously across the images, the tracking algorithm would take this object as a genuine retaining wall. However, it is not difficult to eliminate such cases with minor manual refinements. As an example, Figure 70 shows one FP case.

Figure 70. Photo. Examples of falsely recognized noise barriers as retaining walls (FP case).

The problem of discontinuity mainly comes from obstacles between the camera and the retaining wall, such as a passing vehicle or bridges. The obstacles could separate a complete retaining wall into visually disconnected retaining walls. This problem can be addressed in future implementations. Figure 71 shows an example of discontinuity. In this example, the outcome was refined by combing the 21st and 22nd retaining walls in the final outcome.



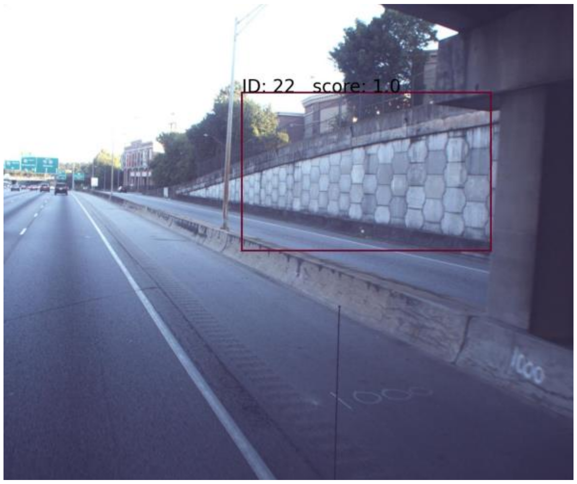


Figure 71. Photo. Examples of double-counted retaining walls due to discontinuity in roadway features (FP case).

The length of each retaining wall was estimated based on the coordinates detected on the collected images. The accuracy of this retaining wall length measurement (the begin and end locations) is also checked using Google Earth Engine (GEE). Figure 72 shows an example of the length measured using Google Earth Engine and its comparison against the beginning and end wall locations detected automatically by the deep learning algorithm. Based on the assessment, it is recommended to use automatic detection and tracking to identify the locations of retaining walls. The detailed measurements (e.g. length) can be measured semi-automatically using Google Earth.

Figure 72. Photo. Discrepancy of retaining wall length measurements.

Image-based retaining wall height measurement

A preliminary test on a height measurement based on a single 2D image was conducted. Using the images taken by the center camera, which directly faced the lanes, for the height measurement. This is a semi-automatic process in which users need to label the lowest point and the highest point of the detected retaining wall; then, the algorithm will calculate the height. Figure 73 shows the height of a retaining wall can be measured semi-automatically using 2D images**.** In Figure 73, the numbers represent the pixel numbers of the line segments.

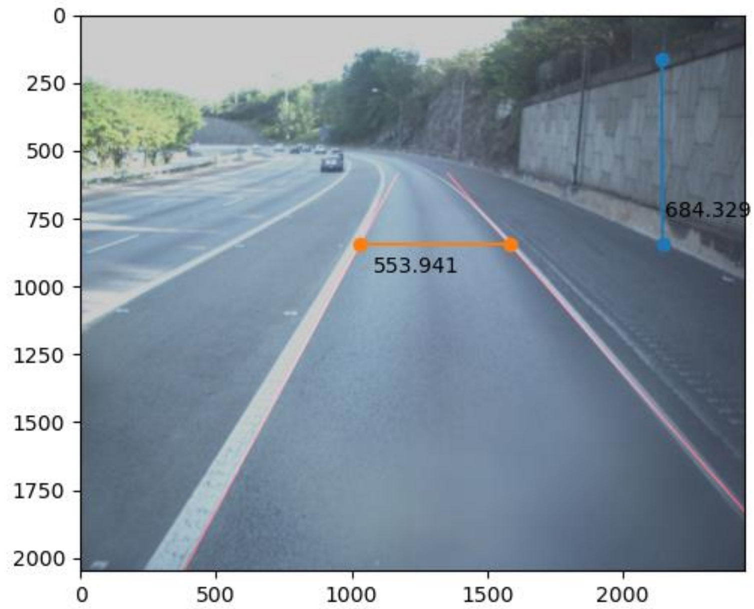


Figure 73. Photo. Measure the height of a retaining wall using 2D images with a semi-automatic method.

Table 50 shows 11 selected retaining walls for evaluating the height measurement accuracy. The height was measured semi-automatically using 2D Image. These heights were then evaluated using the heights measured by 3D Lidar data on the same walls. Table 50 also shows the difference between the heights measured using either Lidar data or using Google Earth Engine with the ones using 2D images. In Table 50, h_image refers to the height measured using 2D images, h_lidar refers to the Lidar based measurement and h_GE referes to the height measured using the Google Earth Engine. was measured using Lidar data and the ones using Google Earth. Based on the preliminary outcome in Table 50, it shows the percentage of errors vary significantly (from 0.5% to 28.1%). There can be some errors with the measurement due to such things as the distortion of the camera lens and different lane widths (Figure 74).

Table 50. Evaluation and Measurement of the Height of Retaining Wall Using 2D Image

No.	RW_ID	X	y	h_image (ft)	h_lidar (ft)	h_GEE, (ft)	□ = Imag - (LiDAR or GEE), (ft)	Error
1	1	-84.391	33.793	12.718		17.7	-5.0	28.10%
2	18	-84.424	33.826	17.884		17.98	-0.1	0.50%
3	19	-84.426	33.832	12.731	15.79	14.05	-1.3	9.40%
4	21	-84.428	33.835	14.778		18.6	-3.8	20.50%
5	24	-84.430	33.840	15.906		18.2	-2.3	12.60%
6	5	-84.456	33.884	16.69		19.55	-2.9	14.60%
7	7	-84.454	33.881	21.239		20.05	1.2	5.90%
8	10	-84.434	33.858	5.421	5.12	2.8	0.3	10.80%
9	18	-84.422	33.818	17.386	18.35	17.16	-1.0	5.60%
10	19	-84.421	33.813	9.506	9.72	8.24	-0.2	2.60%

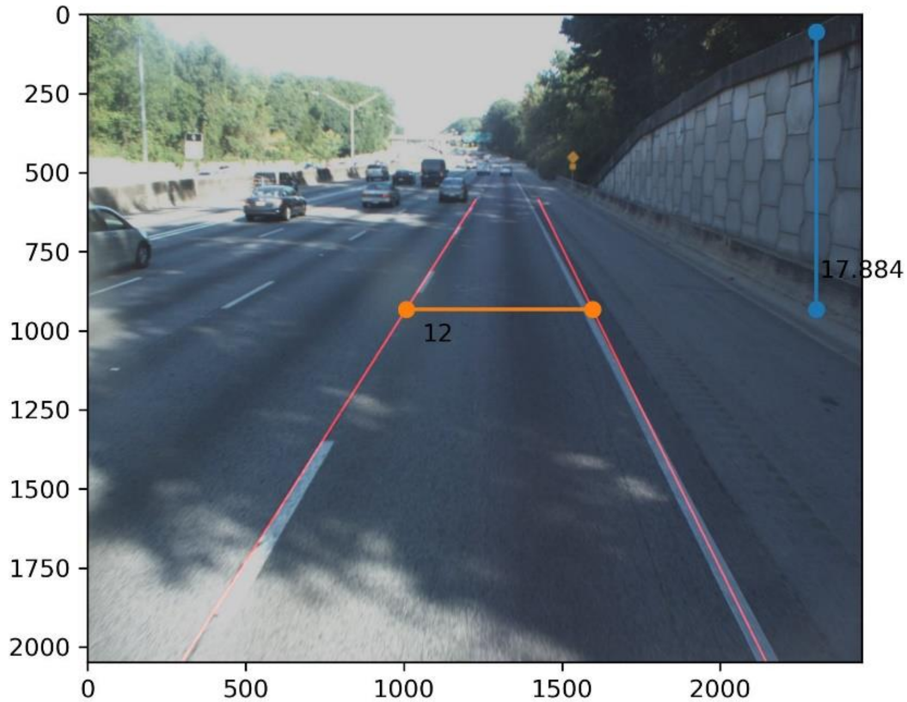


Figure 74. Photo. Measurement error caused by image distortion.

CHAPTER 5. SUMMARY

Geotechnical assets are critical components of safe and effective transportation systems; in this context, several DOTs have conducted efforts to implement GAM programs. The lack of a GAM program in a transportation agency may have potential safety implications and impose additional non-quantified costs in the management of the transportation corridor. Thus, implementing a GAM program can realize significant benefits for a transportation agency. Previous GAM efforts in the U.S. have different maturity levels and have been summarized in Chapter 2. Consistent with the NCHRP (2019), the common practice at different DOTs has been to initiate the development of a GAM program prioritizing simplicity (i.e., a lean start) that can be refined over time. In this way, a transportation agency can start to benefit from a GAM implementation and increase the benefits over time. This lean start approach has been considered in this study for initiating the implementation of a GAM program for the state of Georgia, with an initial focus on retaining walls, which is the geotechnical asset with the highest priority for the GDOT. Experiences at different DOTs have also considered different strategies for implementing GAM programs, from inventorying to risk-based approaches, which are commonly incorporated once a GAM program is mature.

This study has developed a GAM system that can be used for starting a GAM program in the state of Georgia, considering retaining walls (the focus of this study), slopes, embankments, and other geotechnical assets such as culverts and high mast lighting foundations. As part of the system implementation, features of interest for the different considered geotechnical assets have been identified in coordination with the GDOT. The identified features are discussed in Chapter 3. Moreover, the proposed system considers different phases, namely (1) inventory during design, (2) as-built inventory, and (3) maintenance inspection. These phases have been defined in coordination with the GDOT, considering the logistics for inventory and inspection activities that commonly form part of GDOT projects. Details on these phases are provided in Chapter 3. Once the GAM system was defined, a GAM computational platform has also been developed using AGOL applications such as FieldMaps, Survey123, and AGOL dashboards. The FieldMaps application is primarily used for inventory, the Survey123 application is used mainly for inspection activities, and the dashboards are primarily used for visualization and data management. The Georgia Tech team has provided several training sessions at the GDOT office and also in the field on the use of the developed tools. The protocols for using the GAM computational platform are documented in Chapter 3 and also on Appendices B through D.

This study also considered proof-of-concept studies on using image-based techniques based on Lidar technology and deep learning for identifying patterns in retaining walls that can be instrumental in inventory and inspection activities to be implemented in future stages of the GAM program for the state of Georgia. The proof-of-concept studies are described in detail in Chapter 4, after presenting a literature review on different technologies that can be instrumental in geotechnical asset management. The first proof-of-concept study considered collecting retaining wall images of different panel forms for walls in the metro Atlanta area. The images were collected from a vehicle using a phone camera and classified in terms of panel shapes. A deep learning algorithm was trained with a subset of the collected images and used to predict image patterns on a subset that was not used in training, with a significant prediction accuracy (higher than 90%). Thus, the deep learning technology used in the first proof-of-concept study has been shown to be capable of recognizing retaining wall patterns, which, in turn, is promising for the potential future implementation of deep learning-based inspection protocols that would also need to recognize patterns within retaining walls. As discussed in the next section, a database of retaining wall distresses in the state of Georgia would be required towards this end. The second proof-of-concept study focused on identifying retaining walls in a metro Atlanta area for inventory purposes using the Georgia Tech Sensing Vehicle, equipped with a Lidar system, combined with deep learning technology for collecting and inspecting images. The images were collected on 18.6 miles of an interstate highway on I-75 between Midtown and the I-75/I-285 interchange. This second proof of concept study was also promising, suggesting that combining the GTSV and deep learning has the potential to significantly expedite the inventory of retaining walls in the metro Atlanta area and the state of Georgia. Moreover, the study also suggests that it is feasible to leverage the readily available 2D roadway images to detect retaining walls for the initial step of a massive retaining wall inventory.

CHAPTER 6. ROAD MAP FOR A GAM IMPLEMENTATION IN THE STATE OF GEORGIA

In this study, Georgia Tech and the GDOT office of material and testing (OMAT) have established a framework for a GAM program in the state of Georgia, initially focused on retaining walls but also considering other assets (i.e., slopes, embankments, and bridge foundation assets such as culverts and high mast light foundations). Figure 42 presents a schematic representation of the proposed framework and is repeated below for completeness.

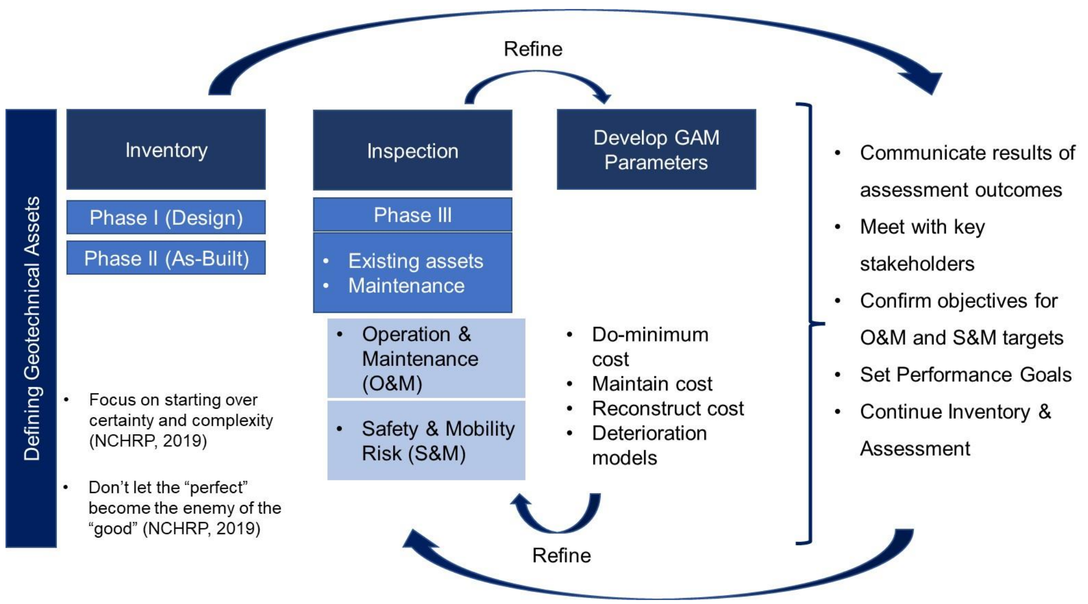


Figure 75. Illustration. Schematic GAM framework for the state of Georgia.

Based on the proposed framework, the following activities are recommended for the short- and long-term development of a GAM program in Georgia.

1. Prioritize the inventory of retaining walls, which are the assets of most interest for the GDOT. The inventory considers the design and as-built phases and can be conducted using the tools and protocols developed in this project, which are

discussed in Chapter 3 and Appendix B. The inventory in the design phase considers the new projects at the GDOT, followed by an as-built inventory after the retaining wall is constructed.

2. Conduct initial inspections of existing retaining walls following Chapter 3 and Appendices B through D recommendations. Of note, the inventory of existing walls (considered an as-built inventory) can be completed simultaneously with the initial inspection with the developed tools in this project. It should also be highlighted that consistent with the lean start approach recommended by NCHRP (2019), simplicity should be prioritized in the initial inspections. The initial inspections are followed by maintenance inspections (for example, in retaining walls, maintenance inspections can be conducted every two years).
3. Further, evaluate the use of image-based technologies considered in this study. Evaluate the commercial marketplace for existing services that can perform data collection, feature extraction, and change detection. For instance, the combination of the Georgia Tech Sensing Vehicle (GTSV), which has a Lidar system incorporated, and deep learning technology has the potential of significantly expedite the location/inventory process of retaining walls compared to manual methods, as suggested by the second proof-of-concept study. In addition, a database of distress patterns for retaining walls in Georgia should be developed. Such a database combined with the deep learning technology used in the first proof-of-concept study has the potential to expedite the inspection processes significantly.

