PROCEEDINGS

1st Geotechnical Asset Management Peer Exchange (GAMPE)
San Juan, Puerto Rico

Submitted by

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Submitted to

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway Transportation Officials
ADT	Average Daily Traffic
ADOT&PF	Alaska Department of Transportation and Public Facilities
A-GaME	Advanced Geotechnical Methods of Exploration
AID	Accelerated Innovation Deployment
AMPS	Asset Management Program Section
ARAN	Automated Road ANalyzer
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
BoR	Bureau of Reclamation
CDOT	Colorado Department of Transportation
NHDOT	New Hampshire Department of Transportation
NHS	National Highway System
CIAPR	Colegio de Ingenieros y Agrimensores de Puerto Rico (College of Engineers and Land Surveyors of Puerto Rico)
CIFS	Center for Innovative Finance Support
CL	Center Line
CTIP	Coordinated Technology Implementation Program
DIGGS	Data Interchange for Geotechnical and Geoenvironmental Specialists
DNER	Department of Natural and Environmental Resources
DOT	Department of Transportation

DTPW	Department of Transportation and Public Works
EDC	Every Day Counts
ER	Emergency Relief
ESRI	Environmental Systems Research Institute
EUAC	Equivalent Uniform Annual Cost
FAST	Fixing America's Surface Transportation Act
FEMA	Federal Emergency Management Administration
FHWA	Federal Highway Administration
FLH	Federal Lands Highways
FLMAs	Federal Land Management Agencies
FMIS	Fiscal Management Information System
FTA	Federal Transit Administration
FWS	Fish and Wildlife Service
FY	Fiscal Year
GAM	Geotechnical Asset Management
GAMP	Geotechnical Asset Management Plan, Geotechnical Asset Management Program
GAMPE	Geotechnical Asset Management Peer Exchange
GIS	Geographic Information System
GRS-IBS	Geosynthetic Reinforced Soil-Integrated Bridge System
HTF	Highway Trust Fund
HSIP	Highway Safety Improvement Program
LiDAR	Light Detection and Ranging
LOR	Level of Resilience
LTAP	Local Technical Assistance Program

MAP-21	Moving Ahead for Progress in the 21st Century
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NHI	National Highway Institute
NHDOT	New Hampshire Department of Transportation
NHPP	National Highway Performance Program
NHS	National Highway System
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NTD	National Transit Database
PMS	Pavement Management System
PRHTA	Puerto Rico Highway and Transportation Authority
PROMESA	Puerto Rico Oversight, Management, and Economic Stability Act
QRA	Quantitative Risk Analysis
RFP	Request for Proposals
RHRS	Rockfall Hazard Rating System
RRS	Risk Reduction Scaling
SDI	Strength Development Inventory
SEO	Soils Engineering Office
SHRP	State Highway Research Program
SOP	Standard Operating Procedure
SPR	State Planning and Research

STIC	State Highway Improvement Council
STP	Surface Transportation Plan
TAM	Transportation Asset Management
TAMP	Transportation Asset Management Program
TRB	Transportation Research Board
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicles
USACE	United States Army Corps of Engineers
USDOT	United States Department of Transportation
USFS	United States Forest Service
USGS	United States Geological Survey
USMP	Unstable Slope Management Program
VMT	Vehicle-Miles Traveled
VPD	Vehicles per Day
WFL	Western Federal Lands
WSDOT	Washington State Department of Transportation
WTI	Western Transportation Institute

PREFACE

The **1st Geotechnical Asset Management Peer Exchange (GAMPE)** was an initiative between the Puerto Rico Highway and Transportation Authority (PRHTA) and the Federal Highway Administration (FHWA) with the primary purpose of exchanging ideas of success stories and lessons learned associated with the implementation of Geotechnical Asset Management Program on other state highway departments in the United States and how they can be adapted to be implemented in Puerto Rico.

GAMPE technical sessions were held at the headquarters of the College of Engineers and Surveyors of Puerto Rico (CIAPR) in San Juan, Puerto Rico on August 27 and 29, 2019. Site visits to highway projects in the island with representatives cut and fill sections and other geotechnical engineering characteristics of interest to the participants were conducted in the morning of August 29, 2019.

This event gathered professionals and spokespersons from the transportation agencies from three US states, the federal government and a territory, namely: Puerto Rico, Colorado, Washington, New Hampshire, FHWA Federal Lands Highway Division, and FHWA Puerto Rico and United States Virgin Islands Division Office.

This event was conceived as a technology transfer event through a collaborative effort between the PRHTA Soils Engineering Office (SEO), the Puerto Rico Local Technical Assistance Program (LTAP) Center, the Resource Center and the PR-USVI Division Office of FHWA.

SPECIAL RECOGNITIONS

The success of the **1st Geotechnical Asset Management Peer Exchange (GAMPE)** was possible due to the commitment of many professionals from PRHTA's Soils Engineering Office (SEO), technical resources from the Federal Highway Administration (FHWA), as well as the resources and experts from each of the DOT's that participated in the different stages associated with the planning of this Peer Exchange. All of them deserve special recognition in the preparation of this report.

Special thanks to Dr. Ricardo Romero, Chief of the SEO of the PRHTA, Eng. María Elena Arroyo and Eng. Cecilia Barbosa for the assistance in the planning and coordination of the Peer Exchange. The leadership of Eng. Migdalia Carrión representing Michael Avery, Associate Division Administrator from FHWA Puerto Rico Division, at the different stages of this Peer Exchange is very appreciated.

The outstanding technical presentations of the representatives of both PRHTA and state DOTs, as well as FHWA staff, namely, Eng. Jaime Lafuente, PRHTA Design Area Director; Eng. Daniel Alzamora, FHWA Resource Center; Eng. Miguel Pellot-Altieri, representing the DTPW Secretary; from the SEO, PRHTA Geologist, Geol. Darysabel Pérez; CDOT Geohazard Program Manager, Mr. Ty Ortiz; WSDOT Engineering Geologist, Marc Fish; NHDOT Engineering Geologist, Krystle Pelham; and FHWA Western Federal Lands Engineering Geologist, Douglas A. Anderson, are also acknowledged.

A special thanks to Mrs. Irmalí Franco Ramírez and Grisel Villarrubia Echevarría, administrative officials of the Puerto Rico LTAP Center, for providing the administrative support during the meeting, and Alexander Molano, graduate research assistant at UPRM, for the technical assistance during the Peer Exchange and in the preparation of the GAMPE proceedings.

DAY 1 – TUESDAY, AUGUST 27, 2019

GEOTECHNICAL ASSET MANAGEMENT PEER EXCHANGE WELCOME

The 1st Geotechnical Asset Management Peer Exchange (GAMPE) started with a welcome from **Dr. Ricardo Romero,** the **Chief of the PRHTA Soils Engineering Office.** This event represents the first occasion in which a peer exchange on this topic is celebrated by PRHTA in Puerto Rico, where geotechnical division representatives from state and federal highway agencies came together to share experiences, innovations, needs and best practices, such that all participants were driven forward in the enhancement of their core missions.

Figure 1: Dr. Ricardo Romero, PRHTA SEO Chief.

Dr. Romero explains the breakdown of the event, which started on Tuesday, August 27 with presentations from each delegation of representatives explaining their current situation with geotechnical practices and asset management. For the second day, Wednesday, August 28, a field trip consisting of five (5) technical site visits around the middle third of the Island was initially scheduled (Note: This field trip was suspended due to adverse weather conditions associated with the potential passage of tropical storm Dorian through the island). Finally, in the third day morning, Thursday, August 29, a field trip consisting of two (2) technical visits was carried out. In the afternoon of the third day, the different participants engaged in a panel discussion in which they debated and shared ideas about their respective prior experience with geotechnical asset management and potential paths and solutions to advance the respective programs.

GEOTECHNICAL ASSET MANAGEMENT PEER EXCHANGE AGENCY PRESENTATIONS, MORNING SESSION

Welcome from the Puerto Rico Highway and Transportation Authority

The first day's presentations started with remarks from **Eng. Jaime Lafuente, Director of the PRHTA Design Area.** He presented the agency's Transportation Asset Management Program (TAMP) overall situation *(1)*. At the time of his presentation, PRHTA had active progress in developing the federally mandated TAMP, consisting of bridges and pavements pertaining to National Highway System (NHS) facilities.

Figure 2: Eng. Jaime Lafuente, Director of the PRHTA Design Area representing the PRHTA Executive Director, welcoming the GAMPE participants to the first day of the peer exchange.

Initially, the Soils Engineering Office (SEO) became interested in Geotechnical Asset Management in 2014. The implementation of GAM has been accelerated due to the exceptional circumstances brought upon by the 2017 Atlantic Hurricane Season, when Puerto Rico was battered by hurricanes Irma and Maria, and whose intense rainfall caused widespread failure of geotechnical assets through the Island's highway network. These events spark a discussion on the management of the assets, specifically emphasizing the need of going beyond the immediate recovery following the extreme weather events, in which preventive maintenance would take on a more proactive role.

Eng. Lafuente frames this discussion in terms of the agency's mission, "to lead Puerto Rico towards an economic, safe and efficient transportation system," and the challenge posed by the geographic and geologic context of Puerto Rico, which consists of numerous soil and rock types heavily affected by extreme weather (hurricanes, flooding) and seismicity. Further influencing the context has been the progressive deterioration of PRHTA's infrastructure amid a financially constrained environment. Eng. Lafuente closes his first presentation by extending an invitation to share the respective experiences.

Welcome from the FHWA Puerto Rico and US Virgin Islands Division

The second introductory presentation and third appearance corresponded to the **Federal Highway Administration's Puerto Rico and U. S. Virgin Islands Division office (FHWA PR-USVI),** conducted by **Eng. Migdalia Carrión**, representing Michael Avery, the Associate Division Administrator. Eng. Carrión opens her presentation by congratulating the PRHTA Soils Engineering Office (SEO) for taking advantage of GAMPE as an opportunity for collaborative technology transfer and thus improvement of their assets and practices. She stated the main purpose of this event, namely encourage state and territory DOTs to bring forth innovative technologies and practices as part of a technology transfer initiative. Eng. Carrión closes her remarks with an acknowledgement to Eng. Daniel Alzamora, Eng. María Elena Arroyo, Dr. Ricardo Romero and Eng. Cecilia Barbosa, as well as to staff members at large from both PRHTA and FHWA PR-USVI staff.

Figure 3: Eng. Migdalia Carrión, representing Michael Avery, the Associate Division Administrator of FHWA PR-USVI.