4. Define initial minimum, maintenance, rehabilitation, and reconstruction costs for retaining walls (and other assets) based on GDOT practices. These costs are required to communicate the benefits of a GAM program.
5. In the initial stages of the GAM program, we suggest using deterioration models suggested by NCHRP (2019). However, after inspection data is regularly collected, deterioration models for assets in Georgia should be developed and refined over time.
6. Once an inventory and initial inspections are completed for an area of retaining walls with high priority for the GDOT, use the collected information to communicate assessment outcomes, inform key stakeholders, confirm targets, and set performance goals. The collected feedback from stakeholders and the updated performance goals can be used to continue the inventory and assessment of the assets of interest.
7. Repeat the activities above considering other assets of interest for the GDOT, i.e., slopes, embankments, and bridge foundations, in that priority order. This means that inventory and initial inspection activities for these assets should be started under a lean start approach. In addition, proof-of-concept studies using technologies such as those discussed in Chapter 4 (e.g., image-based, sensing-based) should be conducted to propose protocols that can expedite the inventory and inspection processes. Similar to retaining walls, also consider deterioration models recommended by the NCHRP (2019) until inspection information that allows the formulation of deterioration models is collected. Finally, using the

assessment outcomes, inform key stakeholders, confirm targets, and set performance goals.

8. Repeat steps 1 to 7 and refine them over time until a mature GAM program is established.

APPENDIX A. GEOTECHNICAL ASSET MANAGEMENT SYSTEMS IN THE US

ALASKA

Alaska was the first state to complete a Geotechnical Asset Management plan through the Alaska Department of Transportation (AKDOT) Planification Facilities Division (AKDOT&PF). The AKDOT GAM is an ArcGIS-based map that can be used to explore the location of geotechnical assets, such as unstable rock slopes, unstable soil slopes, retaining wall assets, and material site assets. The soil slopes and embankments are identified by segments and rated as good, fair, or poor, depending on their hazard level and conditions. Vessely (2017) summarized the Department's efforts to evaluate risk to mobility, safety, and potential financial shortcomings in asset management. The most important features of the AKDOT GAM implementation are represented and captured in the GIS-based interface below. Figure 76 displays a plan view of a desired geographical region, including ratings of the existing retaining walls (noted with colored points green, yellow, and red, for good, fair, and poor, respectively). Figure 77 and Figure 78 show a typical set of data associated with retaining walls, which are one of the different types of inventoried geotechnical assets. Additionally, by clicking on any asset, an informative text box will pop-up with the wall's most relevant characteristics (Table 51). A typical asset report including the Retaining Wall Rating Calculator and the asset's high-resolution photos are shown in Figure 78. The Calculator is a risk-based tailored set of formulations that includes more detailed information and specifies all the considered parameters and concepts needed to quantify Wall Hazard Ratings, Wall Risk Ratings, and Wall Appearance Ratings. Moreover, the report also includes photos depicting details and flaws of the asset's physical condition. The asset's cost-benefit analysis, as well as estimations of future investments associated with the asset's life cycle, were performed using "condition-based programmatic cost estimation, deterioration rates, and maintenance costs" (Landslide Technology, 2020). Furthermore, it is estimated that the Alaska GAM implementation has a return on investment of 106% (Landslide Technology, 2020).

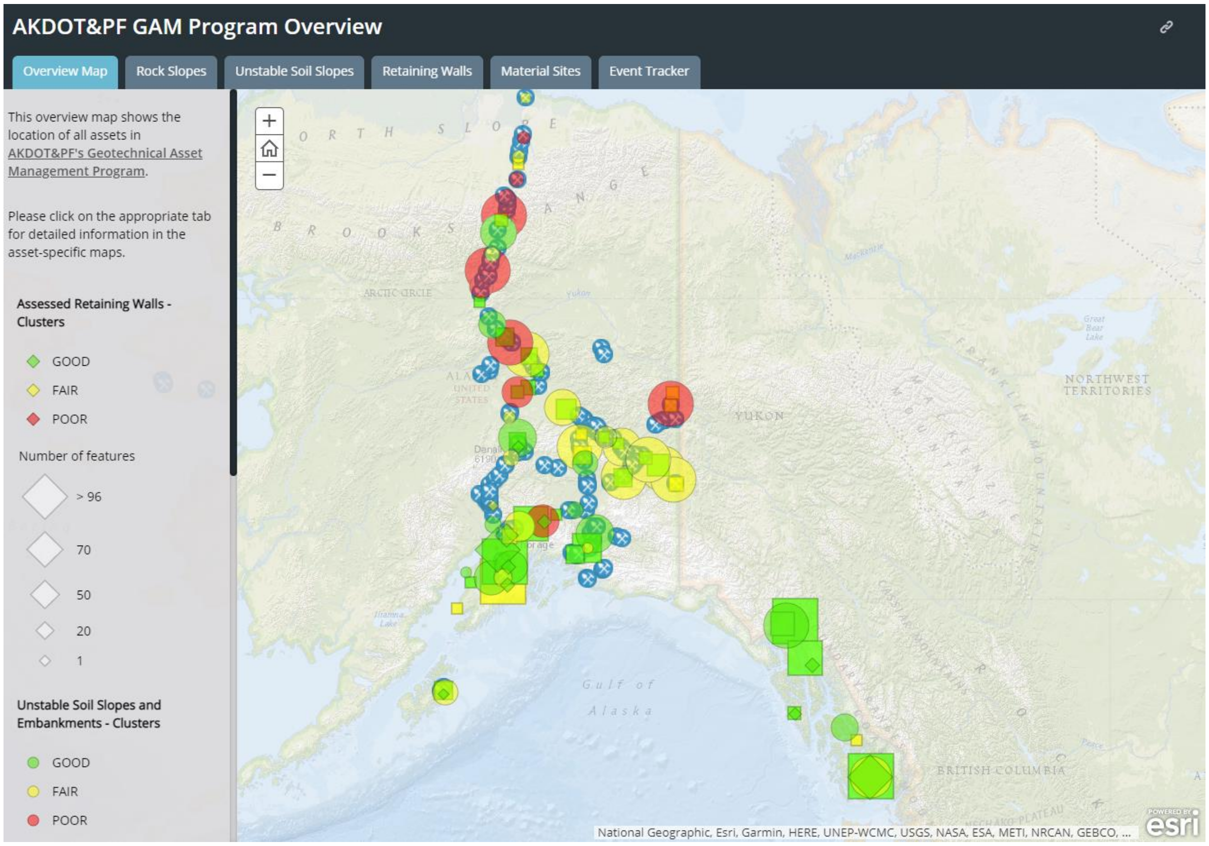


Figure 76. Illustration. Alaska geotechnical asset management program.

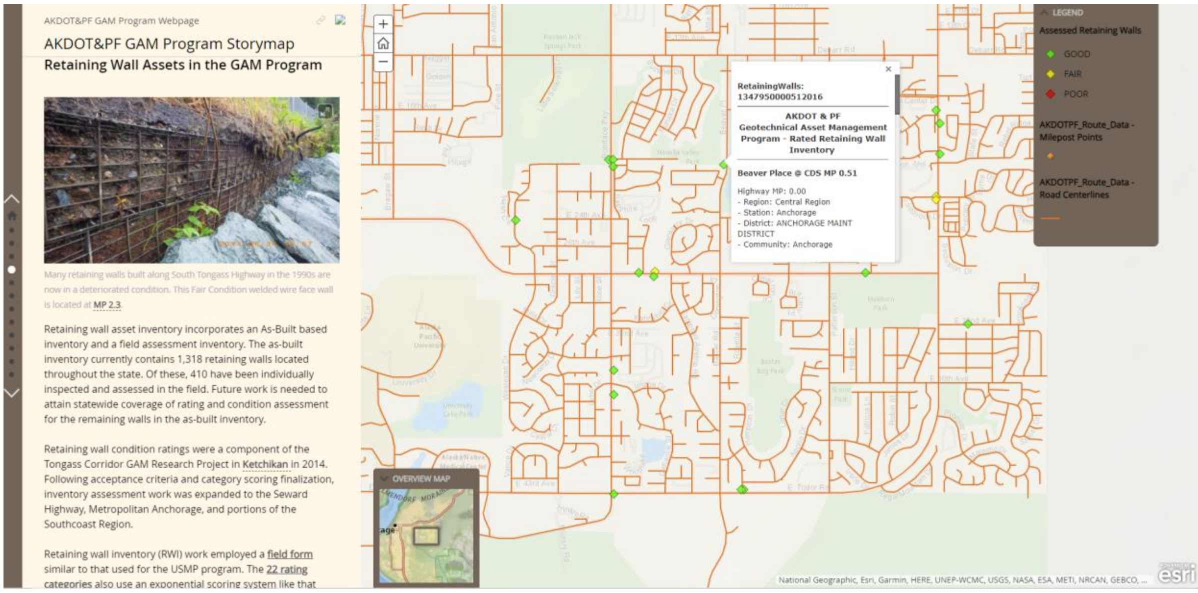


Figure 77. Illustration. AKDOT retaining wall assets in GAM.

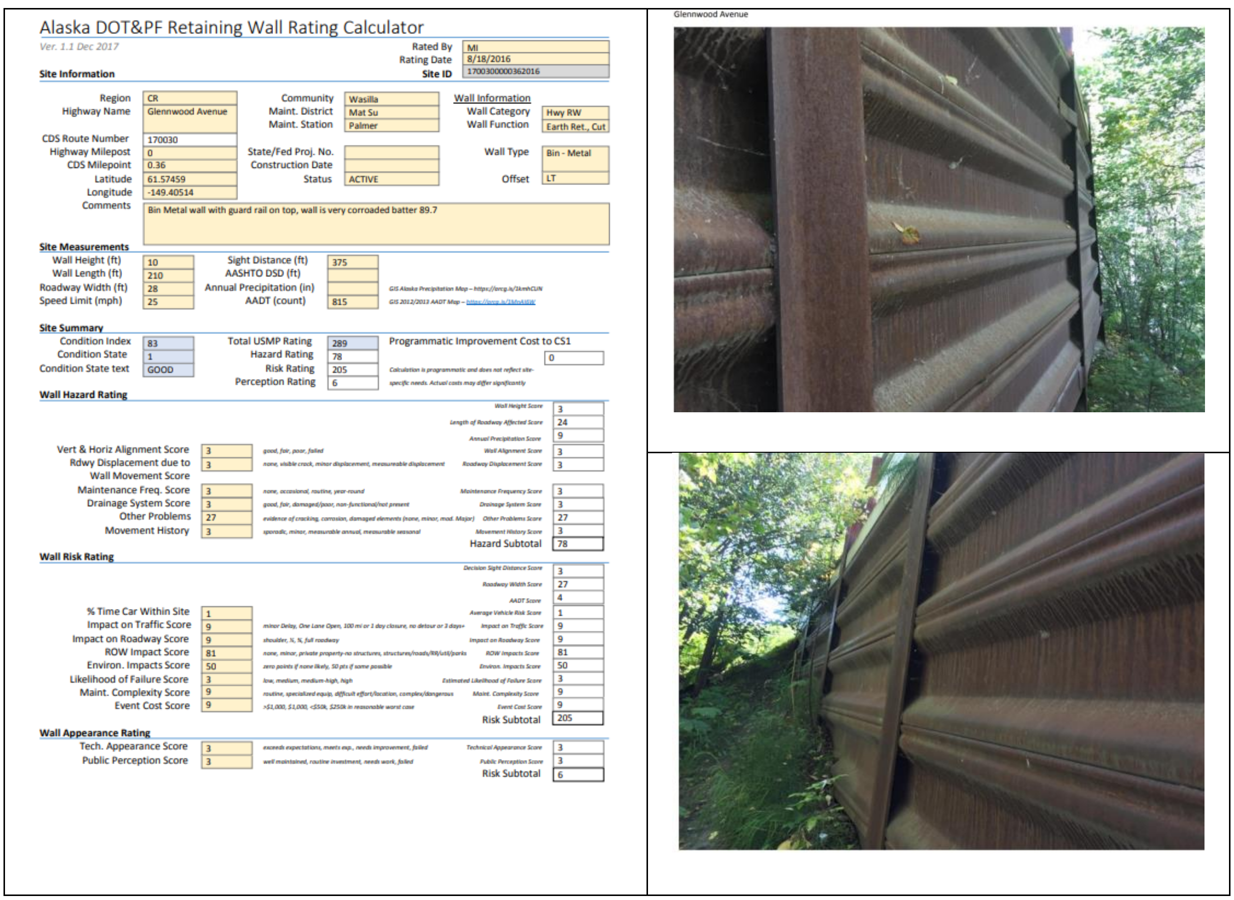


Figure 78. Illustration. AKDOT Retaining wall standard report.

Table 51. Relevant Characteristics of Retaining Walls (AKDOT)

• Report detailing the retaining wall rating calculations	• Precise location, including region, station, district, and community	• Comments such as: Cantilever concrete wall, minor vertical cracking throughout, and large split
• Basic geometry and information	• Condition data and condition state.	• Hazard rating score
• Perception score	• "Rating guide" link	•Identification number

COLORADO

The Colorado Department of Transportation (CDOT) has developed multiple programs/divisions to enhance and manage their comprehensive transportation system. Currently, any single program is responsible for the entire Geotechnical Asset Management implementation as described in NHCRP 903. CDOT has managed geotechnical assets and hazards through a compendium of programs such as: (1) Soil & Geotechnical, (2) Geohazards; and (3) Transportation Asset Management (TAM) programs. According to CDOT official website, CDOT Geotechnical and Geohazards programs are responsible for geotechnical explorations and recommendations and design, risk assessment, mitigation, and construction inspection support. CDOT and TAM programs also manage more than 9,100 miles of highways, 3,400 bridges, 3,000 walls, around 1,600 geologic hazard sites, and complementary infrastructure in all the state, actively implementing risk-based strategies to secure a cost-effective investment to critical assets. Currently, the asset programs in Colorado are one of the most comprehensive programs, managing geotechnical and non-geotechnical assets, such as surface treatment, bridges, walls, culverts, geohazards, and tunnels.

The CDOT has been managing geotechnical and non-geotechnical assets through an ArcGIS-based system named Online Transportation Information System (OTIS). Their team, stakeholders, and the general public can explore through geospatial information related to transportation in all the state, as shown in Figure 79. Between the many specialized maps offered in OTIS, CPLAN is highlighted, which is an online ArcGIS-based mapping platform where all the assets managed by CDOT are identified. Regarding geohazard information, the Colorado Geological Survey (CGS) contributes to the localization and characterization of landslides and rockfalls, showing more complex geohazards risk-based assessments than those shown in the OTIS platform.

Even though GAM practices have not been fully implemented, and only a part of them are under development under different asset management programs, there is an interesting practice related to geotechnical asset management that CDOT has been implementing since 2015. According to the Colorado Retaining and Noise Walls Inspection and Asset Management Manual (RNM-2016), CDOT aims to identify, inventory, inspect and rate all retaining and noise walls located in or near of the right of way (ROW) of Colorado's state highway system and process all the gathered information to positively impact the management of the assets using a risk-based GAM framework.

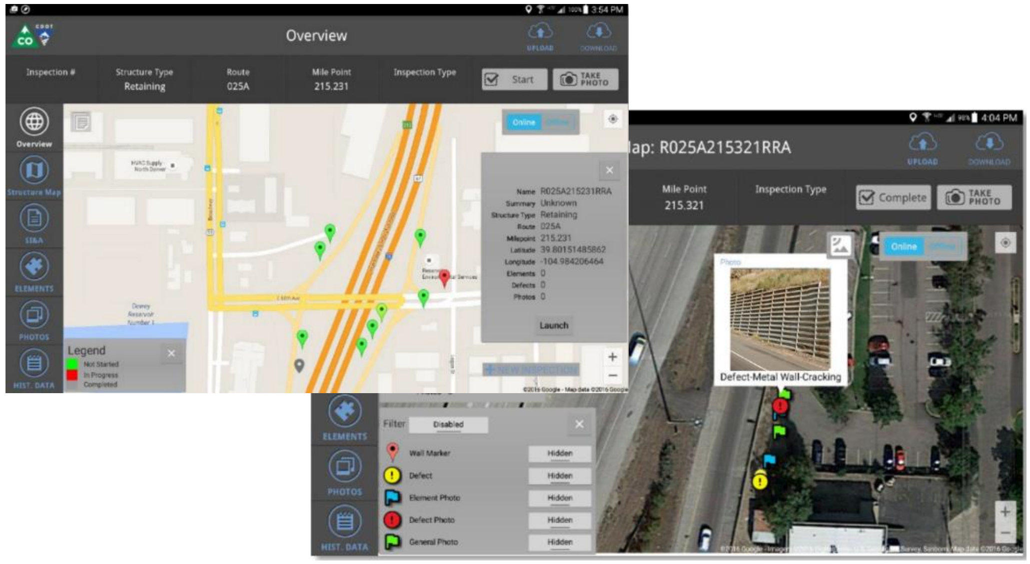


Figure 79. Illustration. ArcGIS-based map for GAM, CDOT.

According to the CDOT official website, the System for Asset Management and Inspection (SAMI) replaces the traditional procedures to inventory, identify and detail relevant information of every inspected asset. Moreover, it provides a geo-spatial platform for data analysis, real-time report editing, and planning. SAMI can also be operated from the field during inspections and from the office if any edition needs to be updated. This remote capability is beneficial for collecting photographs, georeferenced locations, structural details, particular conditions, and any tailor-made feature aligned with the guidelines established in “The Retaining and Noise Walls Inspection and Asset Management Program” published by CDOT in April 2016. Once every asset hs been reported and inspected, all that information will immediately be part of the web-based database, which could be used to elaborate reports, manage data, provide estimates, and schedule future inspections. SAMI is operated by inspection team leaders and used by geotechnical and non-geotechnical CDOT staff. Further details on SAMI are available in the Retaining and Noise Wall Inspection and Asset Management Manual.

LOUISIANA

Louisiana Department of Transportation and Development (LADOTD) focused on assets such as National Highway System (NHS) pavements and bridges. They managed over 16,000 centerline miles of roadway and just fewer than 8,000 bridges. For effective asset management, they classified asset class with interstate, non-interstate NHS, local NHS, state highway system (SHS), regional highway system (RHS). However, LADOTD has not implemented a mature Geotechnical Asset Management program.

According to the Louisiana Transportation Research Center (LTRC), since 2018, they have been developing geotechnical asset management under LTRC research project (18-4GT): Geotechnical Asset Management for Louisiana. LADOTD mainly deals with slope and embankment because they are likely to have some problems due to heavy clays and poor drainage. Also, they manage other geotechnical elements such as retaining walls, tunnels with retaining walls, levees near highways, emergency repair data, petrochemical industry, and geotechnical boring data.

For the inventory of geotechnical assets, LTRC applied several methodologies such as Google Earth and Maps, ArcGIS-based map, and segment breaks. Example of asset inventory by LTRC is represented in Figure 80.

District	Segments (of 4/15/19)	# Walls	Linear, ft	Linear, mi	Linear % of Total	Face Area, sqft
2	50	20	9,964.80	1.89	9.3%	TBD
3	30	12	8,084.70	1.53	7.5%	TBD
4	154	55	51,204.60	9.7	47.8%	TBD
5	22	10	1,103.70	0.21	1.0%	TBD
61	38	17	18,155.30	3.44	16.9%	TBD
62	3	3	115.7	0.02	0.1%	TBD
7	31	15	11,647.40	2.21	10.9%	TBD
8	23	9	6,865.90	1.3	6.4%	TBD
Total	351	131	107,142.10	20.29	100.0%	TBD

Figure 80. Illustration. Example of asset inventory, LTRC.

MINNESOTA

The Minnesota Department of Transportation (MnDOT) does not have an implemented mature Geotechnical Asset Management program, but they have created the Asset Management Program Office, whose function includes handling data and software systems for asset management. They also work and coordinate with different Minnesota agencies to acquire and maintain common databases. According to their GIS information site, MnDOT supervises 4,400 miles of railroad and 140,000 miles of state, city, and county roads.

Inside the MnDOT planning process, they have implemented a Transportation Asset Management System (TAMS), which considers most of MnDOT's non-pavement roads, bridge asset management inventory (Figure 81), and current condition. Currently, MnDOT has brought together a collaborative GIS informative site, which includes:

- A MnDOT tribal map applications
- Minnesota bridge interactive map (Figure 81)
- 2020 construction projects
- Pedestrian asset inventory

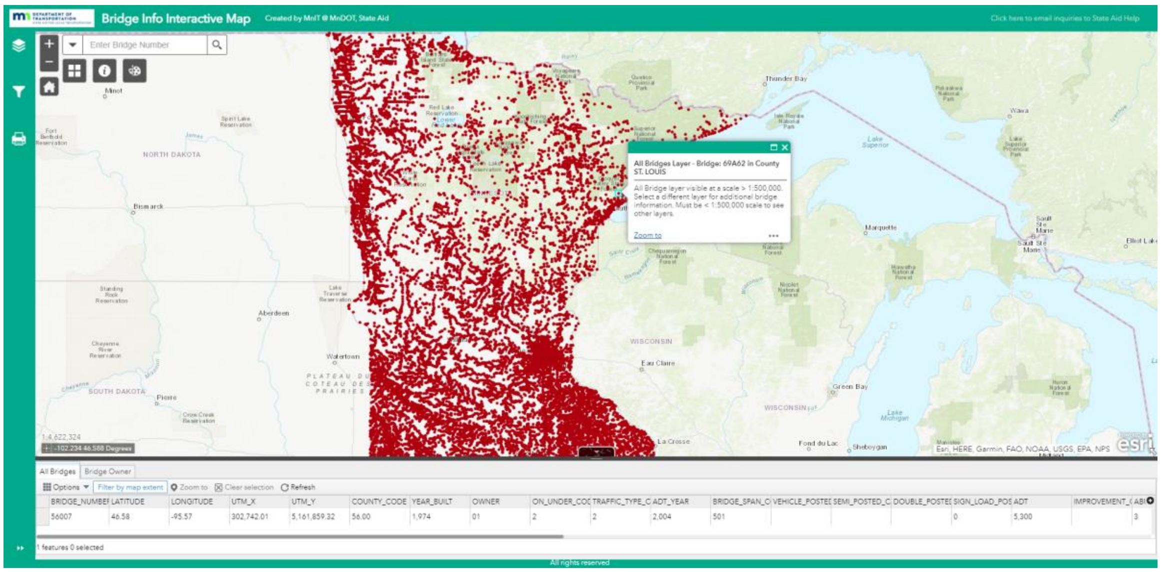


Figure 81. Illustration. Bridge info interactive map, MnDOT.

The closest GAM practice in MnDOT is managed by TAMS, where they maintain and update inventory information using field assessments, work orders, and scheduled inspections over the asset conditions. According to the agency, since mid-2016 TAMS has been implementing maintenance modules for a variety of assets, including pedestrian infrastructure, pavement status, and retaining walls.

In August 2016, TAMS implemented the Lighting module. The next steps will be to implement the Maintenance and Signs modules. Both modules are for assets such as signing, traffic barrier systems, hydraulic and drainage structures, noise barriers, pavement management, pavement markings, pedestrian infrastructure, earth retaining systems, and more. Currently, MnDOT is not inventorying embankments, slopes, and subgrades as specifically defined in Report 903, but they have developed a risk-based Transportation Asset Management Plan (TAMP) in accordance with the national initiative MAP-21.

NORTH CAROLINA

North Carolina Department of Transportation (NCDOT) has been dealing with Geotechnical and Transportation affairs relaying in their Geotechnical Unit (GEU), and the Maintenance & Operation Division. The Geotechnical Unit have been focused on geotechnical, geo-environmental and pavement areas for planning, design, construction, and maintenance of the North Carolina highway system, while M&O Division have been working with multiple subdivisions for developing and implementing comprehensive strategies for maintaining North Carolina's public transportation system inventoried and in optimal conditions. Moreover, one of their subdivisions, the Structure Management Subdivision, have been in charge of the design, construction, maintenance, and inspection of bridges retaining walls, pedestrian bridges, culverts, and other assets.

Ordinarily, NCDOT have been managing geotechnical and non-geotechnical assets through an ArcGIS-based system named GO!NC, in which their team, stakeholders, and general public can explore and upload geospatial information pertaining to transportation in all the state. Between the many maps offered in GO!NC, you can find:

- Data Service (Topographic information)
- Rail System
- Mitigation site map
- NCDOT Pavement condition map
- Structure Map (Figure 82)

The structure map provides information about general assets, such as bridges, tunnels, culverts, and so on. Each selected structure displayed geographical information, dimensions, type of material, and a Google Maps© link, where you can find 360° photos of the site through Google Street View©.

In order to start GAM implementation in the State, since 2017, NCDOT West Office have opened a dynamic ArcGIS-based map that provides location and geotechnical information of failure areas related to: embankments, landslides, rockfalls and rockslides as shown in Figure 83. More detailed information (e.g., bore logs, reports, plan sheets and mitigation recommendations) is also available in the same platform but only for GEU staff. In summary, NCDOT manages and supervises all geotechnical assets (under NCHRP 903 concept) through two well organized divisions; the first one is the NCDOT – GEU, Western Regional Office, and the second, the Structure Management Unit. More details are covered in their corresponding websites mentioned in the reference section.

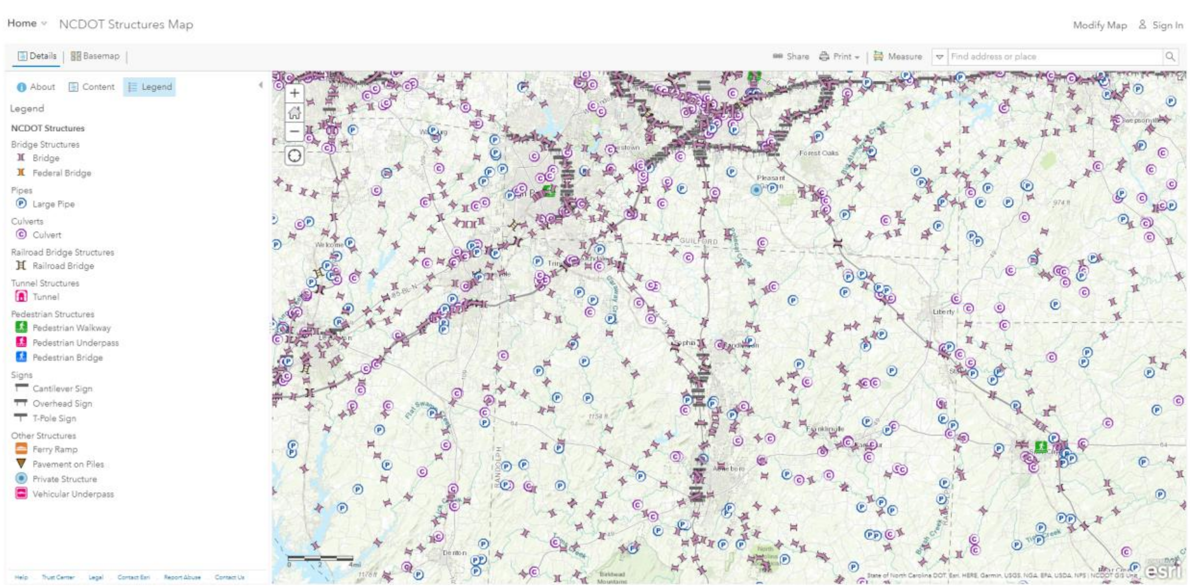


Figure 82. Illustration. Structures map, NCDOT.

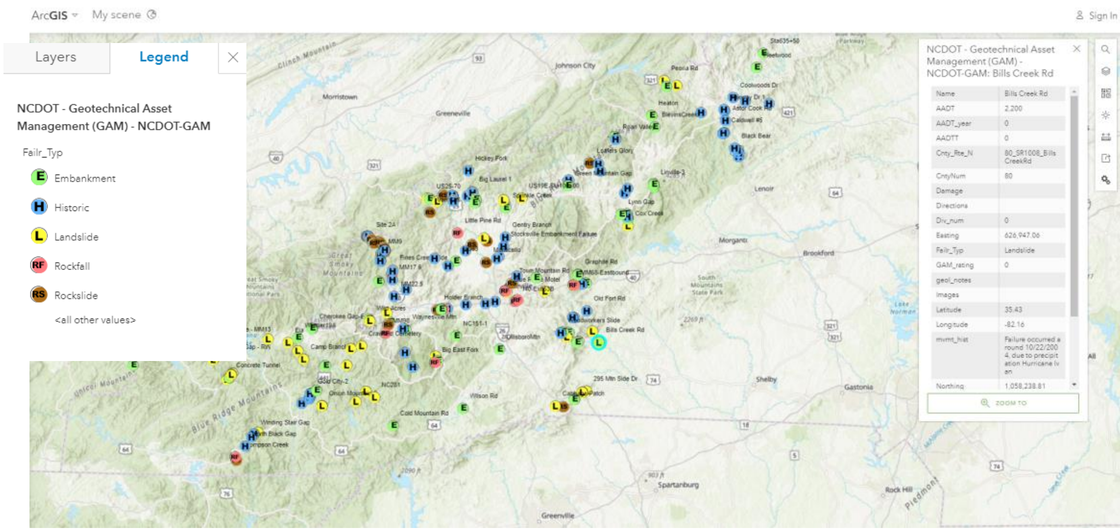


Figure 83. Illustration. ArcGIS-based map for GAM, NCDOT.

OHIO

Ohio Department of Transportation (ODOT) initiated a GAM program based on a general inventory and asset management information already compiled in the Transportation Information Mapping System (TIMS) as shown in Figure 84. This multiagency tool is a web-mapping portal where you can explore geotechnical and non-geotechnical assets related to Ohio's transportation system, identify, and locate potential hazards, create customized maps, and download raw data from their database. The information displayed on this site is collected from many offices across ODOT, and while every effort has been made to ensure accuracy, developers advise using it only for planning purposes.

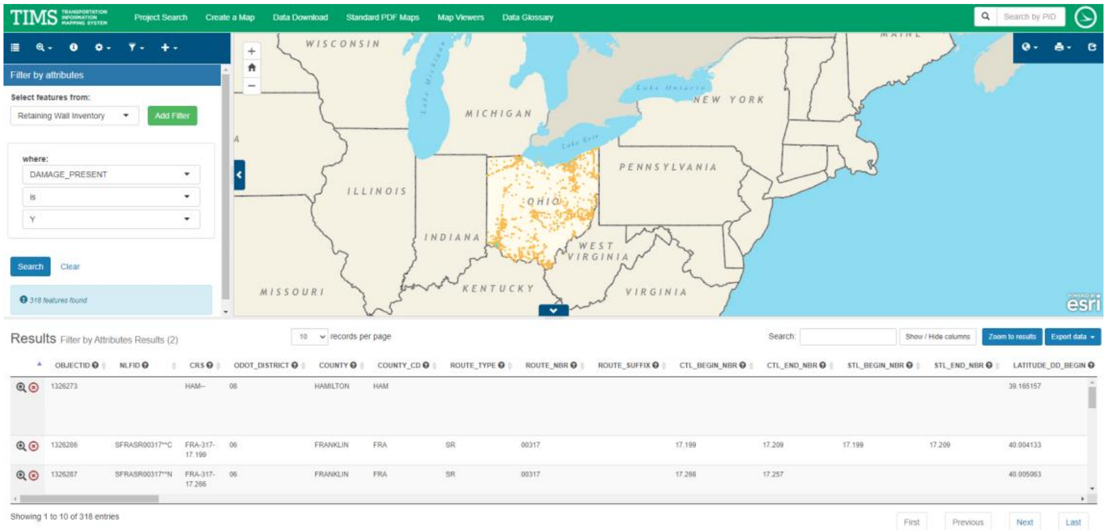


Figure 84. Illustration. Transportation information mapping systems (TIMS).