FHWA Resource Center's Introduction to Geotechnical Asset Management

The third technical presentation was made by **Eng. Daniel Alzamora, Senior Geotechnical Engineer from the FHWA Resource Center's Geotechnical and Hydraulic Engineering Team.** Eng. Alzamora starts by explaining the Federal Lands Highway branch of FHWA, whose duty is to act as the DOT for military facilities, federally-owned lands from various agencies and for Tribal lands, and is divided into three regions: East, Central and West. As part of their duties, Federal Lands staff implements numerous designs and strategies on an experimental basis, and given the jurisdictions in which they operate, they have a wide variety of landscapes in which to deploy new strategies for geotechnical infrastructure and other assets, such as embankments, slopes, retaining walls, rocks and soils as construction materials, highway subgrades and tunnels.

Figure 4: Eng. Daniel Alzamora, Senior Geotechnical Engineer from the FHWA Resource Center.

Transportation Asset Management (TAM) gains traction through efforts conducted by FHWA and the American Association of State Highway and Transportation Officials (AASHTO) to standardize and encourage the adoption of this practice, with the approval of Moving Ahead for Progress in the 21st Century (MAP-21) and the Fixing America's Surface Transportation Act (FAST Act) as legislative milestones. A full implementation of TAM coordinates asset-related activities throughout their lifecycle, reduces costs to what is actually needed in accordance with well-defined priorities and objectives developed through engineering-based decision making and quality information. Thus, TAM activities occur during the planning, construction, operation, maintenance, upgrade and expansion of physical assets.

FHWA has established the development of the Transportation Asset Management Program (TAMP) as a requirement for State and Territory DOTs, encompassing at minimum the pavements and bridges of the National Highway System (NHS), while encouraging the incorporation of other asset classes to an extent commensurate with the resources the agency is willing to commit.

TAMPs must be:

- Policy-driven
- Performance-based
- Directed at reducing expenditures, damage to other highway assets and contribute to safety and economic activity of the DOT's jurisdiction
- Promote efficient use of DOT resources
- Efficient at prioritizing asset classes according to DOT needs and capabilities

As a starting point, DOTs can first inventory and Assess the condition of their assets. A TAMP can become difficult to implement due to barriers such as defining too many "important" elements, developing a plan which is too large to reasonably manage and allocate resources to, defining a plan whose needs and actions cannot be reasonably met with the agency's current resources, or a plan that fails to be policy-based and thus misses out on agency commitments like staff and resources.

Eng. Alzamora stated that Puerto Rico has done a great job in starting their TAMP, both due to what has been preliminarily submitted at the time of the peer exchange and the attitude of the agency towards it. This has been evidenced by a desire to improve agency practice, the initiative to share, collaborate and learn on a mutual basis from peer agencies, and an interest in reviewing relative condition ratings of their assets.

Eng. Alzamora emphasized the vital importance of maintenance and maintainability of assets. Any physical element which cannot be maintained will ultimately fail to fulfil its intended purpose. Of special concern is the relationship between erosion control and performance of drainage systems. Neglected maintenance associated to erosion control ultimately contributes to flooding in stormy conditions, as the geotechnical elements from which eroded soil particles originate contribute to the failure of the drainage system's ability to protect against flood conditions.

Closing his presentation, Eng. Alzamora extends an invitation to all the participating State and Territory DOTs to apply for additional funding through the FHWA Division office. This funding may be used to fund follow-up and continued progression of the peer exchange initiatives. The announcement was further emphasized by the context of the fiscal calendar of the federal government, whose annual cycle concludes by September.

PRHTA Organization & Infrastructure Overview

The fifth speaker was **Eng. Miguel Pellot-Altieri,** the **Special Assistant to the Secretary of the Department of Transportation and Public Works (DTPW) of Puerto Rico**, who explained the agency's organization and infrastructure overview. In Appendix E a detail description of PRHTA organizational infrastructure is presented.

Figure 5: Special Assistant to the Secretary of the DTPW, Eng. Miguel Pellot, presents an overview of PRHTA's history, organization and infrastructure overview.

In summary, as of 2019, the DTPW and its 1,400 employees administer 4,814 centerline miles of roads in Puerto Rico, of which 798 pertain to the National Highway System (NHS), 650 correspond to their primary road classification, 1,000 are secondary roads, 3,164 belong to the tertiary network and all of which include approximately 2,300 bridges.

At the time of the peer exchange, PRHTA was implementing an aggressive plan for the obligation of $155 million in funds allocated through the United States Department of Transportation, of which $135 million for FHWA-related projects and $20 million for FTA-related projects. These funds contribute to four key goals of the agency:

- Completion of their highway system
- Development of key improvements of the highway network
- Traffic Safety
- Congestion mitigation

Historically, PRHTA has been effective in using federal funds for these and previous objectives, but the more recent financially constrained environment has limited the agency's ability of using these funds as it has lacked the corresponding matching funds. To reverse this trend, PRHTA and FHWA established a Memorandum of Understanding (MOU) in February 29, 2016 *(2)*, whose objective is streamlining project delivery and revamping operations, such that their share of federally-allocated funds could be used more effectively. Among the MOU's priorities are:

- Improvement of federal-aid billing procedures,
- Validation of toll credit availability, compliance with FHWA guidance and modification of toll credit utilization
- Development of organizational capacity
- Expediting of project delivery

Attainment of financial and organizational objectives involve use of digital platforms. By July 30, 2019, attainment of the MOU tasks had reached a financial progress level of 67.0%, or $9.04 out of $13.5 million of the MOU budget, and a schedule progress level of 78.8%, or 1,247 out of 1,583 days, with an estimated completion date by June 30, 2020. Additionally, as part of the bankruptcy and financial re-structuring of the Government of Puerto Rico, PRHTA is also subject to the Puerto

Rico Oversight, Management and Economic Stability Act (PROMESA) (3), which has temporarily paralyzed debt service to undergo a restructuring of finances of the Island's government and of its public corporations.

Eng. Pellot closed his presentation by explaining the basics of the PRHTA TAMP. Among its core requirements, the TAMP must specify how PRHTA intends to meet federal pavement and bridge condition targets, demonstrate the adoption of performance-based and standardized asset management practices and the sustenance of highway conditions in the future. The generated document must be certifiable, set and directed to achieve NHS pavement and bridge condition targets and meeting these objectives within the time frame.

PRHTA Geotechnical Asset Management Program

The sixth speaker of the first day was **Geologist Darysabel Pérez** from the **PRHTA Soils Engineering Office (SEO),** who proceeded to explain the agency's geotechnical asset management efforts. Her presentation begins with an overview of the SEO and its history, followed by the geotechnical initiatives of the agency, the birth of the Puerto Rico Geotechnical Asset Management Plan (GAMP), its major tasks, the geographic and geologic context in which it is developed, the challenges posed by hurricanes Irma and Maria and achievements during the post-hurricane recovery period.

Figure 6: From the SEO, PRHTA Geologist Darysabel Pérez giving the PRHTA GAMP presentation.

"Without Geotechnical Asset Management, an agency simply embraces uncertainty, Geotechnical Asset Management Plans combat this attitude."

The SEO was established in 1975 and was originally divided into two sections: geotechnical and geologic, which have since been consolidated, and currently employs 10 staff members. Among its duties are geologic and geotechnical inspections during the design and construction stages of PRHTA highway projects by providing direct support to both the Design Area and Construction Area of the agency. It also provides technical recommendations to municipal governments lacking dedicated geotechnical staff.

Preceding the SEO, PRHTA has already been involved in various geotechnical asset management activities, beginning with the creation of a dedicated library for geotechnical reports, later upgraded to a database report catalog in Microsoft Access and a Rockfall Hazard Rating System (RHRS). Puerto Rico also established its own legal requirements concerning management of geotechnical assets, in the form of the Landslide Mitigation and Response Protocol established through Act 24 of 2008. This piece of legislation mandated the creation of an interagency committee to achieve the law's objectives, with both DTPW and PRHTA having a mandate for contribution of information for a landslide response protocol.

PRHTA then established a Geographic Information System (GIS) inventory for borehole test data and geotechnical reports in 2013, later receiving specific funding in FY 2014-15 as part of the State Planning and Research Program (SPR) and starting with NHS facilities. This inventory is administered internally through an ArcGIS Online website. In addition, the recovery experience following the 2017 Atlantic Hurricane Season involved frequent interaction with private contractors and different government agencies at the municipal, state and federal levels, which demonstrated one of the initially least-apparent challenges: differences in how each individual and organization describes and documents geotechnical assets and concepts in general. This prompted the development of the technical entitled *Guía para el Desarrollo de Base de Datos de Activos Geotécnicos para Puerto Rico* (Geotechnical Asset Database Development Guide for Puerto Rico) *(4)*. This document contributes to GAMP objective attainment by ensuring uniformity in the data collection process.

Geologist Pérez then proceeds to explain the GAMP, its goals, consequences and structure. As the overarching goal, the plan aspires to a lifecycle cost reduction in relation to unplanned repairs and reconstruction, punctuating the message by stating the following:

PRHTA's GAMP defines various dual classes of assets: physical/tangible versus non-physical/non-tangible, NHS-related versus non-NHS related, and structural versus non-structural. Of particular interest is the first pair of classes, whose tangible sub-division includes elements such as sinkholes, slopes, embankments, subgrades, tunnels, bridges, culverts and various kinds of retaining structures among the tangible assets, while the non-tangible includes data, equipment and knowledge.

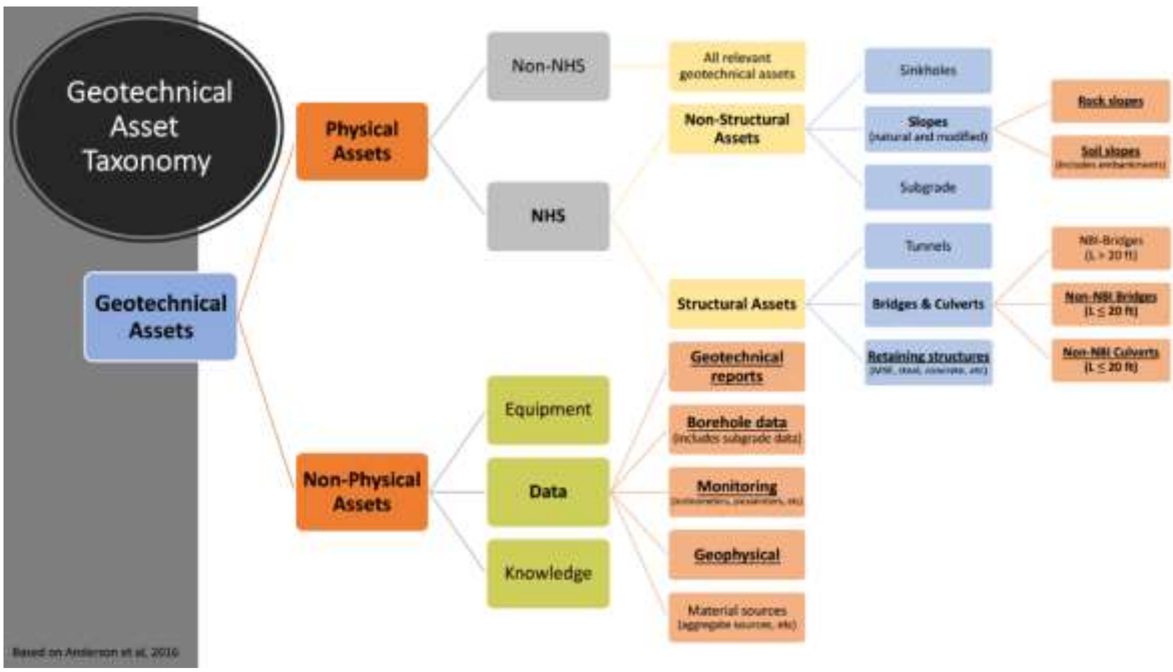

Figure 7: Taxonomy of geotechnical assets adopted by the PRHTA SEO. Source: PRHTA SEO.

As part of its priorities, the SEO defined three priority tasks for the development of the GAMP, all of which were approved by FHWA:

- **Task 621:** Development of an inventory of small bridges, culverts and retaining structures, including a rating system, data query and progress evaluation mechanism. Tools utilized for this task include *ArcGIS* software tools (*ArcGIS Online* and *ArcGIS Collector App),* rangefinders, and drones. Task 621, so far, has collected more than 1,000 structures at the time of the peer exchange.

- **Task 649:** Unification of documents, reports and databases into a single database with cross-linking capabilities, including digitalization of print records as PDF files. This task involves the digitalization, reorganization, clean-up and data migration from various sources and into the ArcGIS platform. The final database will include specific georeferenced sites with all its pertinent associated documents and tagged with key attributes for ease of content search.
- **Task 674:** Establishment of an Unstable Slope Management Program (USMP). In the first implementation of the GAMP, the USMP will apply to qualifying slopes located at or near NHS facilities. They qualify if they meet the following definitions:
  - Rock cuts and natural slopes above the roadway
  - Soil slopes, regardless of their location relative to the road surface (above or below) or origin (embankment, natural slopes, cut slopes)
  - Documentation of progress, not based on number of identified assets or size of assets, but instead by percent of inspected roadway length.

  Supporting this task are a literature research process, including the *Data Interchange for Geotechnical and Geoenvironmental Specialists* (DIGGS) *(5),* the *Rockfall Hazard Rating System (RHRS) Participants' Manual* (6), *NCHRP Research Report 903: Geotechnical Asset Management for Transportation Agencies* (7, 8), engagement in the ArcGIS licensing process and acquisition of inspection equipment required for the task. At the time of the exchange, the SEO was confronting the challenge on how to best apply the methodology to rock slopes, along with the overarching challenges associated to Puerto Rico's context: data gaps, geography, geology, topography and climate.

Figure 8: PRHTA SEO GIS-based Geotechnical Reports Inventory dashboard. Source: PRHTA SEO.

Geologist Pérez also presented an overview of the geographic and geologic context of Puerto Rico. The territory consists of a main island and several minor islands and cays situated atop a microplate along the tectonic boundary between the Caribbean and North American plates and just south of the Puerto Rico Trench. The island has a rugged topography, which, while not having summits above 1,338 meters or 4,389 feet above sea level, consists of numerous steep slopes. Elevation classes range from 55% of the land surface being less than 150 meters or 492 feet above sea level, 21% between 150 and 300 meters and 24% above 300 meters, while landforms consist of 25% coastal plains, 35% hilly terrain and 40% mountainous terrain. Its geologic history, combining accretion, volcanism, karst formations, faulting and humid tropical weathering have resulted in extremely diverse geology, even at a small scale, punctuated by deep river valleys, caverns, deep sediment beds at wetlands, two intricate fault zones and 3 volcanic provinces.

Further adding to the geologic setting is the incomplete and outdated geological information sources, among them:

- Several United States Geological Survey (USGS) topographic quadrangles in Puerto Rico still lack geological mapping, or at best have preliminary mapping. Gaps in these cases have been filled by graduate geology students from the University of Puerto Rico at

Mayagüez, who have developed full topographic quadrangle maps as thesis research projects.

- Outdated landslide susceptibility map, with ongoing efforts to update with the latest information and landslide history associated with hurricanes Irma and Maria, and further risks associated to future cyclonic systems.
- Existence of large bands of landslide prone formations separating the north and south halves of the Island, posing a critical challenge for the north-south aligned roadways.

Concerning hurricanes Irma and Maria in September 2017, rainfall dominated among the natural forces contributing to failure of geotechnical assets along Puerto Rico's highway network. First starting with hurricane Irma, whose closest passage relative to Puerto Rico occurred by September 6, 2017, was associated with intense rainfall of approximately 10 to 15 inches, triggering numerous landslides. Following two weeks later, hurricane Maria made landfall in the southeastern municipality of Humacao on the morning of September 20, 2019. NOAA estimated rainfall ranging from 6 to 38 inches during a 48-hour period associated to hurricane Maria, while the upper bound from NASA satellite estimates indicates rainfall of up to 46 inches during the same period. The extensive rain events from both major hurricanes contributed to a final count of 71,431 slope failure events in total and throughout the Island, inclusive of landslides, rock falls, mudslides, river erosion and storm surge.

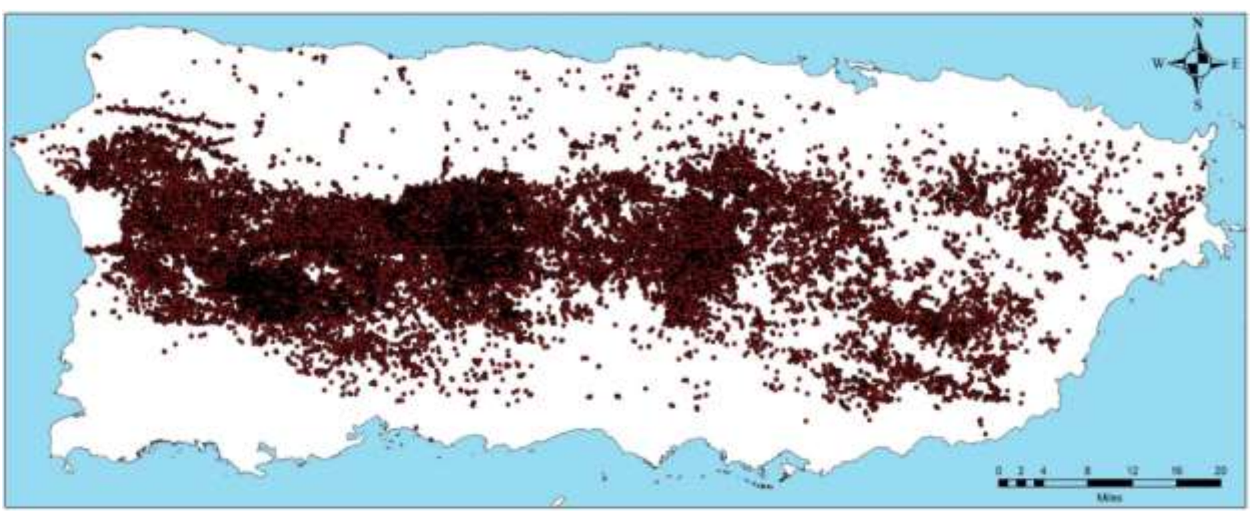

Figure 9: Map showing the location of approximately 71,000 landslides resulting from Hurricanes Irma and Maria in Puerto Rico. Source. SLIDES-PR https://sites.google.com/a/upr.edu/geology/research/slides-pr.

Recovery during the post-hurricane period presented a dual situation of challenge and opportunity. This period was challenging due to the competing priorities associated with the infrastructure recovery process, which demands a high commitment of agency resources and inter-agency collaboration in a physical and institutional environment that hinders communication, the pressure to submit documentation for the procurement of Emergency Relief (ER) funds and the lack of a standardized documentation to rate the numerous storm-induced landslides. At the same time, recovery projects surfaced all over the place on top of generating massive amounts of geotechnical information to provide a clearer picture of the damage and situation at-hand.

Geologist Pérez concluded her presentation with an update on the latest activities and resources available to PRHTA within geotechnical asset management. Most notably:

- FHWA Federal Lands organizing a webinar showcasing the Unstable Slope Management Program (USMP) and its associated application, and the publication of NCHRP Research Report 903, *Geotechnical Asset Management for Transportation Agencies, Volume 2: Implementation Manual*. This has presented a conflicting situation for the SEO, as it is now posed with the choice of either directly adopting the USMP mobile application or re-engineer the form utilized through ArcGIS Survey 1-2-3.
- FHWA Eastern Federal Lands has 400 active projects in Puerto Rico, which represent a significant opportunity for direct collaboration benefitting PRHTA in geotechnical asset management activities. Additionally, these projects also generate an abundance of geotechnical information, which can be incorporated into the geotechnical assets database. This point was brought forth in discussion by Daniel Alzamora (FHWA Resource Center) and Migdalia Carrión (FHWA PR-USVI).
- The author of this GAMPE proceeding, in the role as PR-LTAP Center Director and Civil Engineer, present concerns with respect on how locations with a history of recurrent landslide and geotechnical asset failure associated to extreme weather events are repaired to this original condition recognizing a potential future failure in the future in the same location. The LTAP Director asked to SEO officials which elements and methods were considered for landslide data collection by PRHTA in response to the 2017 hurricanes. Geologist Pérez responded by mentioning the use of Ohio DOT documents, which were later dropped due to being deemed too complicated. Geologist Pérez followed by outlining

the desired requirements of other methodologies the SOE would preferentially use, such that they are simple to fill in and consider factors such as history, of the slope, probability of inflicting damage (i.e. obstruction, damage to asset and harm to road users, etc.) and facility characteristics related to the landslide's potential impacts (i.e. dimensions, ADT, etc.).

Colorado Department of Transportation Geohazards Management

After the mid-morning break, **Ty Ortiz, Manager of the Colorado DOT Geohazards program,** begun the sixth presentation of the day, ***Colorado Department of Transportation Geohazards Management.*** He starts by providing an introduction of the geographic and geologic context of Colorado. The State of Colorado sits at the boundary between three major geographic regions of the contiguous United States: the Great Plains to the east, the Rocky Mountains along the Continental Divide, with 54 peaks exceeding 14,000 feet and 600 peaks exceeding 13,000 feet, and the Western Basins. Geology plays a major role in the State's history, particularly with the initial economic boom associated to gold mining since 1858. The state's particular situation provides three major geologic contexts, which are especially important at a national scale due to the crossing of two principal Interstate highways: I-25, traversing from north to south, and I-70, one of the major east-west corridors of the Nation.

Figure 10: CDOT Geohazards Program Manager Ty Ortiz explains the geologic context of the State of Colorado.