Inside TIMS, Geotechnical assets do not have their own category, but they can be found under two different ones (layers): (1) Assets and (2) Geohazard. The inventory of all types of retaining walls by county can be found inside “Assets”. Also, potential hazards grouped and labeled as landslides, rockfall, and abandoned underground mine inventory and risk assessment (AUMIRA) can be found under “Geohazard”. It seems ODOT has been following NCHRP 903 recommendations about not registering landslides or similar hazards as geotechnical assets. Currently, ODOT is not inventorying embankments, slopes, and subgrades as specifically recommended in NCHRP Report 903.

ODOT has also integrated an additional web tool for managing geohazards. All registered Ohio geohazards are uploaded in: http://ghms.odotgeoms.org/. Figure 86 shows an example of how the data is visualized. This does not have an interactive GIS-based map where each geohazard can be located, but useful information about each one of them can be found, such as:

- Probability of landslide occurrence: rated as low, moderate, high, and very high.

- Probability of landslide reaching the traffic lane: rated from low to very high, as well.
- Current and potential impact of landslide on the area beyond right of way (ROW).
- Location & GPS information
- Roadway, slope, and hazard area
- Additional information (e.g., hydrology, remediation, adjacent structures)

An additional benefit that ODOT is getting from GAM implementation is compiling historic geotechnical information and secondary data. This means all boreholes and geotechnical exploration campaigns performed in the past have been located, identified, and collected from all over the state. This will let ODOT enhance their GAM experience and save money in drilling and laboratory testing costs by the availability of geotechnical data for future projects. Despite having a great number of boreholes registered in TIMS, since 2019, ODOT has been working in making their Geotechnical data compatible with both the data interchange for geotechnical and geo-environmental specialists (DIGGS) and the geotechnical and geo-environmental software (gINT) as well.

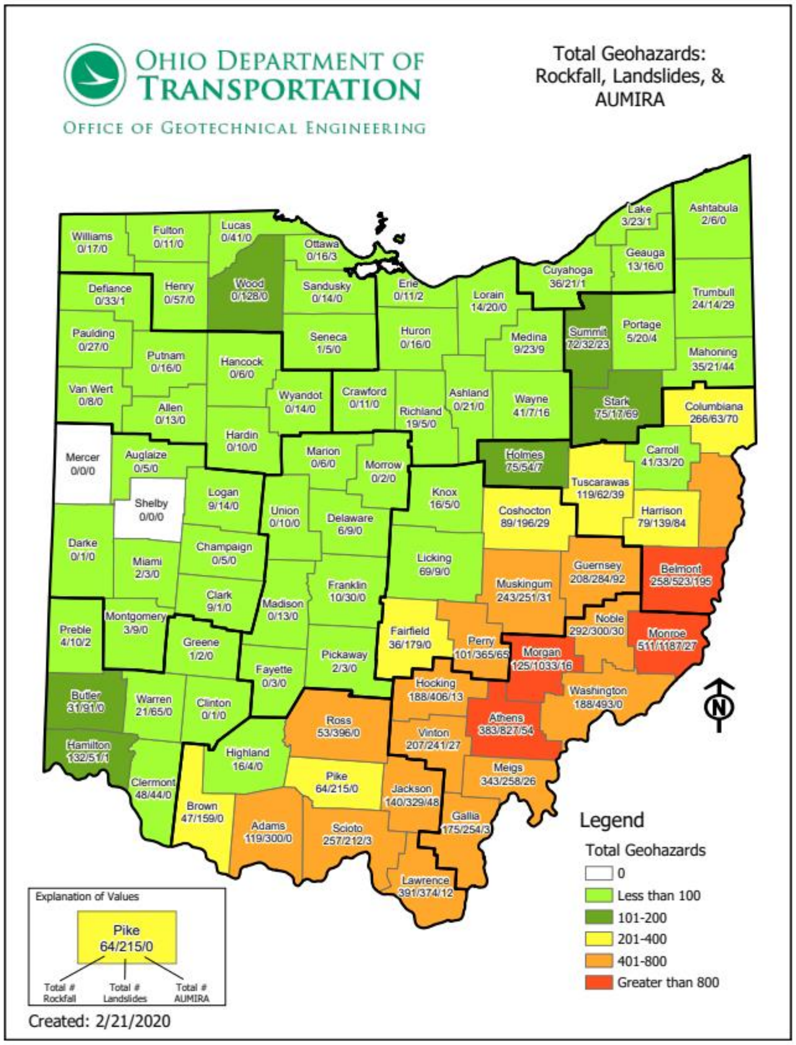


Figure 11. Illustration. ODOT total geohazards summary.

VERMONT

The Vermont Agency of Transportation (VTrans) has implemented asset management since 1995. They first introduced a pavement management system (PMS) and continuously developed their asset management practice. In 2002, they completed VTrans Asset Management Vision and Work Plan to reduce the maintenance cost of assets in terms of culverts under 20 feet of fill on the interstate, new bridge membrane, and pavement substructure. In 2014, VTrans focused on making a cohesive framework for asset management, including data management, performance and risk, and budget and programming. They managed 1141 miles of roads on the NHS and 483 bridges on the NHS. The managed pavement and bridge inventory by VTrans is represented in Figure 85. Also, a typical condition assessment for asset management is shown in Figure 86.

NHS Pavement & Bridge System (Owner)	NHS Bridges (Number)	NHS Pavement (Miles)
Interstate (State)	313	699
Non-Interstate (State)	154	407
Non-Interstate (Municipality)	16	35
Total	483	1,141

Figure 85. Illustration. Managed pavement and bridge inventory, VTrans.

In recent years, VTrans built Vermont Asset Management Information System (VAMIS) for data integration and information sharing and applied Deighton Total Infrastructure Management System (dTIMS). It will support full management implementation and finding optimal maintenance strategies in terms of asset such as pavement, rock slopes, retaining walls, stockpiles, long and short structures, small culverts, stormwater and ditches, guardrail, signals, rail, and buildings.

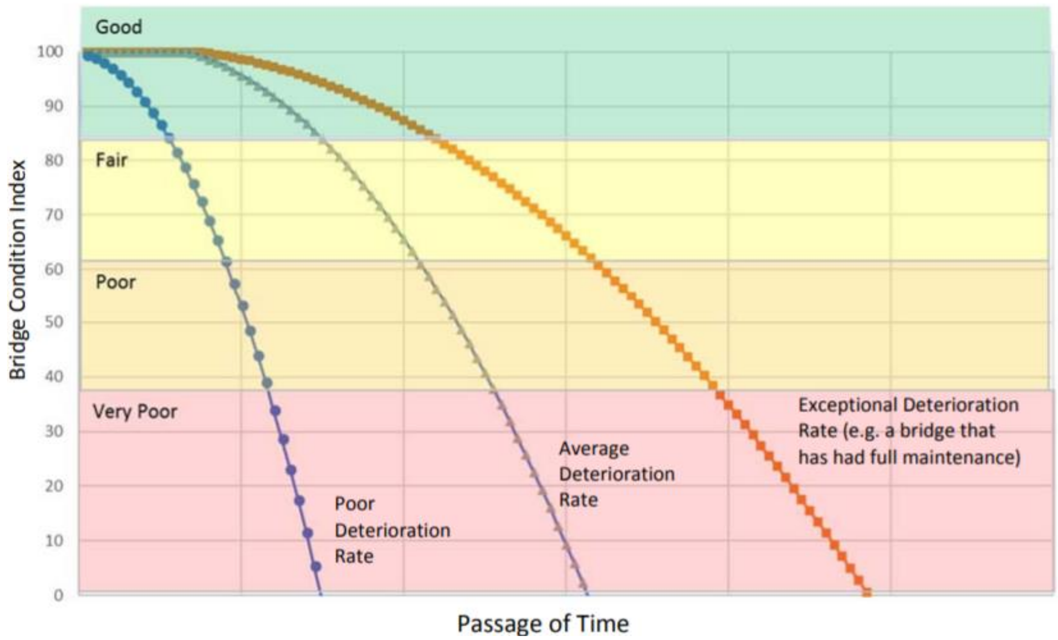


Figure 86. Illustration. Typical interstate bridge deterioration curves, VTrans.

WASHINGTON

For the Washington State Department of Transportation (WSDOT), asset management is a strategic, risk-based approach to cost-effectively and efficiently manage all the transportation assets involved in the Washington transportation system. WDOT is aware that for managing more than 75,000 lane-miles of roadways, 3,800 bridges, and different geotechnical structures, they will have to facilitate the development of long-term statewide asset management plans to positively impact the life cycles and utility of each one of their assets. Although WDOT has not fully implemented a GAM program into their practices, they have been following a transportation asset management guideline and, separately since 1990's, have been managing a geotechnical program focused on unstable slope management (Figure 87).

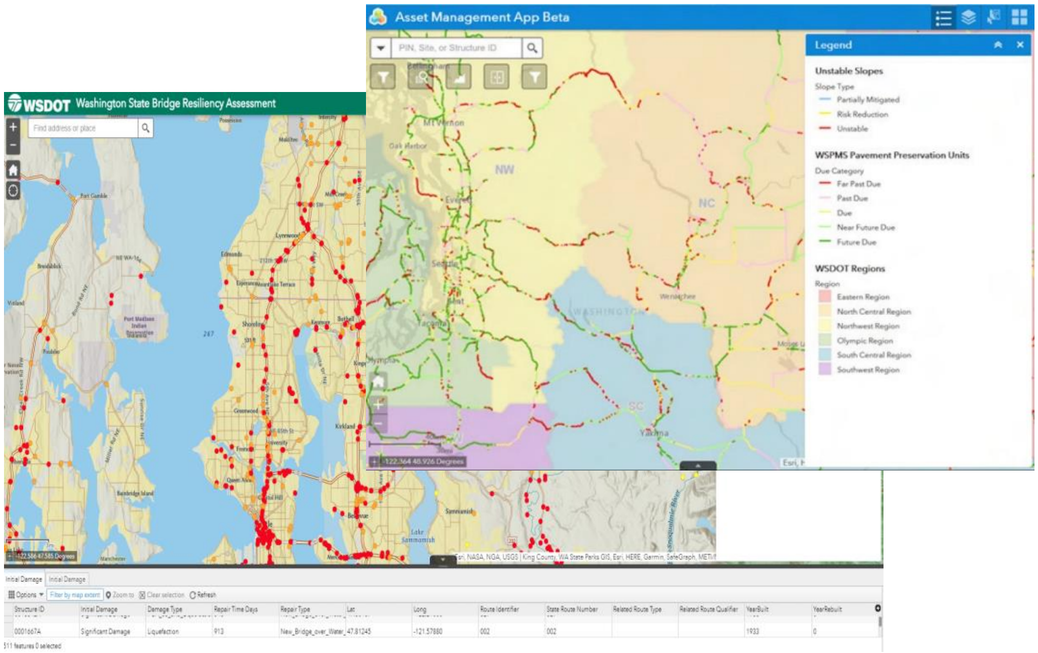


Figure 87. Illustration. Bridge and unstable slope location, WSDOT.

One of the priorities at the WSDOT is the Transportation Asset Management Plan (TAMP), which is mainly responsible for overseeing bridges and pavements statewide. TAMP follows international standards, federal directives, and unified goals aligned with the National Highway System (NHS). Furthermore, WSDOT is also following the Federal Highway Administration (FHWA) objectives through a Nation's surface transportation program (MAP-21).

In 1993 WSDOT implemented the Unstable Slope Management System (USMS) to address approximately 3,200+ known unstable slope hazards in the area of influence or ROW of the transportation network (GAMPE, 2020). The last update on USMS efforts to identify, characterize and mitigate possible landslides or rockfalls, reported in terms of around 250 slopes. The slopes had been fully mitigated either by selective efforts based on cost-effective informed decisions or as part of a collateral effect due to nearby project developments.

As shown in Figure 88, the Washington Geospatial Open Data Portal contains a GIS-based web application specifically for asset management, including tracking structures affected by natural hazards. The Washington Geologic Information Portal has a GIS-based map which can navigate among landslides and other registered natural hazards. Currently, they are working on a beta version for inventory geotechnical (e.g., unstable slopes) and non-geotechnical assets.

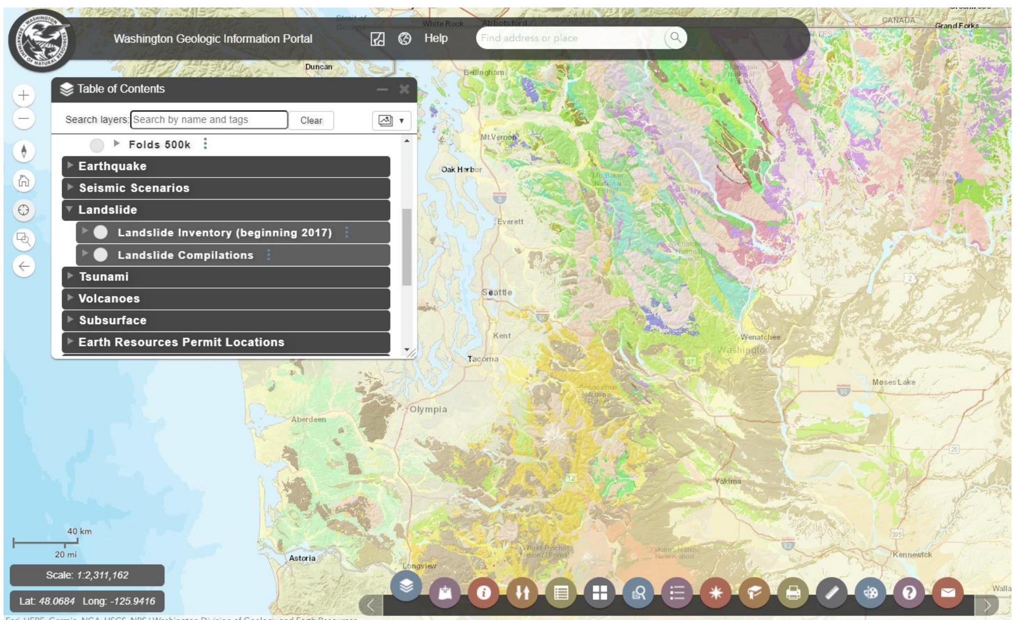


Figure 88. Illustration. Natural hazards - landslides, Washington geologic portal.

One of the plans that differentiate WSDOT from other agencies is the Statewide Transportation Asset Management Plan (STAMP), which according to their officials, represents the desire to incorporate and unify all asset management plans developed by each one of Washington's State's agencies under one master plan, including but not limited to: ferries, highways, geotechnical assets, hydraulic, barriers, real estate, aviation.

APPENDIX B. USER MANUAL FOR THE GDOT GEOTECHNICAL ASSET DATA COLLECTOR FORMS USING ARCGIS FIELD MAPS

SIGN-IN

After downloading ArcGIS Field Maps from the App Store or Google Play, sign in as follows (Figure 89).

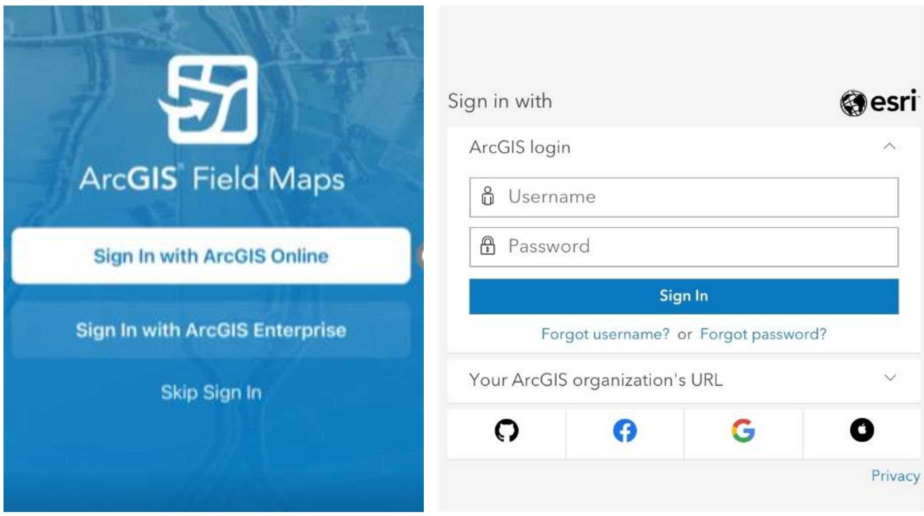


Figure 89. Illustration. Sign-in process for ArcGIS Field Maps.