Geology in the state can be characterized along the aforementioned three general areas. The Great Plains consist of a fertile prairie dominated by sedimentary deposits originating in the Continental Divide. Over millennia, these sediments have built up into deep alluvial soils thousands of feet deep, contributing to pervasive soil swelling and heaving issues, which represents the most common and costly geologic hazard faced in the United States. The Rocky Mountains and Continental Divide area is dominated by tall and steep mountains, which are especially prone to both soil mass movements (rockslides, landslides, mudflows, debris flows) and snow-related issues (avalanches and ice heaving), and additionally this area also faces flooding along the mountain valleys. The western plateau and basin zone has numerous rock fall events associated to sandstone and shale formations, and has both collapsible and swelling soils. Contrasting with Puerto Rico, Colorado does not possess karst geology but still experiences sinkhole formation, these instead originate in relation to underground mining activities.

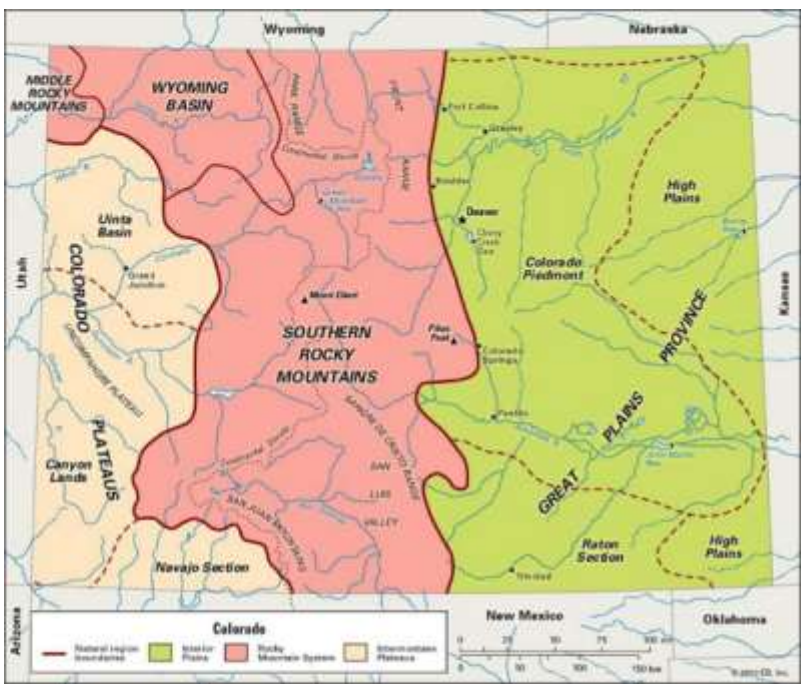

Figure 11: Physiographic provinces of the State of Colorado. Source: EB, Inc, CDOT.

Mr. Ortiz then changes focus to explaining his agency, the Colorado Department of Transportation (CDOT). CDOT is a government agency encompassing 5 districts, 3,000 employees, an annual

VMT of 28 billion, an annual budget of $2.1 billion for all of the state's transportation modes and servicing a population of 5 million inhabitants, of which 3 million are concentrated around the Denver metropolitan area. Some notable CDOT infrastructure assets include 3,451 bridges, 35 mountain passes and the oversight of 278 out of 522 avalanche paths of this state. Transportation, and in particular freight, represent a very large portion of Colorado's economy, moving $341 billion worth of goods per year, equivalent to an annual 75 tons per capita and representing up to a third of economic activity, both directly and indirectly. Due to this high reliance on transportation for its economy, congestion represents a major challenge, where 1 hour of congestion affecting I-70 represents a $1 million loss to the state's economy. In relation to geotechnical challenges, I-70 suffers periodic closures along Glenwood Canyon associated to rock falls and rock slides interrupting traffic.

CDOT actively engages in a robust Asset Management Program, encompassing 12 asset classes with an annual budget of $764 million per year. Geological hazards were first incorporated in 2014 as a dedicated asset class. It boasts a dedicated budget of $10 million and defined separately to other geotechnical assets classes, such as tunnels, culverts and walls. In this program, a wide variety of assets is included: 5,990 culverts with an inner diameter of 48 inches or more, 20 tunnels, 3,225 retaining walls and 3,437 geohazard segments of interest; all of which are of interest for cross-asset optimization goals. The program addresses issues such as landslides, rock falls, rock slides and embankment distress issues. Not included are snow avalanches, which currently are addressed through maintenance, but in which CDOT has interest in addressing in the Geological Hazards asset class.

CDOT measures performance by monetizing risks, defining intervention thresholds for hazard prioritization, and conducts corridor-level evaluations to identify relevant geohazards which are then rated, monetized and subject to a comprehensive risk reduction. Risk monetization is expressed with the following equation:

$$Annual\ cost\ to\ transportation\ system = Likelihood\ \times \begin{bmatrix} Safety\ consequence, \$ \\ Mobility\ consequence, \$ \\ Maintenance\ consequence, \$ \end{bmatrix}$$

CDOT also defines mobility through the state as an abstract asset, which itself derives from the physical and functional condition of tangible assets. This mobility is threatened by geohazards, which have been considered as a priority along 42 corridors. Their selection was done with a mathematical procedure, in which they are ranked by the average risk a corridor experiences from all the sites and segments it contains. The Geohazards Program has faced the challenge of securing DOT leadership support for the definition of these corridors, as the Program is still in the process of defining actionable performance metrics to substantiate its importance.

The agency has also adopted the latest technology for geohazard reconnaissance and mitigation, in particular LiDAR and photogrammetry systems deployed through Unmanned Aerial Vehicles (UAVs) and land-based systems. These allow for detailed monitoring of mass movements, in which changes are detected between consecutive geomorphologic maps of formations of interest. Small changes of a portion of a slope relative to the main feature thus act to precisely delineate landslide and rock fall blocks.

Figure 12: CDOT makes use of Unmanned Aerial Systems (UAS) as a way to collect terrain data for its Geohazards program. Source: CDOT.

Mr. Ortiz then presents two case studies based on photogrammetry: US-160 along La Veta pass and I-70 along DeBeque Canyon. In these sites, ground-based photogrammetry (US-160) and LiDAR (I-70) was utilized to monitor slopes with exposed soil and rock. A comparison between consecutive months was conducted using software analysis to identify the degree of change of the corresponding point clouds for each slope. In this manner, creep and other gradual movements of major soil and rock blocks can be identified, and further calibrated with ground-based instrumentation (i.e. inclinometers, groundwater monitoring wells). Additional monitoring capabilities can be derived from the use of wavelengths beyond the visible light spectrum. These wavelengths can allow, for instance, the identification of water seepage as a less apparent contributing factor when using infrared imaging.

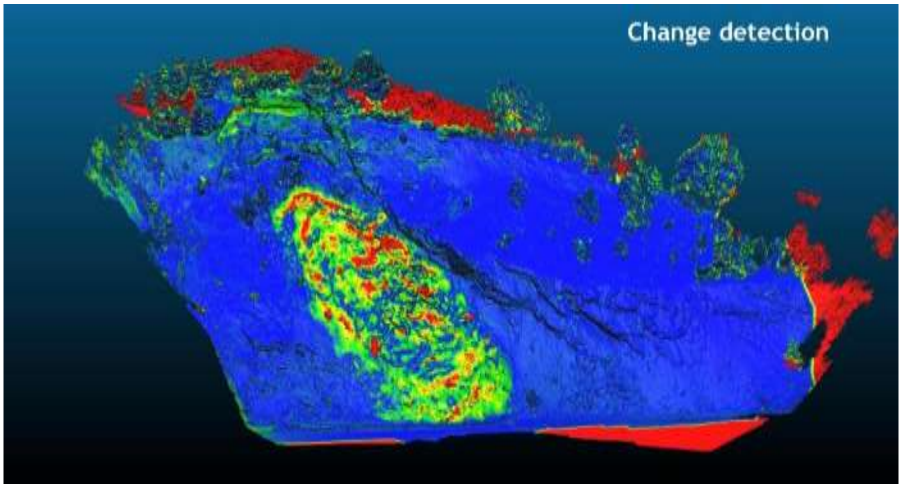

Figure 13: Change detection analysis using ground-based photogrammetry at US-190 at La Veta Pass. Source: CDOT.

Mr. Ortiz follows up by talking about how the Geohazards Program will address the challenge of DOT leadership support in order to increase the effectiveness of the GAM activities at CDOT. For this purpose, the Geohazards Program has undertaken the updating of performance metrics. Priority aspects of the update are the incorporation of the effects of mitigation elements, their deterioration, maintenance costs, data analysis methods to more accurately ascertain likelihood of geohazard events, and the effects of extreme weather. Their data analysis has identified three major variables associated to extreme weather influencing geohazards: temperature extremes, precipitation (rain, snow) events and occurrence of fires. Temperature extremes are associated with thermal stresses affecting rock formations, in the form of drought, wildfires (not applicable to Puerto Rico, but mentioned in his presentation includes freeze-thaw cycling, onset of snowmelt), and heat waves, which ultimately induce rock falls and rock slides. Precipitation extremes are associated with storms and flash flooding, which induce debris flows, mudslides and shallow landslides.

The CDOT presentation finishes with a discussion on the concept of resilience and how it is being implemented into the DOT's asset management practices. Mr. Ortiz introduces the topic with the definition of resilience adopted by Colorado in the *Update Colorado Disaster Emergency Act (9):*

> *"The ability of communities to rebound, positively adapt to, or thrive amidst changing conditions or challenges, including human-caused and natural disasters, and to maintain quality of life, healthy growth, durable systems, economic vitality, and conservation of resources for present and future generations."*

This definition broadens the concept to ultimately reach the well-being of the population, and applies the concept beyond the traffic elements immediately pertinent to DOTs.

Resilience is assessed through the four Rs of resilience:

- Resourcefulness: measured as county and community response, associated to criticality model
- Redundancy: measured as the availability of alternative roadways in the network, associated to criticality model
- Robustness: measured by asset or network vulnerability, associated to risk model
- Rapidity: measured as the potential closure days due to a disruption event, associated to risk model

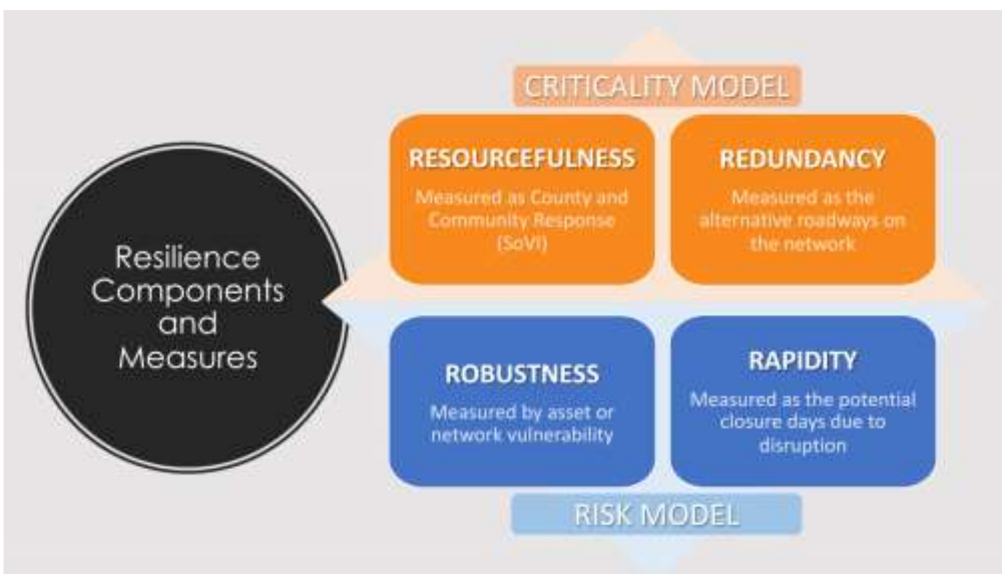

Figure 14: CDOT Resilience Components and Measures for geotechnical asset management. Source: CDOT.

Out of these factors, the CDOT GAM developed a corridor resilience level evaluation in 1-mile roadway segments, which were rated using a Level of Resilience (LOR) Index related to Total Annual Risk. This index was divided into five levels, labeled with letters from A to E and in which A corresponds to a very high resilience and E corresponds to a very low resilience.

Mr. Ortiz concluded his technical presentation with an example originating in Taiwan, showcasing a mountain freeway in which the roadway elements were in good condition, but which could not operate due to a large landslide obstructing the full width of the freeway. Mr. Ortiz used it as a way to emphasize how the lack of proper geotechnical asset management can result in the full negation of the state of good repair and functionality of the other roadway elements.

GEOTECHNICAL ASSET MANAGEMENT PEER EXCHANGE AGENCY PRESENTATIONS, AFTERNOON SESSION

Washington State DOT Geology, Organizational Structure and GAM Efforts

The afternoon session begins with the seventh presentation, given by **Marc Fish, the Assistant Chief Engineering Geologist of the Washington State Department of Transportation (WSDOT).** Engineering Geologist Fish begins his technical presentation by providing an overview of the geology of Washington State, explaining it along the nine (9) physiographic provinces forming the state's landmass. The landscape of Washington State derives from various geological and climatic forces, including a subduction zone, volcanism, earthquakes, glaciation, alpine mountains, an extreme contrast of precipitation between the coast and the interior, and riverine environments. The nine physiographic provinces are listed below and further detailed in the presentation *Washington State: 9 Physiographic Provinces* included in Appendix E:

- The Okanagan
- North Cascades
- South Cascades
- The Olympics
- Willipa Hills
- Columbia Basin
- Blue Mountains
- Puget Lowland
- Portland Basin

The second part of his presentation was titled *WSDOT Organizational Structure & What We Do.* He starts by describing his agency, headquartered in the capital city of Olympia and administering transportation infrastructure in six regions of the state: Northwest, North-central, East, Southwest, South-central and Olympic Peninsula. WSDOT's Geotechnical Office provides services to all regions, needing up to 5 to 6 hours to reach most locations in the state, and up to 3 days when reaching the most remote parts of the distant areas. Their staff includes 11 engineers, 10 geologists and 16 drillers divided into five crews, and is directed by the State Geotechnical Engineer, a position distinct from that of the State Geologist. Among the staff duties, geotechnical engineers specialize in project management and foundations of structures (bridges, retaining walls), while engineering geologists manage projects related to linear earthworks (cuts, fills, trenches) and slope stability issues (slope ratings, mitigation designs and project management).

Figure 15: WSDOT Engineering Geologist Marc Fish explains the agency's unstable slope management program.

WSDOT has a general annual budget of $2 billion and oversees 75,000 lane-miles of roadway, covering a land area roughly equivalent to the State of Colorado, but with twice the population. As part of its activities, WSDOT applies various geologic and geotechnical designs to address issues related to the slopes and cliffs found throughout the state, with conceptual designs incorporated into 10-year Surface Transportation Plan (STP). These include rock blasting, rock fall nets, rock fall fences, debris flow fences, rock bolts and dowels, horizontal drainage systems, shear keys, slope benching, shear-key shaft drilling, shotcrete and slope scaling (removal of loose rock pieces).

Engineering Geologist Fish now explains the geotechnical asset management activities conducted by WSDOT. Prior to the ongoing development of its first GAMP, the agency had 30 years of other separate activities, more specifically unstable slope management conducted since the 1990s. This process addresses rock slides, landslides, embankment settlement and rock falls, which are inspected, rated, and prioritized, but were not administered through a comprehensive asset management process. WSDOT then opted to modernize the process, from an institutional perspective this formally starts with the drafting of their GAMP in early 2019, which will be then incorporated to the DOT's TAMP. Meanwhile, from a tool perspective, the plan calls for the use of devices such as drones/UAVs, ground and aerial LiDAR, tablet-based data entry and data management through ArcGIS Online, web browser data entry, and sequel server databases.

WSDOT's Geotechnical Asset Management Plan (GAMP) consists of nine chapters, as follows:

1. Introduction
2. Objectives and Measures
3. Inventory and Condition
4. Lifecycle Planning
5. Risk Management
6. Revenue and Financials
7. Performance Scenarios
8. Investment Strategies
9. Implementation and Systems

The plan's primary objective is sustaining a *state of good repair and low risk*. WSDOT has to contend with 3,038 active known unstable slopes, and administers 188 constructed geotechnical assets. These include two types of slope protection systems, rock fall fences and horizontal drains in soil. These systems are used in ongoing mitigation activities, as the agency recognizes that these fixes do not last forever and require maintenance and periodic replacement to maintain their effectiveness.

Geotechnical mitigation activities encompass a history of 133 sites containing geotechnical assets, with a cumulative investment of $176 million. Out of this sum, $68 million has been invested in rock slopes, $90 million in soil slopes and $18 million in slope scaling for risk reduction. The GAMP also defines performance measures and targets for asset condition. The 2025 goal is to have at least 85% of constructed geotechnical assets classified at fair or better condition, currently standing at 88%, while keeping assets in poor condition below 5%, which still stand at 12%. The plan also seeks a balance between the costs associated with remediating the different types of geotechnical assets in the plan.

WSDOT also developed its Unstable Slope Rating form, a document used to evaluate and prioritize slopes for geotechnical interventions. The form contains ten items, including the slope characteristics, mass movement characteristics, traffic characteristics, history of problems and maintenance costs. Each item is rated from 1 to 5 in terms of likelihood and consequences associated to the slope's instability, potential impacts to traffic and asset condition, which are then combined into a risk-based matrix. The total score applicable to each slope is added up and compared to various condition assessment thresholds. Elements rating below 250 are classified as "good", from 250 to 299 classifies as "fair" and from 300 onwards classify as "poor". In addition, the four main types of constructed geotechnical assets are classified according to their operational status and maintenance needs, with elements working well and in no need of maintenance actions classified as "good", those needing minor maintenance as "fair", while those needing major maintenance, reconstruction and/or not functioning as designed are rated "poor".

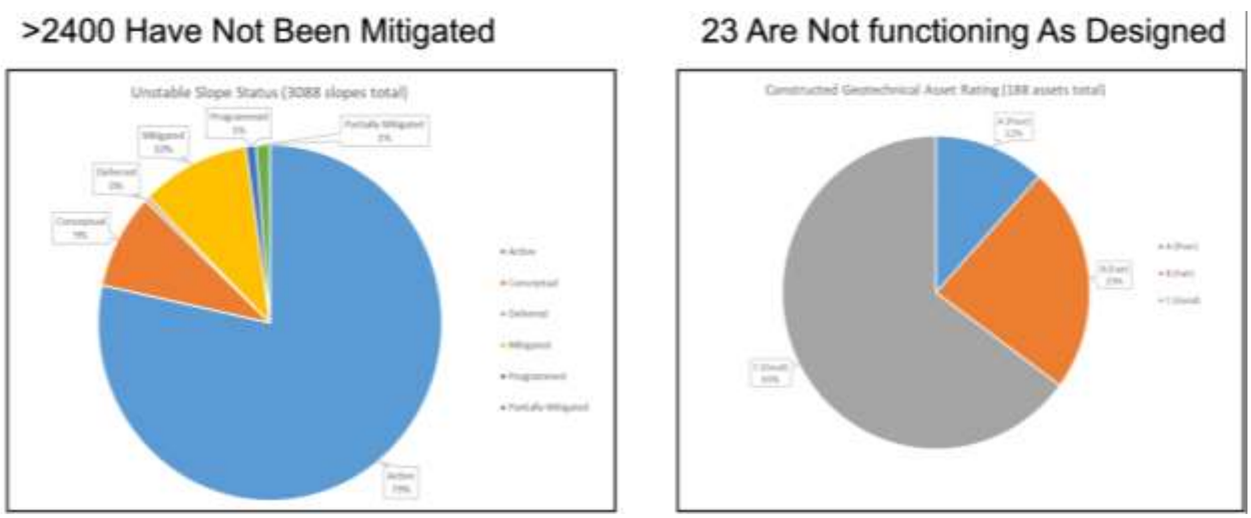

Figure 16: Mitigation status and condition of WSDOT geotechnical assets. Source: WSDOT.

At the time of the peer exchange, only 10% out of 3,088 unstable slopes have been fully mitigated, while 23 out of the 188 constructed geotechnical assets are not functioning as intended. The agency has mitigation progress on 297 slopes. Out of the 297 slopes, mitigation progress includes 32% of those rated as "poor", 13% as "fair" and 5% as "good". When looking at a historic perspective of the identified unstable slopes along WSDOT's highway network, the highest concentration is in those with ages from 76 to 100 years, and chiefly dominated by rock fall and erosion issues. As for the geotechnical assets, their historic record spans approximately the 30 years during which the Unstable Slope Management Program has been in place. The bulk of these assets consist of type 1 netting, whose age most typically ranges from 6 to 10 years and 20 or more years of age.