INVENTORY FORM SELECTION

After logging in to Field Maps, select GDOT Geohazard Asset Data Collectors (Figure 90).

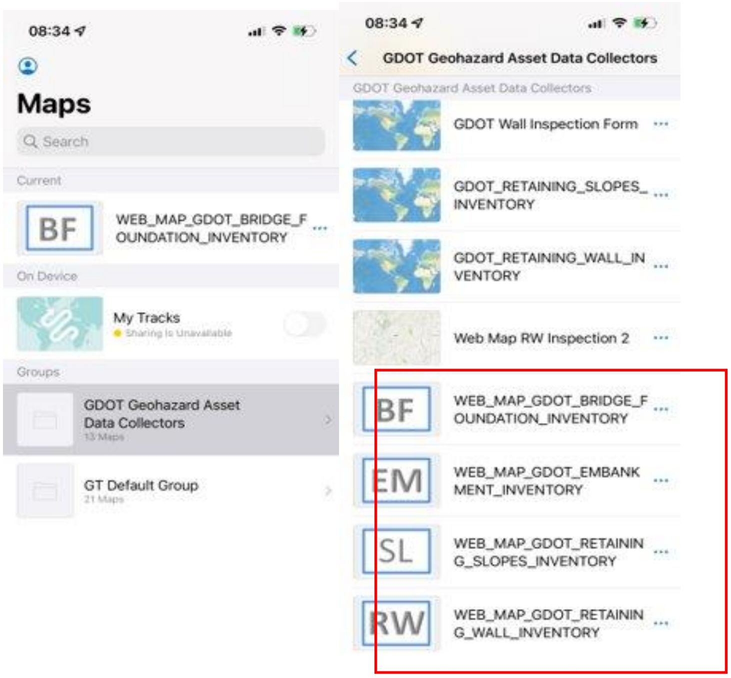


Figure 90. Illustration. GDOT Geohazard Asset Data Collectors and inventory forms for asset management.

The following inventory forms for geotechnical asset management will be used:

- WEB_MAP_GDOT_RETAINING_WALL_INVENTORY (RW)
- WEB_MAP_GDOT_SLOPES_INVENTORY (SL)
- WEB_MAP_GDOT_EMBANKMENT_INVENTORY (EM)
- WEB_MAP_GDOT_BRIDGE_FOUNDATION_INVENTORY (BF)

Select the appropriate inventory form according to the relevant geotechnical asset type (i.e., retaining wall, slope, embankment, or bridge foundation).

INVENTORYING PROCESS (EXAMPLE: RETAINING WALLS)

The inventorying process in the ArcGIS Field Maps for GAM is illustrated for retaining walls. Other assets (i.e., slopes, embankments, and bridge foundations) follow similar processes.

Identify location

In this process, the asset location is identified by clicking the add button (plus) (Figure 91). Subsequently, locate the GPS pointer on the asset's location and begin asset inventory by using "Add Point" function. On this screen, inspectors can take photos and attach files relevant to the asset being inventoried.

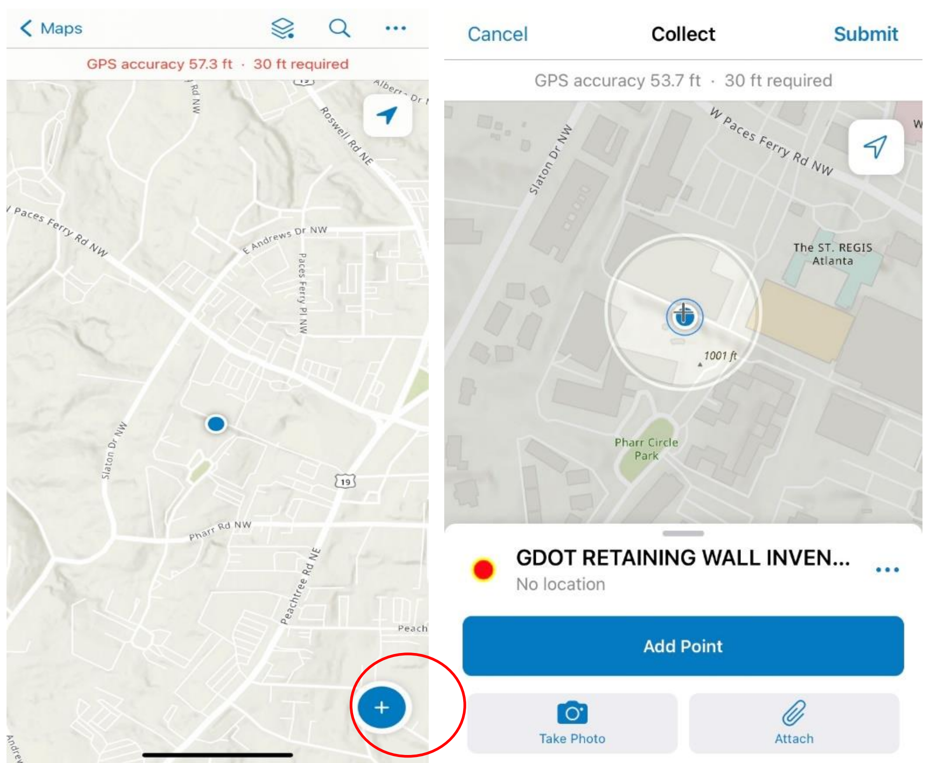


Figure 91. Illustration. Identify asset location in ArcGIS Field Maps.

General Information

General information for assets includes the following data:

PI number

: Data entry field to enter Current GDOT Project Identifier. GDOT project identification number is assigned to each project to facilitate local tracking operations.

Description (Mandatory field)

: Data entry field to enter the asset's description, including observed distresses, distinctive characteristics, referential location and defective elements, if any. Example: "*The wall is at milepost 125 on the southbound lanes of Interstate 985 in Jonesville. The retaining wall, which seems to be an MSE wall, appears bulging and cracked in some areas. In addition, there is a nearby slope that shows signs of soil erosion along its toe*."

PI Asset No.

: Data entry field to enter defined asset number.

Construction year (Mandatory field)

: Data entry field to enter the year construction was completed. If it is unknown, enter 2000, which is used as a generic identifier. GDOT will assume it was constructed prior to the 2000.

Perform an inspection?

: Automatically generated field.

Have you uploaded plans?

: Drop down option to select from "Yes" or "No".

Have you uploaded Approved Shop Drawings?

: Drop down option to select from "Yes" or "No".

Have you uploaded Other Files?

: Drop down option to select from “Yes” or “No”.

Location Information

Location information includes the following data:

Easting/Northing in degrees

: Data entry field to enter coordinate in degrees in terms of easting/northing to define exact location of asset.

County (Mandatory field)

: Drop-Down list includes 159 Georgia Counties (Table 52Table 51).

Table 52. County and District Lists in Georgia

County (Drop-Down List)						
District 1	**District 2**	**District 3**	**District 4**	**District 5**	**District 6**	**District 7**
BANKS	BALDWIN	BIBB	ATKINSON	APPLING	BARTOW	CLAYTON
BARROW	BLECKLEY	BUTTS	BAKER	BACON	CARROLL	COBB
CLARKE	BURKE	CHATTAHOOCHE	BEN HILL	BRANTLEY	CATOOSA	DEKALB
DAWSON	COLUMBIA	COWETA	BERRIEN	BRYAN	CHATTOOGA	DOUGLAS

County (Drop-Down List)						
District 1	**District 2**	**District 3**	**District 4**	**District 5**	**District 6**	**District 7**
ELBERT	DODGE	CRAWFORD	BROOKS	BULLOCH	CHEROKEE	FULTON
FORSYTH	EMANUEL	DOOLY	CALHOUN	CAMDEN	DADE	ROCKDALE
FRANKLIN	GLASCOCK	FAYETTE	CLAY	CANDLER	FANNIN	
GWINNETT	GREENE	HARRIS	CLINCH	CHARLTON	FLOYD	
HABERSHAM	HANCOCK	HEARD	COFFEE	CHATHAM	GILMER	
HALL	JASPER	HENRY	COLQUITT	EFFINGHAM	GORDON	
HART	JEFFERSON	HOUSTON	COOK	EVANS	HARALSON	
JACKSON	JENKINS	JONES	CRISP	GLYNN	MURRAY	
LUMPKIN	JOHNSON	LAMAR	DECATUR	JEFF DAVIS	PAULDING	
MCDUFFIE	LAURENS	MARION	DOUGHERTY	LIBERTY	PICKENS	

County (Drop-Down List)						
District 1	**District 2**	**District 3**	**District 4**	**District 5**	**District 6**	**District 7**
OCONEE	LINCOLN	MCINTOSH	EARLY	LONG	POLK	
RABUN	MACON	MERIWETHER	ECHOLS	MADISON	WALKER	
STEPHENS	MORGAN	MONROE	GRADY	MONTGOMERY	WHITFIELD	
TOWNS	NEWTON	MUSCOGEE	IRWIN	PIERCE		
UNION	OGLETHORPE	PEACH	LANIER	TATTNALL		
WALTON	PUTNAM	PIKE	LEE	TELFAIR		
WHITE	RICHMOND	PULASKI	LOWNDES	TOOMBS		
	SCREVEN	SCHLEY	MILLER	WARE		
	TALIAFERRO	SPALDING	MITCHELL	WAYNE		
	TREUTLEN	STEWART	QUITMAN	WHEELER		
	WARREN	SUMTER	RANDOLPH			

County FIP code

: Automatically generated field by selected county.

GDOT District (Mandatory field)

: Drop-Down list includes seven districts (Table 53 and Figure 92).

Table 53. Drop-Down Lists of GDOT Districts

GDOT District (Drop-Down List)
District 1: Northeast Georgia
District 2: East Central Georgia
District 3: West Central Georgia
District 4: Southwest Georgia
District 5: Southeast Georgia
District 6: Northwest Georgia
District 7: Metro Atlanta

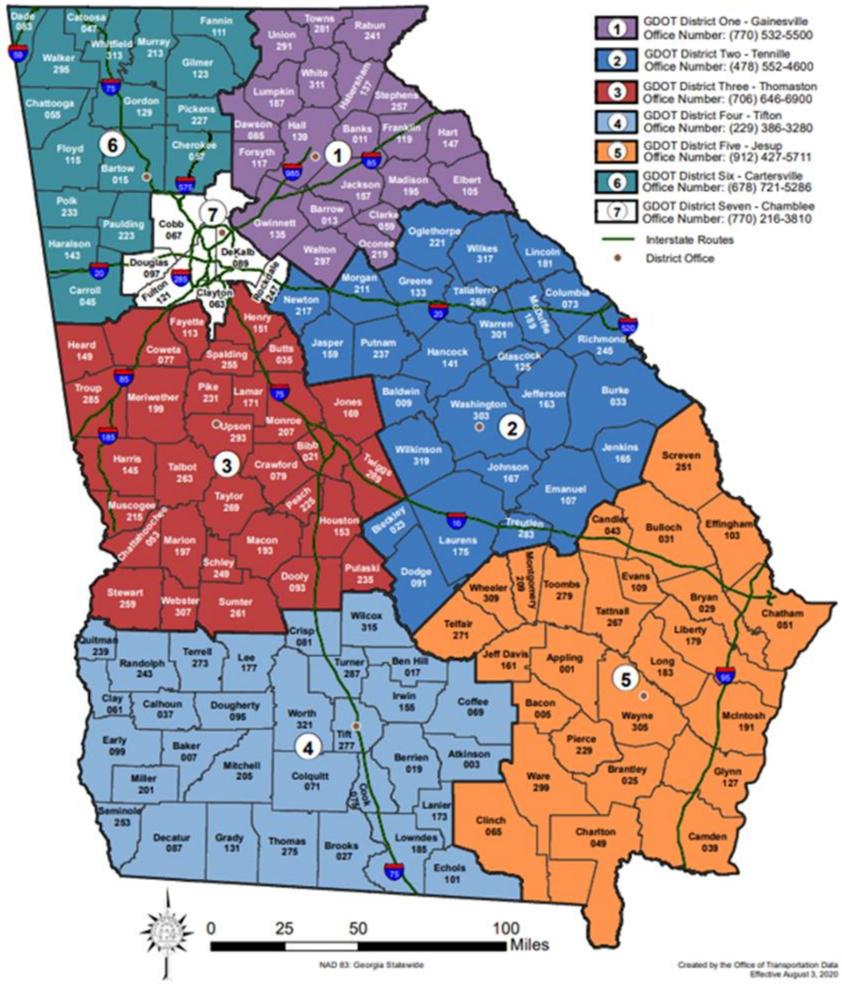


Figure 92. Map. Georgia district classification by GDOT.

District area

: Drop-Down lists of district area designated for periodic inspections (Table 54 and Figure 93).

Table 54. Drop-Down Lists of GDOT District Area

District Area (Drop-Down List)			
District 1	**District 2**	**District 3**	**District 4**
Gainesville Area 1	Milledgeville Area 1	Thomaston Area 1	Valdosta Area 1
Athens Area 2	Dublin Area 2	Columbus Area 2	Douglas Area 2
Carnesville Area 3	Louisville Area 3	Perry Area 3	Donalsonville Area 3
Cleveland Area 4	Augusta Area 4	Macon Area 4	Moultrie Area 4
	Madison Area 5	Lagrange Area 5	Albany Area 5
District 5	**District 6**	**District 7**	
Baxley Area 1	Cartersville Area 1	Chamblee Area 1	
Waycross Area 2	Dalton Area 2	Marietta Area 2	
Brunswick Area 3	Buchanan Area 3	College Park Area 3	
Statesboro Area 4	Rome Area 4		
Savannah Area 5			

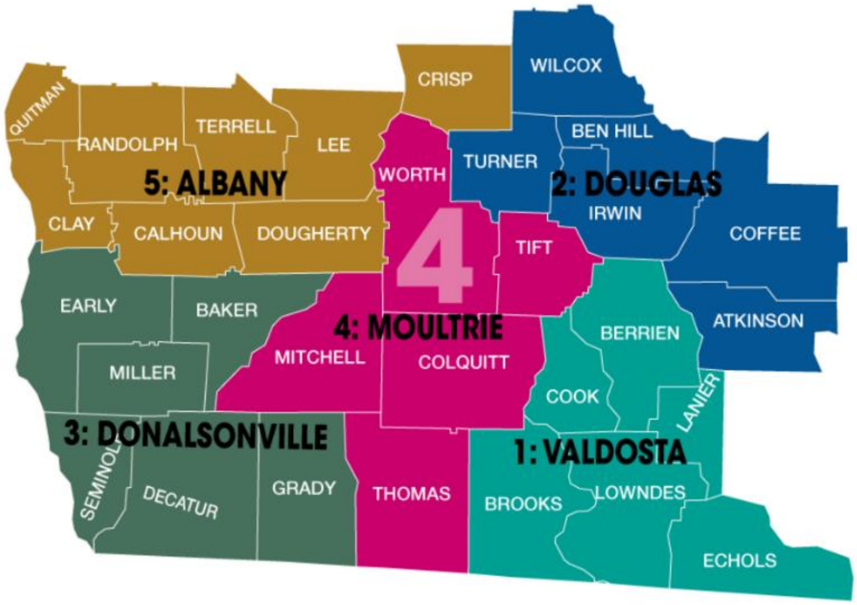


Figure 93. Map. Example of district area by GDOT.

Route type

: Drop-Down list includes all possible route types in Georgia (

Table 55). The route type includes all possible route types in Georgia, as well as those listed in both the Linear Reference System (LRS) and the Road Characteristics Link Identification (RCLINK) systems implemented in the transportation network in Georgia (GDOT, 2020).

Table 55. Route Type Lists

Route Type (Drop-Down List)
US Highway
State Route
Projected Road
Private Road
Interstate
County Road
City Street
Other

Route Number

: Data entry field to enter route number.

Unique structure number (Asset ID)

: Automatically generated field. It will be used in Survey123 for asset inspection.

Relative positions depending on relative location of wall placement (Mandatory field)

: Drop down option to select from “Above” or “Below”.

Nearest milepost/Asset’s milepost

: Data entry field to enter milepost. Milepost is recorded to indicate where asset starts, in miles. Milepost location should be taken at the midpoint of the asset (nearest 0.1). If the CDS milepost does not coincide with the asset's midpoint, a secondary reference should be entered.

Begin wall station/End wall station

: Data entry field to enter begin and end wall stations on plans.

Wall location in reference to the road:

: Data entry field to enter wall placement distance from roadway.

Classification

In this process, the asset is classified according to properties such as asset type and geometry, including:

Wall function (Mandatory field)

: Drop-Down list includes five wall functions (Table 56).

Table 56. Function of Retaining Wall

Wall Function (Drop-Down List)
Bridge Abutment
Cut
Fill
Other
Water Retention

Wall type (Mandatory field)

: Drop-Down list includes seven retaining wall types (Table 57).

Table 57. Type of Retaining Wall

Wall Type (Drop-Down List)
MSE Wall
Rigid Retaining Wall
Soldier Pile Wall (with or without tiebacks)
Tie-Back Wall
Soil Nail Wall
GDOT Standard Wall
Other Wall Types

Trademark

: Data entry field to enter the brand of a pre-cast wall, trademark, or wall supplier.

Wall Geometry

Geometric properties include the following data:

Total length (Mandatory field)

: Data entry field to enter the total length of asset, in feet.

Max. exposed height (Mandatory field)

: Data entry field to enter height at the tallest part of wall, in feet.

Min. exposed height

: Data entry field to enter height at the shortest part of wall, in feet.

Collector Details

Collector details include the following data:

Inventory responsible (Mandatory field)

: Data entry field to enter the last name followed by the first name of the inventory responsible. For instance: *"Sonare Parimal", "Adelakun Adebola."*

GDOT Office/Contractor

: Data entry field to enter the Inspector ID.

Inventory date (Mandatory field)

: Data entry field to enter the inspection date when the inventory is performed (Figure 94).

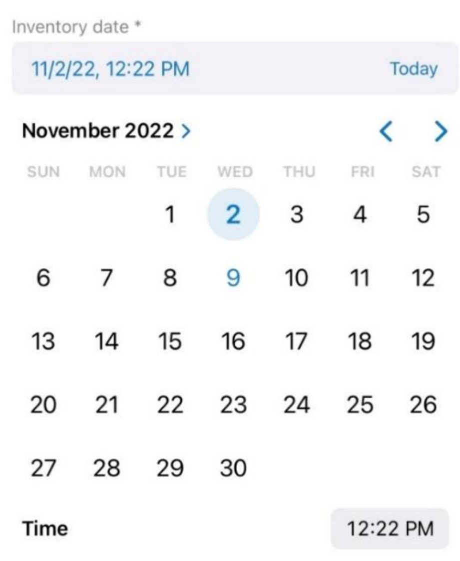


Figure 94. Illustration. Inventory Date in ArcGIS Field Maps.

APPENDIX C. ARCGIS SURVEY123 INSPECTION MANUAL

SIGN-IN

After downloading ArcGIS Survey123 from App Store or Google Play, sign in as follows Figure 95:

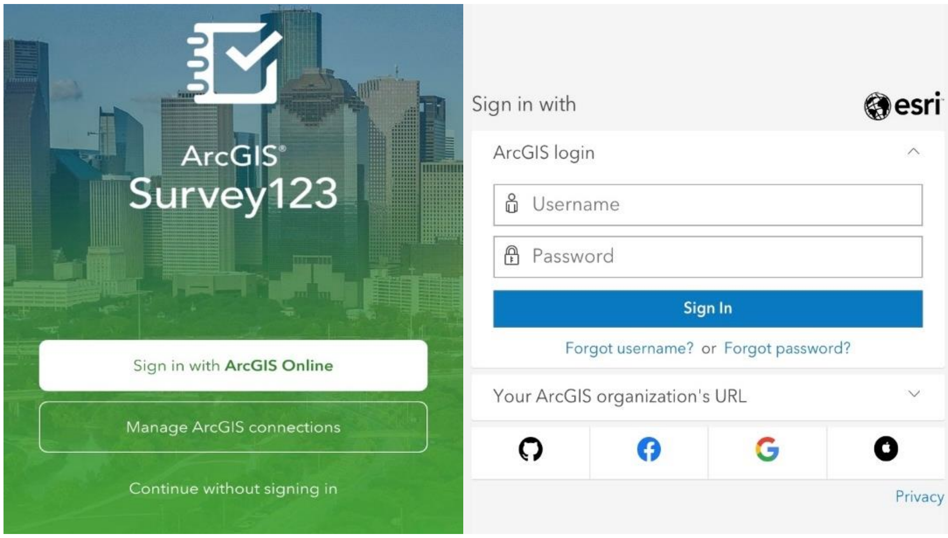


Figure 95. Illustration. Sign-in process of ArcGIS Survey123.

DOWNLOAD INSPECTION FORM

After you login to the ArcGIS Survey123, click the user account icon at the top of the interface. Select “Download Surveys” (Figure 96):

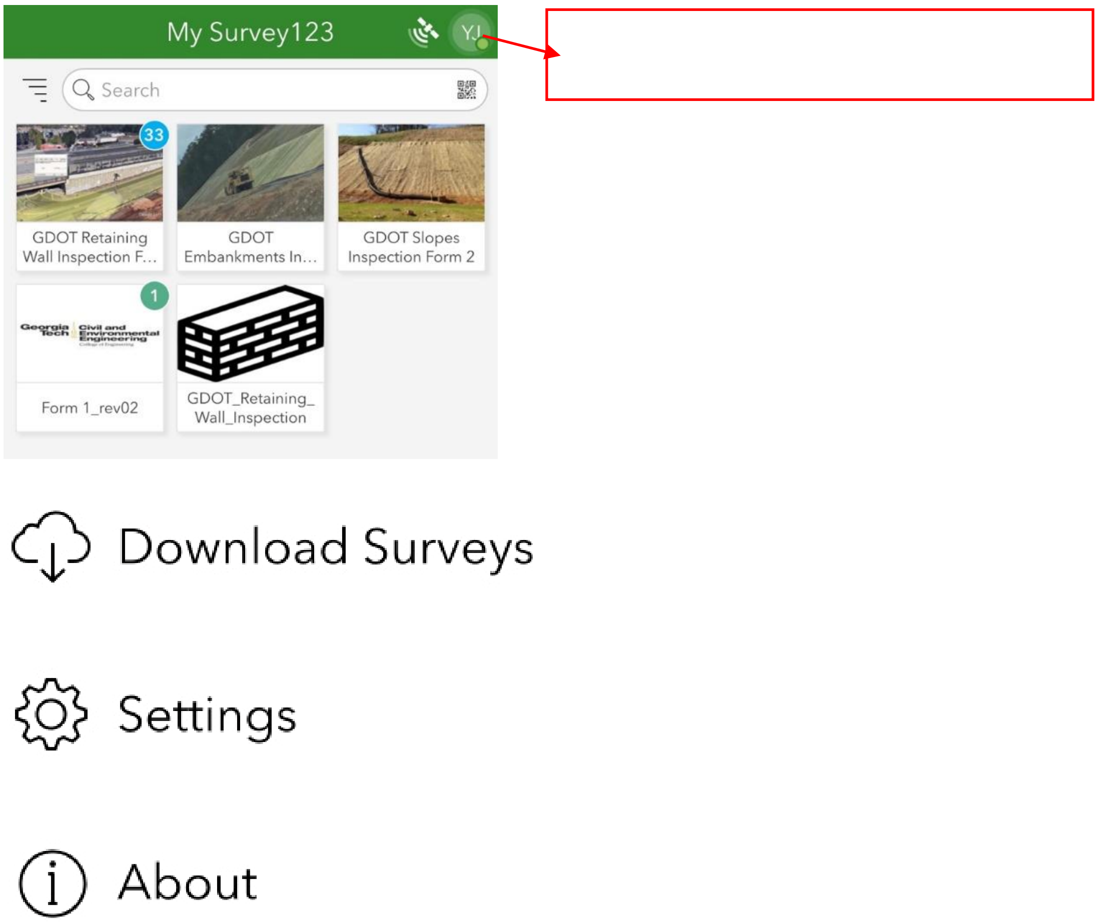


Figure 96. Illustration. Process to download surveys in ArcGIS Survey123.

The ArcGIS Survey123 will show downloadable surveys as shown in Figure 97.

Inspectors can download three inspection forms for geotechnical asset management:

- GDOT Retaining WALL Inspection Form 2
- GDOT Slope Inspection Form 2
- GDOT Embankment Inspection Form 2

Select form(s) and download.

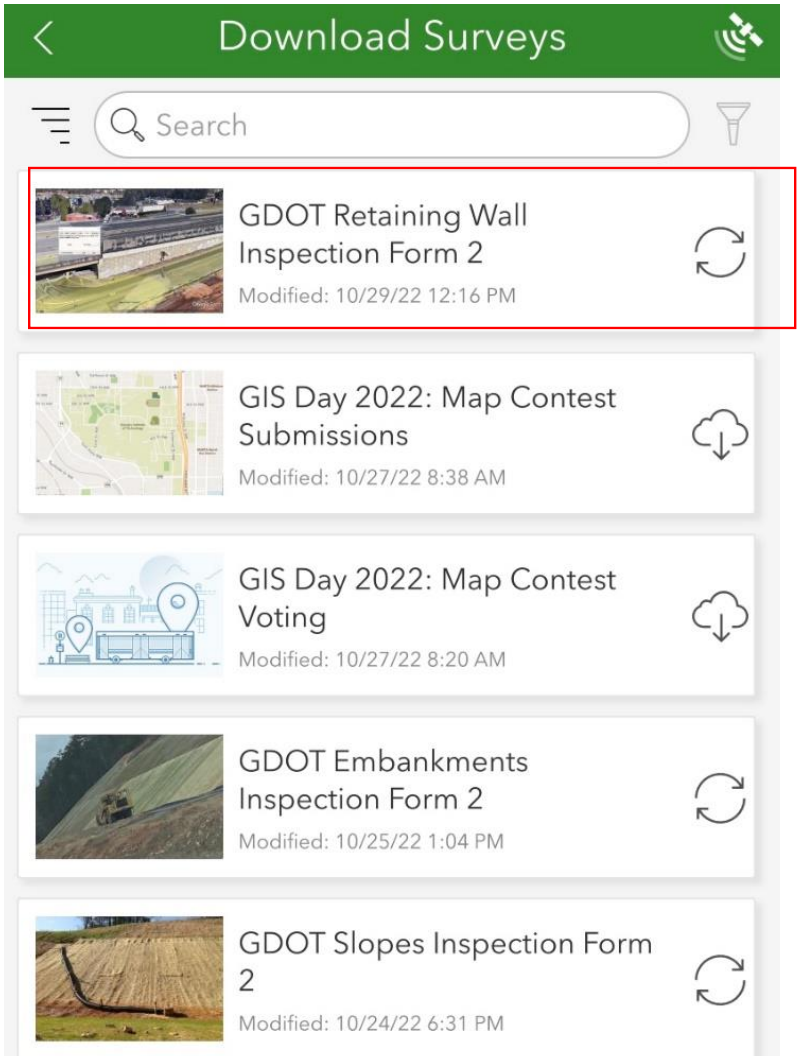


Figure 97. Illustration. Lists of GDOT survey form in ArcGIS Survey123.

INSPECTION PROCESS (EXAMPLE: RETAINING WALLS)

The ArcGIS Survey123 for GAM is illustrated for retaining walls. GDOT Retaining WALL Inspection Form 2 has three options (Collect, Inbox, Overview) (Figure 98). Start inspection of retaining wall assets by selecting “Collect.” Review the inspected retaining wall assets by selecting “Inbox” and “Overview.” Other assets, such as slopes and embankments, follow similar procedures.

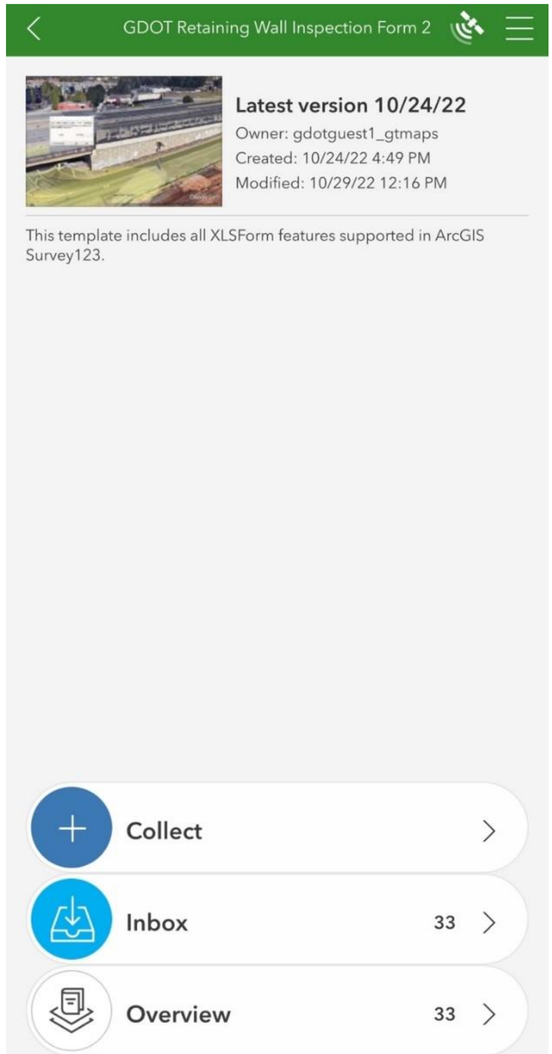


Figure 98. Illustration. Example of GDOT Retaining WALL Inspection Form 2.

Rater Details

Rater details in terms of asset inspection include the following data:

Inspector's name/email (Mandatory field)

: Data entry field to enter the last name followed by the first name of the inventory responsible. For instance: *"Sonare Parimal", "Adelakun*

Adebola."

Inspection date (Mandatory field)

: Automatically generated field.

GDOT Office/Contractor (Mandatory field)

: Data entry field to enter the Inspector Identification.

Weather condition

: Select weather conditions when an inspection is conducted. There are five options (sunny, cloudy, windy, rainy, and stormy).

ID & Location Details

ID and location details of assets include the following data:

Asset ID (Mandatory field)

: Data entry field to enter Unique Structure Number (Asset ID) which is generated in ArcGIS Field Maps.

Draw retaining wall outline

: Drawing field (from south to north, and from west to east) with several types of shapes and/or line in the lower side of interface as shown in Figure 99.