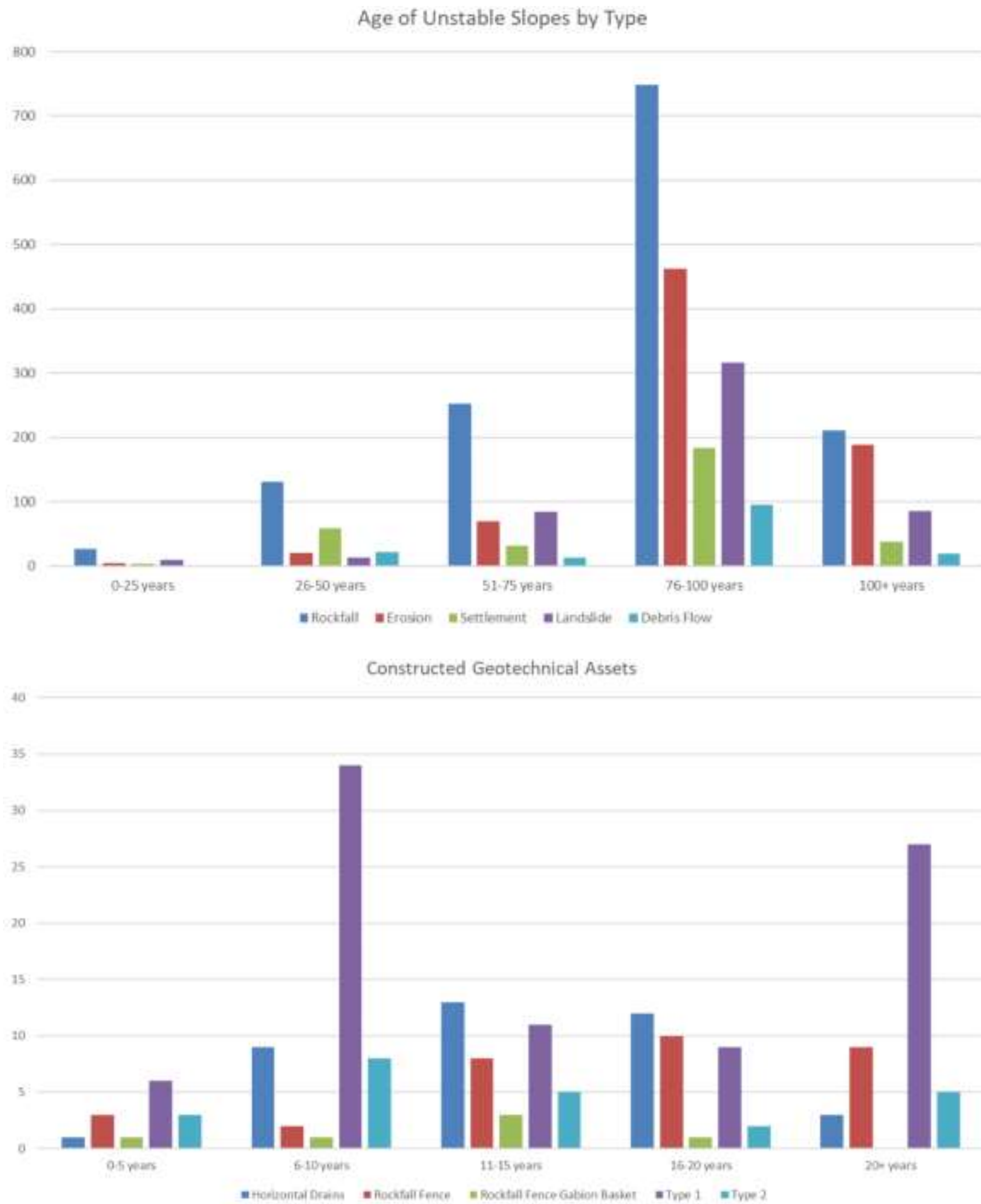

Figure 17: Number and age of WSDOT unstable slopes (top) and constructed geotechnical assets (bottom). Source: WSDOT.

In the process of assessing unstable slope condition, the plan assumes trends based on the general deterioration process. Slopes in good condition currently represent 75% of the 3,088 identified and their number trends downward, those in fair condition represent 10% and their number trends upward, while the poor slopes represent 15% of the total and their trend is upward. Among geotechnical assets, those in good condition represent 65% of the 188 total, those in fair condition represent 23% and those in poor condition represent 12%. Their trends are the same as those of slopes in the same condition categories.

- Slopes in **good condition** are characterized by possessing good catchment areas for the loose material, produce small-sized particles and/or low soil/rock/debris volumes, with a low failure frequency. They require no remediation actions and only need routine maintenance, whose annual cost does not exceed $5,000.
- Slopes in **fair condition** tend to experience larger failures, albeit still infrequently and without causing major damage to the roadway. Typical interventions do not require remediation, but do require cleaning of debris and occasional specialized maintenance, which exceed an annual cost of $5,000.
- Slopes in **poor condition** experience large magnitude mass movements which damage the highway structure and displace road furniture. They require remediation actions and major maintenance, requiring an annual maintenance cost exceeding $10,000, while remediation action cost ranges from $100,000 to several million dollars.

WSDOT's GAMP also incorporates a list of remediation actions, which include the maintenance strategy, work type, life extension, average cost, unit construction cost and unit Equivalent Uniform Annual Cost (EUAC). Among the notable highlights of the agency's experience:

- Soil slope repairs are twice as costly on average versus rock slopes of comparable size
- Among constructed geotechnical assets, gabion nets experience corrosion and destabilization issues following drainage ditch clean-up activities

When WSDOT prioritizes projects, it first considers the rating and risk assessment of the slopes of interest, ADT and a full benefit-cost analysis, which itself incorporates 20 years of maintenance and associated delay costs to the project costs. Other criteria considered include risk reduction scaling, regional needs (staff, environment, population, and economics) and mitigation activity costs. Historically, the agency has spent $20 million of state and federal funds each year on geotechnical assets, mainly through emergency response. Out of these funds, $6 million are used for maintenance, typically in the form of clean-up of debris from highways, but not from ditches.

The GAMP's 10-year STP requires $112 million compared to $82 million used in planned preservation spending. This does not account for 496 unstable slopes that could still be prioritized, which represents an additional $750 million worth of unfunded capital needs. To account for the unfunded capital needs and the 10-year STP funding, approximately $27 million must be spent annually over 30 years. In addition, WSDOT must also continue to scale rock slopes, maintain its constructed geotechnical assets, and balance the projects types between 30% rock slopes, 30% soil slopes, 25% risk reduction scaling, and 15% constructed geotechnical assets. This project balancing and additional work is estimated to be another $18 million annually, for a total of $45 million of annual GAM needs over a 30-year period.

In addition to funding, WSDOT also needs additional staff, to raise the equivalent available employee-hours from 2.2 full-time employees (FTE) to 4.5, in order to accomplish:

- 775 inspections of unstable slopes and constructed geotechnical assets each year
- Conceptual designs
- Benefit-cost analysis
- Program enhancements, chiefly involving information technology.

Closing the discussion, the following topics were shared between the speaker and the audience:

- Use of GIS-based analysis to correlate asset performance with conditions of its context
- The challenge of distinguishing deterioration from failure, along with the development of deterioration models.
- Three different challenges affect the same program: vegetation, data storage and staffing.
- Dual purpose tools: plowing vehicles are also used to clean-up debris during the summer period, in addition to snow removal during the winter.
- Inspection capabilities are insufficient to deal with the amount of slopes in the WSDOT highway network, with much of the information reaching the Geotechnical Office through communication with other DOT staff members, or occasionally through news reports informing of landslides before DOT staff even becomes aware of the particular event. Communications with maintenance staff of the different WSDOT regions helps

disseminate information on unstable slopes more quickly and thus accelerate responses, ultimately improving safety.

New Hampshire Department of Transportation Organization, Infrastructure Overview and Geohazards Management

The eighth presentation of the day was given by **Krystle Pelham, an engineering geologist from the New Hampshire Department of Transportation (NHDOT).** Engineering Geologist Pelham opens her presentation by explaining NHDOT's organization. This DOT guides its actions in accordance to its mission and purpose statements:

- **Mission:** Transportation excellence enhancing the quality of life in New Hampshire.
- **Purpose:** Transportation excellence in New Hampshire is fundamental to the state's economic development. The Department is charged with providing safe travel options for people and goods and to provide a system that is well maintained, efficient, and reliable.

NHDOT is headed by a Commissioner, Deputy Commissioner, and the Assistant Commissioner and Chief Engineer, and is divided into five divisions: project development, operations, finance, policy and administration, and the Aeronautics, Rail and Transit division. The Asset Management Office responds directly to the Commissioner and is given a higher hierarchy than the DOT groups.

Figure 18: NHDOT Engineering Geologist Krystle Pelham explains how the organization of her agency represents a challenge for the successful implementation of geotechnical asset management.

As part of its responsibilities, the DOT has 1,643 permanent employees, operates with a budget of $668 million as of FY 2018, sourced from federal funds (33%), State Highway Fund (30%), turnpike/toll revenues (17%), general funds (7%) and capital (3%). Out of this budget, $406 million are used for construction and aid to municipal infrastructure, while $262 million correspond to operating costs. The main infrastructure elements of associated with New Hampshire are summarized below:

- 4,600 Center Line (CL)-miles of roadway
- 100,000 highway signs
- 75 million feet of striping
- 440 signalized intersections
- 203 miles of active state-owned rail lines
- 25 public airports and landing strips, of which 12 of these eligible for federal funding
- 12 local public transit systems
- 89 miles of turnpike (toll freeway)
- 2,161 state bridges and 1,688 municipal bridges

Geologic and geotechnical projects are created through the Project Development, but struggle to maintain a consistent funding level. Like other NHDOT projects, these undergo planning, engineering design and construction, with projects scheduled as part of 10-year transportation plans through 2-year update cycles. The bulk of geotechnical program investments derives from the $22.4 million betterment program.

Geotechnical activities form part of the Bureau of Materials and Research, a department consisting of 22 full-time positions including administration, the Geotechnical section, Materials Technology, Pavement Management and Research. Geotechnical staff totals 15, including 3 geologists and 5 geotechnical engineers. Among the activities conducted through this section are:

- Subsurface exploration, including exploration logs
- Geotechnical evaluations and treatment developments for all DOT-owned structures: roadways, slopes, fills, bridges, walls, drainage structures, sound barriers, small buildings, among others.

- Provision of geotechnical reports summarizing evaluations and treatment recommendations
- Conduct geological evaluations of bedrock and maintaining a rock cut inventory.

Engineering Geologist Pelham now proceeds to explain NHDOT's Geotechnical Asset Management Efforts. The guiding document is the Strategic Plan for Asset Management *(10)*, which involves five major focus areas: inventory, performance, policy & records, data & systems, and work order. These are all administered and executed through the Commissioners and the Asset Management Program Section (AMPS). The outcome from this plan is the development of policies, analyses, establishment of statewide system performance targets, integrated asset condition information and statewide coordinated work plans.

Unlike other state DOTs, NHDOT took the initiative of expanding asset management beyond pavements and bridges early on. Geotechnical assets in particular were additional steps ahead due to extensive and detailed efforts from the Geotechnical section at the time when federal policy first started endorsing asset management for bridges and pavements. This, process, however, has not been free from its own obstacles. Firstly, geotechnical data collection has been less effective due to the more limited interactions between the Geotechnical section and the Data and Systems work group, and thus having less of a say in how the asset databases are made. Secondly, NHDOT's budget operates in a centralized manner, which limits opportunities for specific fund allocations for the different asset types in a programmatic manner.

One audience member asked about the possibility of harmonizing pavement management databases with geotechnical asset management databases, owing to similar engineering properties of soils and rocks when compared to pavements. Another member inquired on how to increase data sharing between activities for optimized project integration.