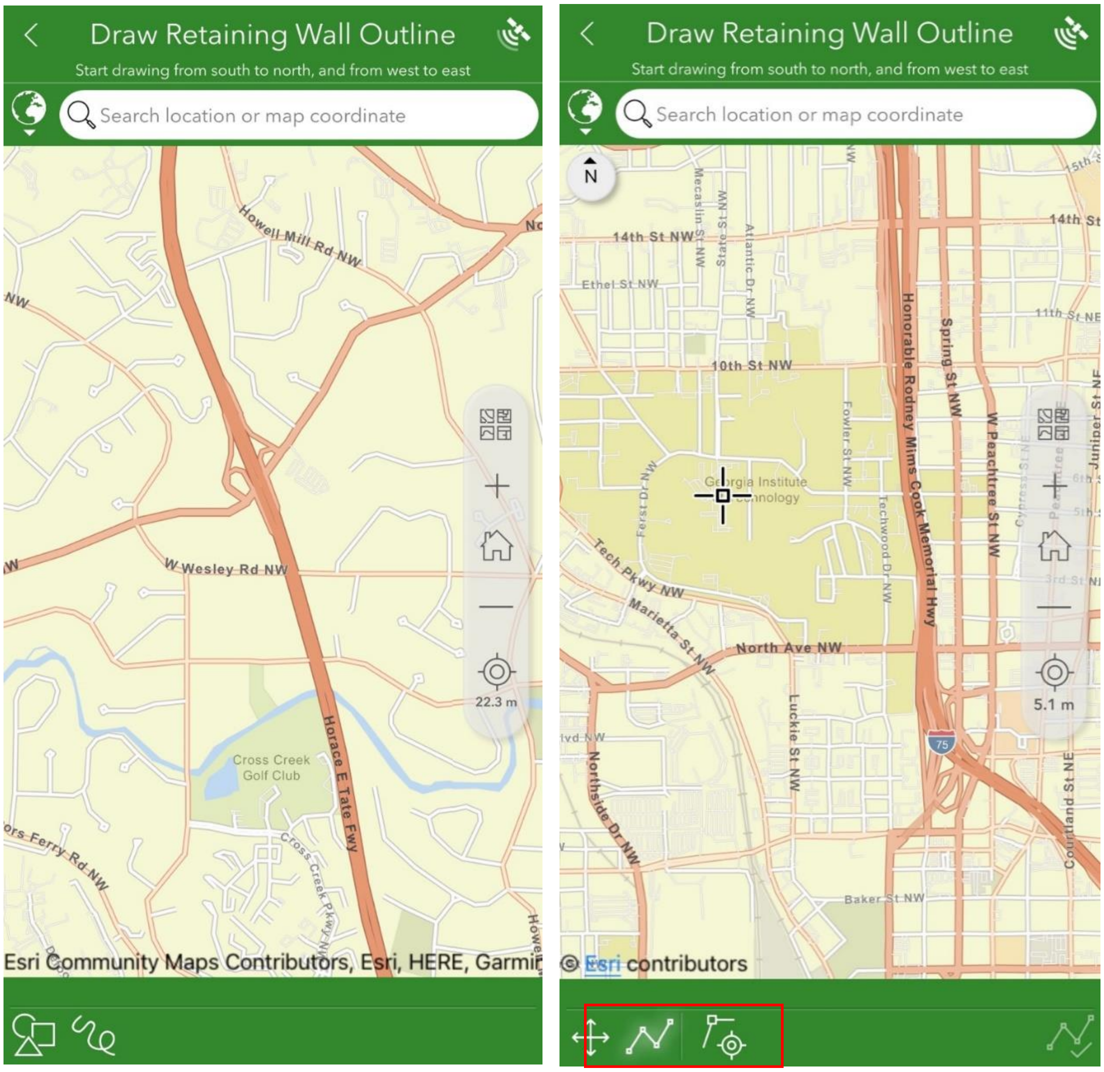


Figure 99. Illustration. Interface for drawing retaining wall outline.

Enter the location of the beginning/end of the wall

: Data entry field to locate beginning/end of the wall in the map as shown in Figure 100.

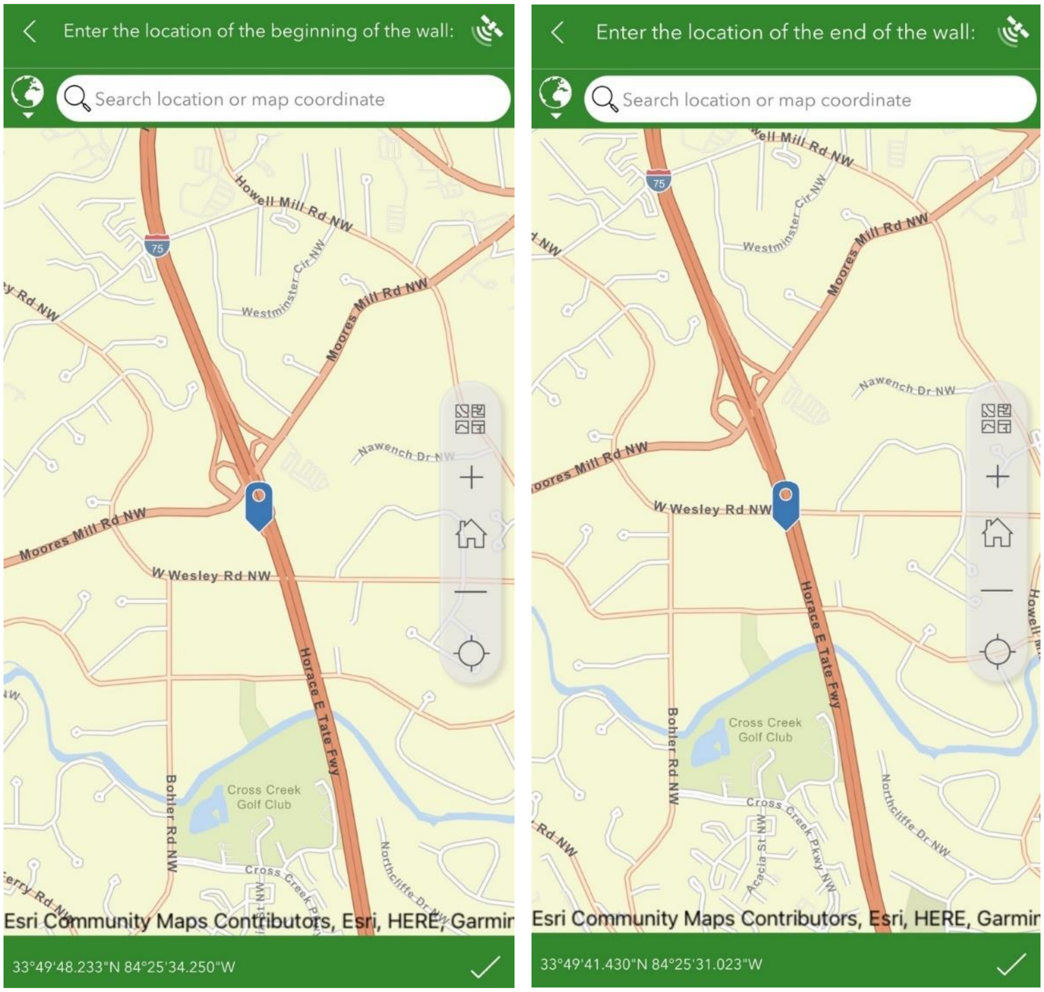


Figure 100. Illustration. Location of the beginning and end of the retaining wall.

Wall Geometry

Geometric properties of assets include the following data:

Wall length

: Data entry field to enter length of wall assets, in feet.

Maximum wall height (Mandatory Field)

: Data entry field to enter maximum height of wall assets, in feet.

Vulnerability, Distresses and Condition

Inspection results in terms of condition state and details include the following data:

Zone of influence

: Automatically generated field. It is typically two times the maximum wall height.

Accelerated deterioration?

: Drop down option to select from “Yes” or “No”.

Select all vulnerable elements within [vulnerable zone] ft. of this wall:

: Mulitple-choice list comprised of roadway, parking, structures, pedestrian path, and others.

Select all observed distresses:

: Mulitple-choice list comprised of undesired surcharges, tilting, cracking, spalling, local bulges, missing panels, staining, erosion, settlement, misaligned joints, scour, blocked drains, root penetration, wall vegetation, sinkholes, and none.

Photos and annotations of the wall, including distresses you observe

: Data entry field to add photos and details in terms of wall view, distresses observed, or relevant information.

Select the wall condition that better fits your assessment (Mandatory Field)

: Determine asset condition (New-1, Minor Loss-2, Fair-3, Poor-4, Critical-5) based on rating criteria as shown in Figure 101.

Condition		Performance Criteria	Maintenance Criteria
Good	1	**Brand new wall** with no signs of significant distress.	No maintenance needed
Good	2	**Low severity damage.** Highly functional wall that is showing minor cracks, mild spalling or misalignments in the joint zones, panels or elements, stains and graffities.	Few hours
Fair	3	**Greater maintenance is needed** due to the high extent of low severity distresses and/or low extent of high severity distresses. Most common scenarios are: **high extent** of **minor cracks** or spalls, **partial disrupted** drainage outlets, extra loading in the backfill, medium extent of missing elements, misalignments or root penetration in joints and panels, and evidence of erosion or scour.	About 1 week
Poor	4	**Significant deterioration observed.** Medium-to-high severity distresses are observed, and some wall elements might be compromised. Some examples are **regular** rockfall, **collapsed** drainage system, **significant** area with exposed steel reinforcement, visible **mild** settlements, local bulges, tilting or deformations.	Periodic or regular
Poor	5	**Failed asset, no longer performing as intended**, and **is affecting nearby structures** or regular transit.	Replacement or rehabilitation

Figure 101. Illustration. Rating criteria for the condition assessment.

Evaluating Wall Elements or Components

: Determine wall element(s) should be rehabilitated or replaced to prevent further localized deterioration of failure as shown in Figure 102.

Figure 102. Photo. Examples of localized deterioration to cause failure.

Consequence and Risk Factors

Safety consequences and mobility consequences for risk assessment include the following data:

Select the more likely safety consequence if the wall fails (Mandatory Field)

: Determine safety consequences based on their impact magnitude. There are five levels of safety consequences:

- No Impact Possible
- Impact to Shoulder Possible
- Impact to Travel Lane Possible but Avoidable
- Vehicle Damage Possible
- Fatality or Injury Possible

Select the more likely mobility consequence if the wall fails (Mandatory Field)

: Determine mobility consequence based on its impact magnitude. There are five levels of mobility consequence:

- No Impact Possible
- Impact to Shoulder Possible
- Impact to Travel Lane Possible
- Road Closure Possible: 1 day or less

Road Closure Possible: > 1 day

Risk Analysis based on NCHRP-903 Guidelines

The results of risk analysis based on NCHRP-903 guidelines include the following data:

Mobility risk score

: Data entry field to enter mobility risk score (maintenance condition level x mobility consequence). Ranges from 1 to 25.

Safety risk score

: Data entry field to enter safety risk score (maintenance condition level x safety consequence). Ranges from 1 to 25.

Total GAM risk score

: Data entry field to enter total GAM risk score (mobility risk score + safety risk score). Ranges from 2 to 50.

GAM grading

: Automatically generated field. It has five level of grades (A to F) (Table 58).

Table 58. Guidelines for Level of Risk Grade Assessment

Total GAM risk score	Level of risk grade
< 10	A
10 - 20	B
20 - 30	C
30 - 40	D
> 40	F

Others

Do you want to perform additional inspections?

: Drop down option to select from “Yes” or “No”.

Do you want to edit the deterioration and cost models?

: Drop down option to select from “Yes” or “No”.

APPENDIX D. VISUALIZING THE GDOT GEOTECHNICAL ASSETS USING THE GDOT ARCGIS DASHBOARDS

INTRODUCTION TO THE GDOT ARCGIS DASHBOARDS

The Georgia Department of Transportation (GDOT) inventory and inspect geotechnical assets using structured surveys hosted in ArcGIS Online (AGOL). Field Maps® and Survey123® are customized commercial off-the-shelf (COTS) solutions selected for the GDOT to gather data on the field using mobile devices (cellphones, tablets). Both COTS store the collected and inspected geotechnical data in different databases within the AGOL cloud environment. The GDOT ArcGIS Dashboards® have been designed to visualize all the data collected, including all inventoried fields and dedicated viewers to display photos taken during inspections. Figure 103 shows the GAM computational system diagram with all the databases/layers considered in the inventory and inspection processes and how they are organized and displayed on various ArcGIS Dashboards.

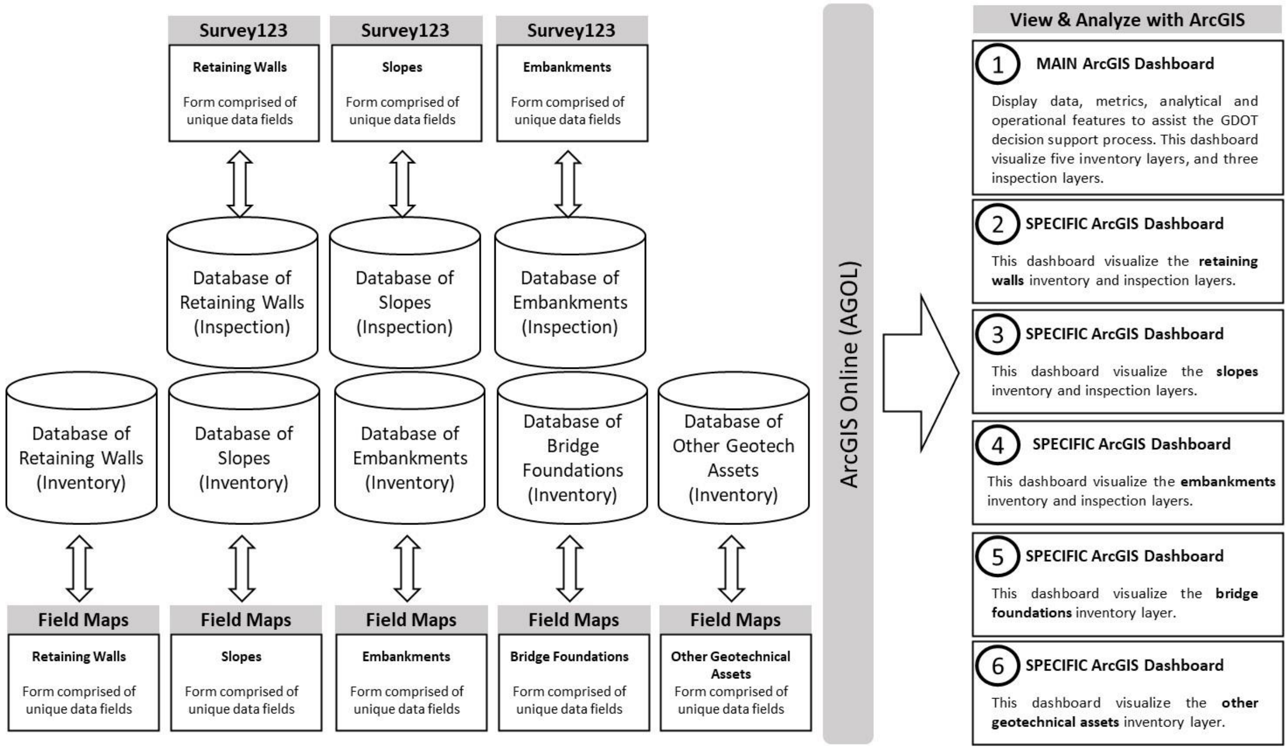


Figure 103. Illustration. GAM computational system diagram

Six different dashboards visualize and ease the management of all data collected from geotechnical assets. Table 59 lists the names of the GDOT dashboards, the nature of the databases displayed, and brief descriptions of the overall content.

Table 59. List of the GDOT ArcGIS Dashboards, including considered databases

No.	ArcGIS Dashboards	Inventory	Inspection	Observations
1	**Main**	X	X	All assets, including a dedicated viewer to display photos taken during inspections
2	**Retaining Walls**	X	X	Summary of the number of walls inventoried and inspected, number of walls by type, GAM grading, condition, essential features, and walls inspection viewer
3	**Slopes**	X	X	Summary of the number of slopes inventoried and inspected, number of slopes by type, GAM grading, condition, essential features, and slopes inspection viewer
4	**Embankments**	X	X	Summary of the number of embankments inventoried and inspected, number of embankments by type, GAM grading, condition, essential features, and embankments inspection viewer
5	**Bridge Foundations**	X		Summary of the number of bridge foundations inventoried, and essential features
6	**Other Geotechnical Assets**	X		Summary of the number of culverts and high-mast foundations inventoried, and essential features from both

Note that the maintenance inspections for bridge foundations and other geotechnical assets (culverts and high-mast foundations) are out of the scope of the current research project; therefore, the respective GDOT dashboards only display inventory data.

How to sign-in

- Sign in via ArcGIS Online https://www.arcgis.com/index.html (Figure 104)
- Enter your AGOL username and password (Figure 105)
- Once signed in, select the "Content" tab, then click on My Content. As shown in Figure 106, locate the search text box, type the name of the dashboard you want to access, and click on it.
- A window will open displaying the name, description, and terms of use that will apply to the selected dashboard. To explore the content managed by the

selected dashboard, click on "View Dashboard." For instance, Figure 107 shows the GDOT Main Dashboard home page.

Figure 104. Illustration. ArcGIS Online Homepage.
https://www.arcgis.com/index.html

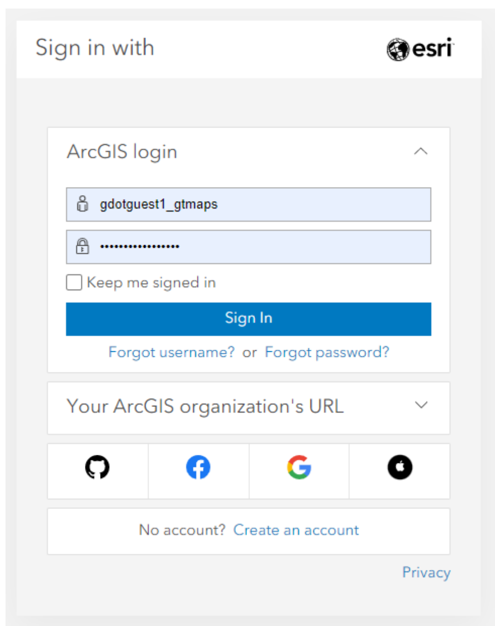


Figure 105. Illustration. Sign-in with ESRI

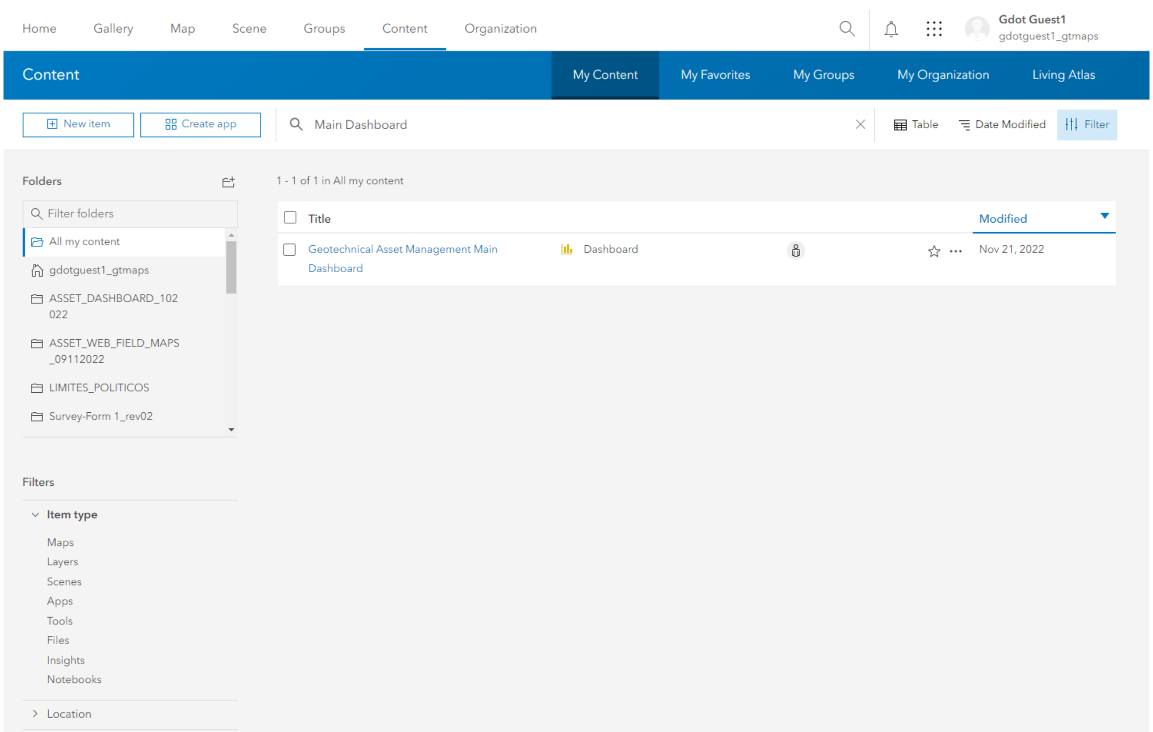


Figure 106. Illustration. Searching within all my AGOL content

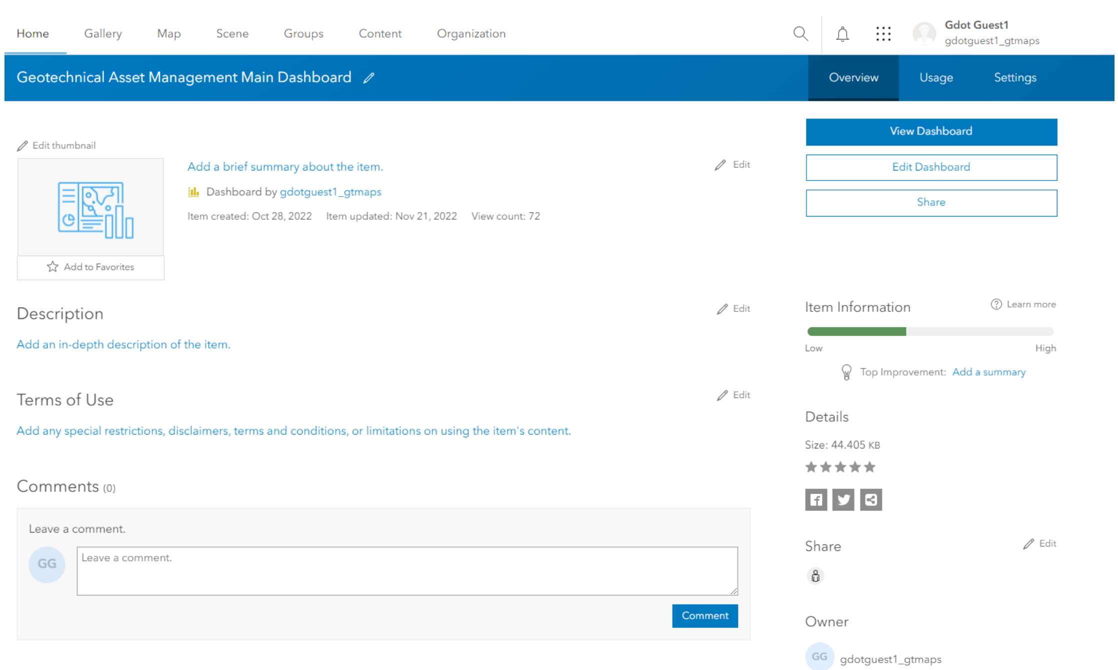
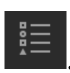


Figure 107. Illustration. Viewing the selected dashboard

ARCGIS DASHBOARDS ORGANIZATION

Main Dashboards

The Main Dashboard was designed to provide managers and executives fast access to relevant data from all geotechnical assets hosted on their respective inventory or inspection databases. Additionally, it displays the data as soon as the collectors and raters submit the forms, which is an essential feature for monitoring the development and progress of the GAM implementation statewide. Figure 1 illustrates the GDOT Main Dashboard and its seven different zones designed to serve the following purposes:

- **Zone 1:** the web map that visualizes ten layers , all geotechnical assets from the inventory and inspection databases, the GDOT Districts, and Georgia counties. All the inventoried geoassets are stored as "point" feature classes and the inspected ones as "line" feature classes. To visualize the different types of markers and lines used to represent every group of assets, click on the legends icon .

Click on the point or line of interest to display a pop-up window with all the features collected during the inventory and inspection processes. The photos taken during inventory tasks will appear at the end of the pop-up window; however, those taken during inspections will only be displayed if the feature is selected using the selection tools provided in zone 5.

Note that all the statistics shown in the dashboard will be updated every time the user zooms in or zooms out of the web map window.

- **Zone 2:** displays the current number of geotechnical assets inventoried per type, which are retaining walls, embankments, slopes, bridge foundations, and other geotechnical assets (culverts and high-mast foundations).

- **Zone 3:** shows the current number of geotechnical assets inspected per type, which are retaining walls, embankments, and slopes. The condition levels per group of assets are five and are represented in pie styles. The integers next to each condition label represent the number of geoassets rated as such. The main report explains the five-level condition rating in more detail.

- **Zone 4:** comprises three viewers programmed to display the photos of geotechnical assets taken during inspections. The viewer windows will only show the photos from an asset previously selected with the selection tools from zone 5.

- **Zone 5:** displays the "selection" tool  designed for exploring inspected assets and display their respective related photos in zone 4. The "point" option can select a unique asset, and the "line," "lasso," "rectangle," and "circle" options can select multiple inspected assets at once.

- **Zone 6:** shows the different available filters to narrow down the number of assets displayed on the map. This functionality improves productivity when working with massive amounts of data. The user can filter geoassets by GDOT Districts, Georgia counties, and/or creation date. For additional filtering tools, the user can click on the unpinned list  in the middle left to organize data by condition rating, length, height, and/or GAM grading.

- **Zone 7:** lists shortcuts to effortlessly redirect the user to any of the five GDOT Specific Dashboards. This list includes retaining walls, slopes, embankments, bridge foundations, and other geotechnical assets.

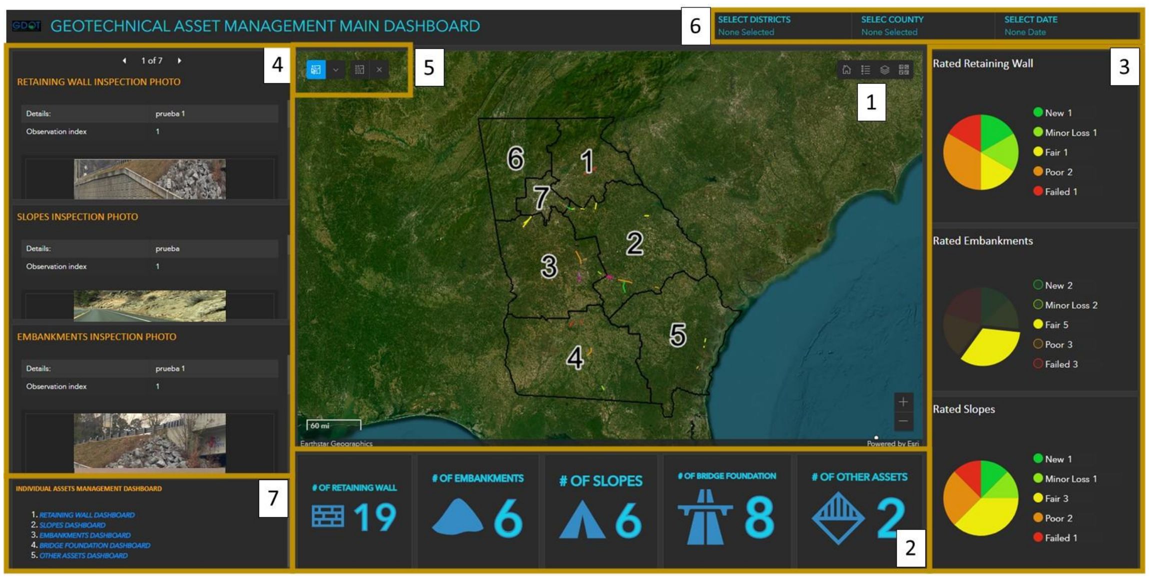


Figure 108. Illustration. The GDOT Main Dashboard layout for geotechnical assets

Specific Dashboards

The Specific Dashboards were designed to provide managers with a comprehensive view of the GAM implementation statewide per type of geotechnical asset. Additionally, these layouts portray inventory, condition, and risk data to facilitate decision-makers identify assets performing poorly. Figure 109 illustrates a typical GDOT Specific Dashboard and its ten different zones focused on:

- **Zone 1:** the web map that visualizes up to four layers , the selected type of geotechnical asset from the inventory and inspection databases, the GDOT Districts, and Georgia counties. All the inventoried assets are stored as "point" feature classes and the inspected ones as "line" feature classes. To visualize the different types of markers and lines used to represent every group of assets, click on the legends icon .

Click on the point or line of interest to display a pop-up window with all the features collected during the inventory and inspection processes. The photos taken during inventory tasks will appear at the end of the pop-up window; however, those taken during inspections will only be displayed if the feature is selected using the selection tools provided in zone 7.

Note that all the statistics shown in the dashboard will be updated every time the user zooms in or zooms out of the web map window.

- **Zone 2:** bar plot showing the number of inspected assets organized by condition.
- **Zone 3:** displays the most relevant features from the latest inspection of the selected asset, for instance: coordinates, list of observed distresses, condition, GAM grading, and so on.
- **Zone 4:** displays the most relevant features from the inventory phase, such as the GDOT project ID, the GDOT district, and a list of features that vary depending on the asset type selected.

- **Zone 5:** provides the inventory numbers of the selected geotechnical asset organized by asset subtype in pie styles. The integers next to each subtype label represent the number of geoassets identified as such. The main report explains the subtypes of assets per type of geotechnical asset in more detail.
- **Zone 6:** displays in real time the total number of assets inventoried and inspected.
- **Zone 7:** shows the "selection" tool  designed for exploring inspected assets and display their respective related photos in zone 8. The "point" option can select a unique asset, and the "line," "lasso," "rectangle," and "circle" options can select multiple inspected assets at once.

- **Zone 8:** portrays one viewer programmed to display the photos taken during inspections. The viewer window will only show the photos from an asset previously selected with the selection tools from zone 7.
- **Zone 9:** bar plot showing the number of inspected assets organized by GAM grading.
- **Zone 10:** shows the different available filters to narrow down the number of assets displayed on the map. This functionality improves productivity when working with massive amounts of data. The user can filter geoassets by GDOT Districts, Georgia counties, and/or creation date. For additional filtering tools, the user can click on the unpinned list  in the middle left to organize data by condition rating, length, height, and/or GAM grading.

- **Bottom-right-corner:** a shortcut to effortlessly redirect the user to the GDOT Main Dashboard.

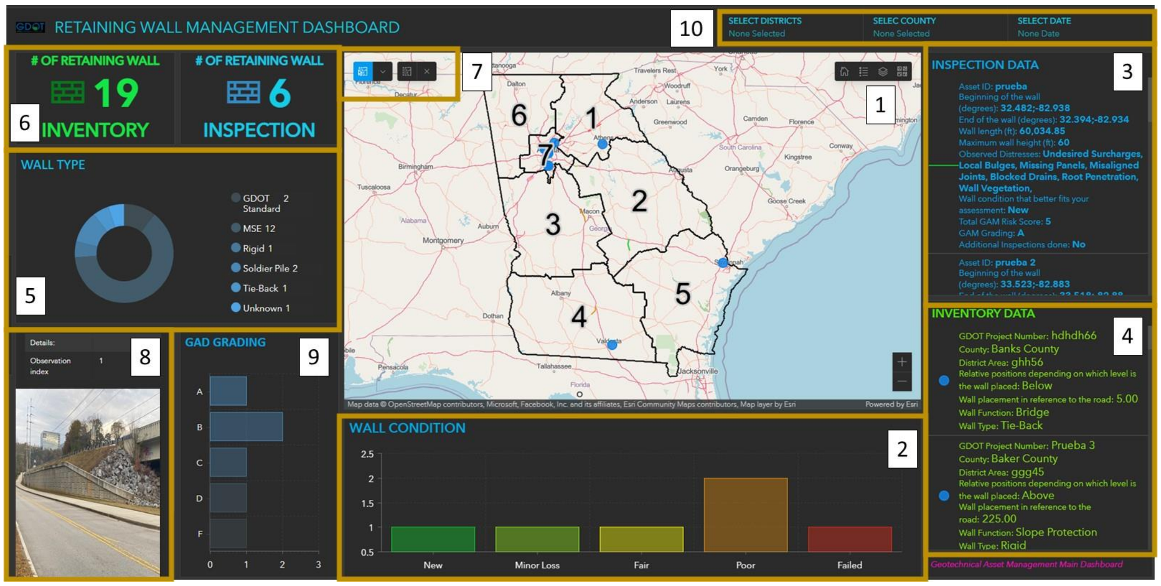


Figure 109. Illustration. A typical specific dashboard for geotechnical assets

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