NHDOT Asset inventories encompass 60 types of assets, distributed between sub-groups, classes and sub-classes. In addition to properties specifically defining each asset type, they also include properties related to their mobility impacts, safety impacts and replacement values. Due to the centralized workings of the DOT, geotechnical assets tend to get attention as one element of large prioritized projects. Further complicating the process, pavements and bridges consume more than 40% of the municipal aid and construction funds, and also enjoy well-established national data standards, while geotech still lags behind in these aspects. They face the challenge of inconsistent terminology and evaluation metrics, which, if harmonized, would contribute to clarity, transparency and objective appraisal.

The federal legal framework brought policy changes, first through MAP-21 and then through the FAST Act. These established major performance frameworks like the Highway Safety Improvement Program (HSIP), the National Highway Performance Program (NHPP) and the National Transit Database (NTD). Joining these are Transportation Asset Management Programs, which further include risk management plans and investment strategies. Underlying all is the quest for prioritization of transparency, such that quality data, standardization of practices and public availability of information encourage outcomes such as effective and accountable decision-making, and support of community values.

Geologist Pérez brings to the attention of the speaker the pertinent specific experience of PRHTA in relation to the post-hurricane recovery. Due to the massive activation of recovery projects, a plethora of geotechnical data was becoming available, representing an opportunity to form a more complete and up-to-date geotechnical asset database, albeit with a limitation on it not being in a digital format given the collapse and slow recovery of electricity and telecommunication services.

Engineering Geologist Pelham now focuses on the specifics about the technical aspects of geotechnical asset management. The major asset classes they document include embankments, rock and soil slopes, retaining walls and constructed subgrades within rights-of-way. Out of these, retaining walls are not administered through the geotechnical division, but instead by the bridge division, whereas constructed subgrades are administered by dedicated embankment staff. All of these assets have *ad-hoc* inventories.

NHDOT’s geotechnical asset management history dates back to the 1970s, with the completion of the first rock slope hazard survey in 1975 *(11).* This survey was later updated and enhanced in 1983 with the FHWA Rock Slopes Manual *(12).* These surveys were gradually modernized, with the greatest prior instance being a research project funded by the FHWA’s State Planning and Research Program (SPR), and whose report was published in 2002. Following this was the development of a GIS database for rock slopes. GIS tools like these have aided the DOT in conducting geotechnical asset management with more efficiency and lower staff demands, while any field work that cannot be conducted effectively by the Geotechnical Section is contracted out.

Slope management conducted by NHDOT primarily investigates threats characteristic of the state’s geography: ice falls, rock falls and rock slides. These slopes are rated and grouped into three categories: A-rated slopes requiring annual inspections, B-rated slopes requiring inspections every 3 years, and C-rated slopes requiring inspections every 5 years. When deciding which slopes to intervene, NHDOT bundles slopes with relatively high hazard ratings with projects programmed for the particular location, these are paid for with funds from the ten-year plans and the betterment funds of the DOT.

Technological innovations for geotechnical data collection mainly rely on 3D models derived from photogrammetry, which are used to define rockfall ditch area catchments and monitor hazardous unstable slopes. Their deployment is conducted with State Transportation Improvement Council (STIC) funds, which provided a grant for the use of ground-based cameras and survey of ground control points for the development of georeferenced point clouds derived from photogrammetry and structure from motion, and analyzed using the *RocFall* software, and later expanded under the fifth round of *Every Day Counts (EDC-5)* innovations. One less conventional strategy used by NHDOT is a software-based analysis method called *SmartRock*, in which the 3D models of the slopes are subject to virtual rock falls to examine potential behavior, and the results are calibrated by making instrumented rocks slide down the rock slope of interest. This method allows for right-sizing of right-of-way dimensions, avoiding overly conservative estimates.

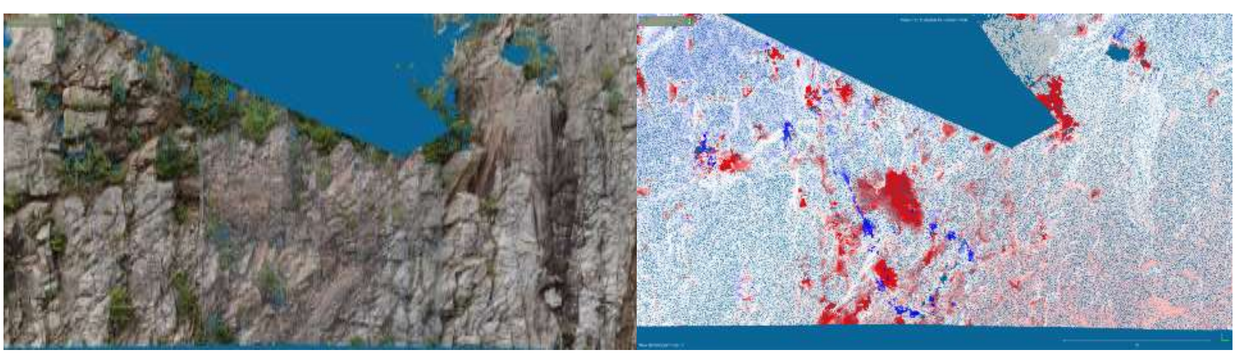

Figure 19: Change detection mapping using photogrammetry-based rock slope model. Source: NHDOT.

Among the challenges faced in this process was the visual obstacle represented by vegetation. This is less so of a problem in more hazardous slopes with active soil and rock movements, as this results in exposed soil masses, but it is more of a problem in less hazardous slopes, where more limited soil and rock movement allows for denser vegetation growth. Thankfully, given the highly seasonal climate of the state, lower hazard slopes can be investigated more effectively during autumn, as foliage falls off trees and shrubs, exposing the soil below. With this strategy, NHDOT was able to examine 20 slopes with the aforementioned methods during the autumn of the first year. An additional problem confronted was that of data storage, as photogrammetry generates very large files and thus have large data storage demands.

NHDOT also contended with a significant instance of tropical storm damage related to tropical storm Irene in 2011. Due to this weather event, the state confronted $35 million worth of damages, of which $9 million corresponded to NHDOT assets, distributed among 6 facilities, including flooding, slope and bridge failures. At the time, the agency lacked dedicated staff to document the resulting damages, which prompted the creation of dedicated DOT group for this task.

Concluding her intervention, audience members Daniel Alzamora and Marc Fish used the questions section to a comment on the possibility of including geophysical exploration data. With the growing ability of digitally organizing data, having the more detailed data available with borehole inventories and 3D models of slopes can provide a more complete picture. Data from the geophysical investigation does not have to be stored in the original analysis files, but rather their analysis output in a more compatible format for convenient access.

Federal Lands Highway Unstable Slope Management Program and Tools

The last presentation of the first day was given by **Douglas A. Anderson, Engineering Geologist of the FHWA Western Federal Lands (WFL) Division**. Before his official start, he takes the opportunity to express amazement and congratulate PRHTA by saying “Puerto Rico has done GAMP activities over the last 3 years that would have taken most State DOTs 20 years to do,” recalling his past geotechnical asset management experience in other agencies throughout his career.

Figure 20: FHWA WFL Engineering Geologist Douglas A. Anderson explains the organization of his agency, its Unstable Slope Management Program and associated software tools.

The speaker then formally starts by explaining what FHWA Federal Lands Highways (FLH) Division in general, and WFL in particular, and what they do. Unlike most of FHWA, Federal Lands acts as the federal civil design consultant of choice for the infrastructure for the DOT, for the Department of Defense, Native American Tribal Lands and the numerous Federal Land Management Agencies (FLMA's), which together represent approximately 30% of the land in the United States. Additionally, Federal Lands will also assist Federal Highway partners in providing assistance to states and territories in critical scenarios, such as might be the case when confronting major natural disasters. To meet its obligations, the agency has a 700-member strong staff and is divided into three regional divisions, distributed by the amount of total land area owned by the federal agencies located within each:

- **Eastern:** covers the states and territories adjacent and east of the Mississippi River, headquartered in Sterling, VA.
- **Central:** covers the states and territories of the Great Plains, the Southwest and the Pacific, headquartered in Lakewood, CO.
- **Western:** covers the Pacific Northwest states and Alaska, headquartered in Vancouver, WA.

This agency provides cradle to grave services to federal land owner partners that encompasses scoping, design, construction, inspections, operation, maintenance and rehabilitation. Many of the road of FLH partners have low traffic volumes, but due to the variety of environments and land uses it handles, Federal Lands has its own design and construction offices, equipment, design details, specifications and estimation documents. It also leverages the diversity of environments to deploy innovative designs and practices during their research and development stage, contributing knowledge and experience to research and innovation programs including the State Highway Research Program (SHRP), EDC, NCHRP and the Coordinated Technology Implementation Program (CTIP).

Each fiscal year, WFL conducts 50 project designs and administers 50 construction projects, representing a financial obligation of $200 million with approximately 200 employees. FY 2017 had a larger budget of $242 million. Geologic and geotechnical activities are the responsibility of its Geology and Geotechnical team, consisting of 1 supervisor team leader, 3 engineering geologists and 6 geotechnical engineers/geological engineers.

Engineering Geologist Anderson now transitions to one of the numerous bulk of geotechnical activities of WFL, the Unstable Slope Management Program (USMP) *(13)*, one of the key tools they use for helping their federal land management partners in understanding road corridor performance and offering strategies for them to reduce the risk of unstable slopes impacting their roadway asset and mobility. Under this program, strategies implemented primarily address low-volume roads, with the additional challenge of doing this for a wide variety of soil types and environments throughout its jurisdiction. Among the unstable slope challenges it handles are embankment failures, debris flows, mudslides, rock slides, rock avalanches and rock falls. Surpassing these in frequency and total cost is the swelling and heaving of soil and subgrades, the speaker indicates that WFL’s experience with this issue can prove useful to PRHTA due to the abundance of laterite and swelling clay soils present throughout Puerto Rico.

Applying GAM throughout its jurisdiction becomes a complicated challenge due to the huge number of customer agencies WFL has:

- National Park Service (NPS)
- U. S. Forest Service (USFS)
- Bureau of Land Management (BLM)
- Bureau of Reclamation (BoR)
- Bureau of Indian Affairs (BIA), approximately 40% of the FHWA budget
- U. S. Fish and Wildlife Service (FWS)
- U. S. Army Corps of Engineers (USACE)

Out of these, the NPS, the USFS and the BLM tend to have the most consistent interest in adopting the USMP for FLMA tool, and thus have become the strongest partners of WFL.

For the implementation of its USMP, FLH conducted two implementation phases. Phase 1 had support from the Alaska Department of Transportation and Public Facilities (ADOT&PF) and Landslide Technology, a division of Cornforth Consultants. During this phase, the main challenge was coordinating the interests, needs and scope of the different federal land management agencies, including specific details on how to classify and inspect the different slope assets to manage. The two partner entities WFL teamed up helped bring best practices from a practitioner's perspective. During Phase 2, the agency had the assistance of the Western Transportation Institute (WTI) from Montana State University's College of Engineering and Computer Science Department, Landslide Technology, D. A. Stanley Consulting and Paul D. Thompson Consulting. At this stage, the focus was modifying the USMP to act as a performance management system.

FLH adopted three increasingly important concepts through its USMP: risk reduction, maintenance and resiliency. FLH seeks the reduction of maintenance costs, the increase of resiliency of its partners road corridors and the adoption of a risk reduction approach for more recurring problems, in contrast with the full mitigation strategies in more extreme cases. Specific goals for the USMP include:

- Utilization of existing and proven unstable slope systems, specifically the WSDOT USMP, the ADOT&PF USMP, CDOT's Corridor Focus and the RHRS
- Inclusion of roads with low to very low Average Annual Daily Traffic (AADT<400 vpd) and recognition of the rural context for hazard and risk rating
- Proactive management of unstable slopes on roads and trails, inclusive of soil, rock and thaw-unstable slopes.
- Generation of a single standard set of forms for all client agencies to use
- Development of unstable slope condition surveys, along with the provision of monitoring and deterioration tracking methods for the effective scheduling and prioritization of preventative maintenance
- Development of scalable and flexible program elements to meet differing agency missions and data availability for the USMP

FLH's GAMP also defines its Six (6) Steps for Success:

1. Evaluate transportation system use and needs, target USMP implementation. This first step is extremely important to ensure an adequate scoping and goal-setting for the program.
2. Rate identified transport corridors based on maintenance problem areas and input, critical to include non-geotechnical specialists. Its identified challenge is making this process economical for large scale implementation.
3. Prioritize rated slopes.
4. Development of conceptual designs and estimates, this stage is intended for a dedicated geotechnical focus.
5. Evaluate benefit-costs of the conceptual stage projects to reprioritize rated slopes for proactive project selections.
6. Track unstable slopes using living rating system to watch deterioration trends requiring proactive risk reduction interventions.

Engineering Geologist Anderson takes the opportunity to emphasize why slope assets are important, by stating that their condition and performance dramatically affect pavement and access to bridges if slopes fail. Slopes are often the forgotten asset. We can have a good conditioned bridge but poor slopes leading up to the bridge; therefore, the corridor resiliency is less than good. Following these steps, the speaker now introduces a web-based unstable slope rating system. Credentials to access it are as follow:

- Domain: https://usmp.info/client/login.php
- Username : level1@email.com (level "one")
- Password: level1 (level "one")

He then begins showing and explaining the web application's layout and features, which correspond to those of a web-based database. The website contains various features geared towards slope management, including a Google Maps-based GIS view, rating forms and analysis tools. Users can click on icons showing the geolocalized entries of slopes already entered in the system. These entries include location, slope characteristics, rating information and the five most recent photographs of the slope.

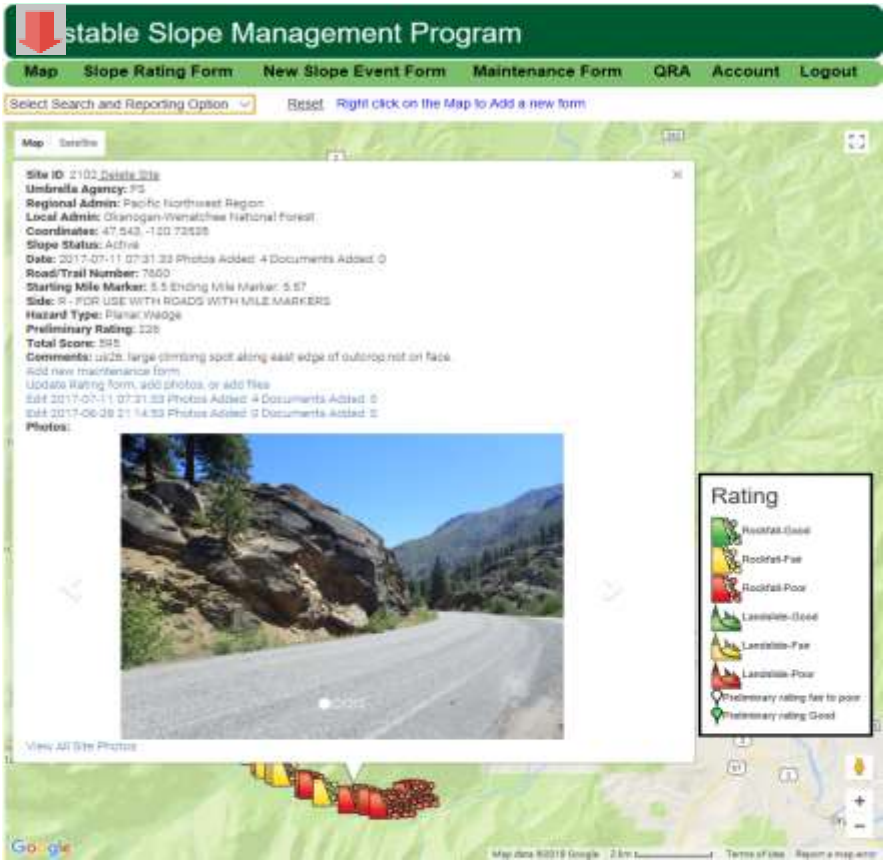

Figure 21: Federal Lands Highway Unstable Slope Management Program GIS interface. Source: FHWA Federal Lands.

One feature developed for ease of work is the use of Rapid Assessment Tools, which allow users to only fill more basic parameters of good slopes. This helps save time and effort which can be better devoted at documenting and intervening with slopes in fair or poor condition. If a slope is screened as having a potentially fair or poor condition, the user instead fills out the detailed evaluation form.

Preliminary Ratings					
Category Rating:	**3**	**9**	**27**	**81**	**Score:**
A. Landslide - Roadway Width Affected:	0-5 percent	6-25 percent	26-50 percent	51-100 percent	0
B. Landslide - Slide/Erosion Effects:	Visible crack or slight deposit of material / minor erosion	1 inch offset, or 6-inch deposit of material / major erosion will affect travel in < 5 years	2-inch offset or 12-inch deposity / mod. erosion impacting travel annually	4-inch offset or 24-inch deposity / severe erosion impacting travel consistently	0
C. Landslide - Roadway Length Affected:	25 ft	100 ft	225 ft	400 ft	0
D. Rockfall - Ditch Effectiveness: (consider launch features)	Good	Moderate	Limited	No Catchment	0
E. Rockfall - Rockfall History:	Few Falls	Occasional Falls	Many Falls	Constant Falls	0
F. Rockfall - Block Size or Volume per Event:	1ft or 3yd^3	2ft or 6yd^3	3ft or 9yd^3	4ft or 12yd^3	0
G. All - Impact on Use:	Full use continues with minor delay	Partial use remains Use modification required, short (3mi / 30min.) detour available	Use is blocked - long (>30min.) detour available or less than 1 day closure	Use is blocked - no detour available or closure longer than 1 week	0
H. All - AADT/Usage/Economic or Recreational Importance (highest rating applies):	50 Rarely Used Insignificant economic / rec. importance	200 Occasionally used Minor economic / rec. importance	450 Frequently used Moderate economic / rec. importance	800 Constantly used Significant economic / rec. importance	**Use AADT in calculation:** ☑ 0
Preliminary Rating Landslide Total (A+B+C+G+H):					0
Preliminary Rating Rockfall Total (D+E+F+G+H):					0
Preliminary Rating Good (15-21 pts) | Fair (22-161 pts) | Poor (>161 pts)					0

Figure 22: Preliminary rating form for the FLH USMP web application. Source: FHWA Federal Lands.

The detailed form allows users to enter specific details about geological hazards and associated consequences at a slope of interest. These include factors affecting stability, exposure impacts, financial impacts, future consequences if unmitigated and potential complexity of mitigation work.

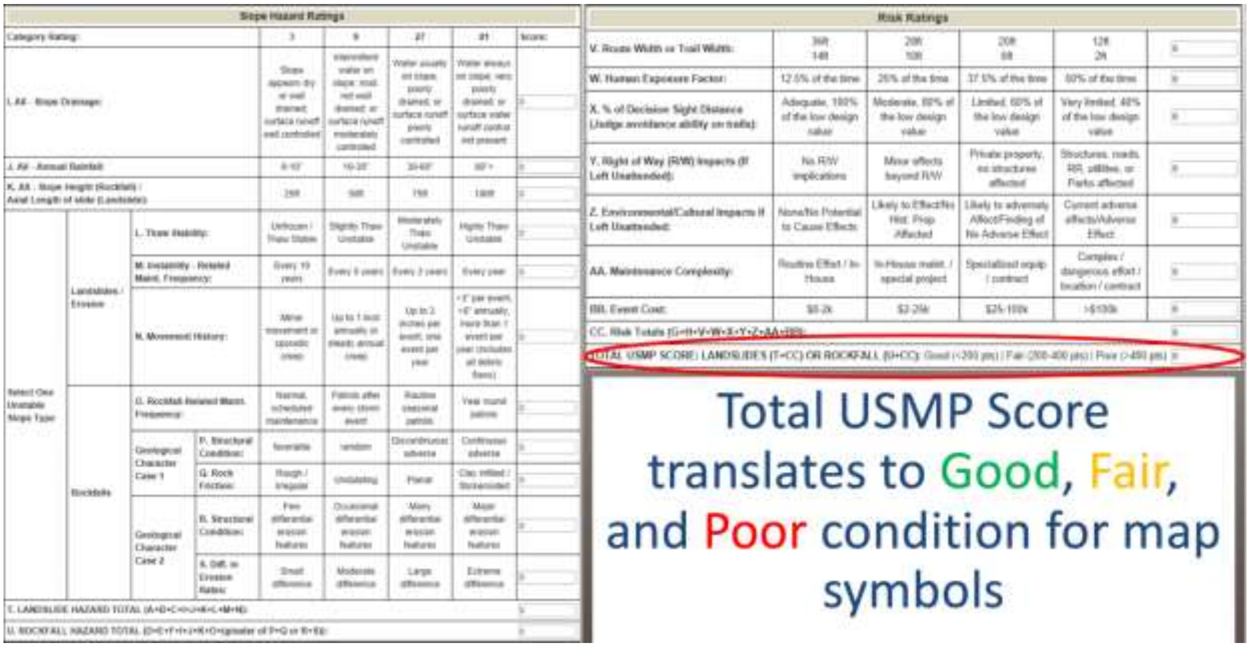

Figure 23: Detailed analysis form for slopes. Source: FHWA Federal Lands.

Data entered in the evaluation forms automatically calculates the ranking score and generates the map symbol to indicate the slope rating. Additional forms supported in this web application include a new slope event reporting form for use by agency staff, and a maintenance form in which maintenance and correcting actions can be documented and tracked.

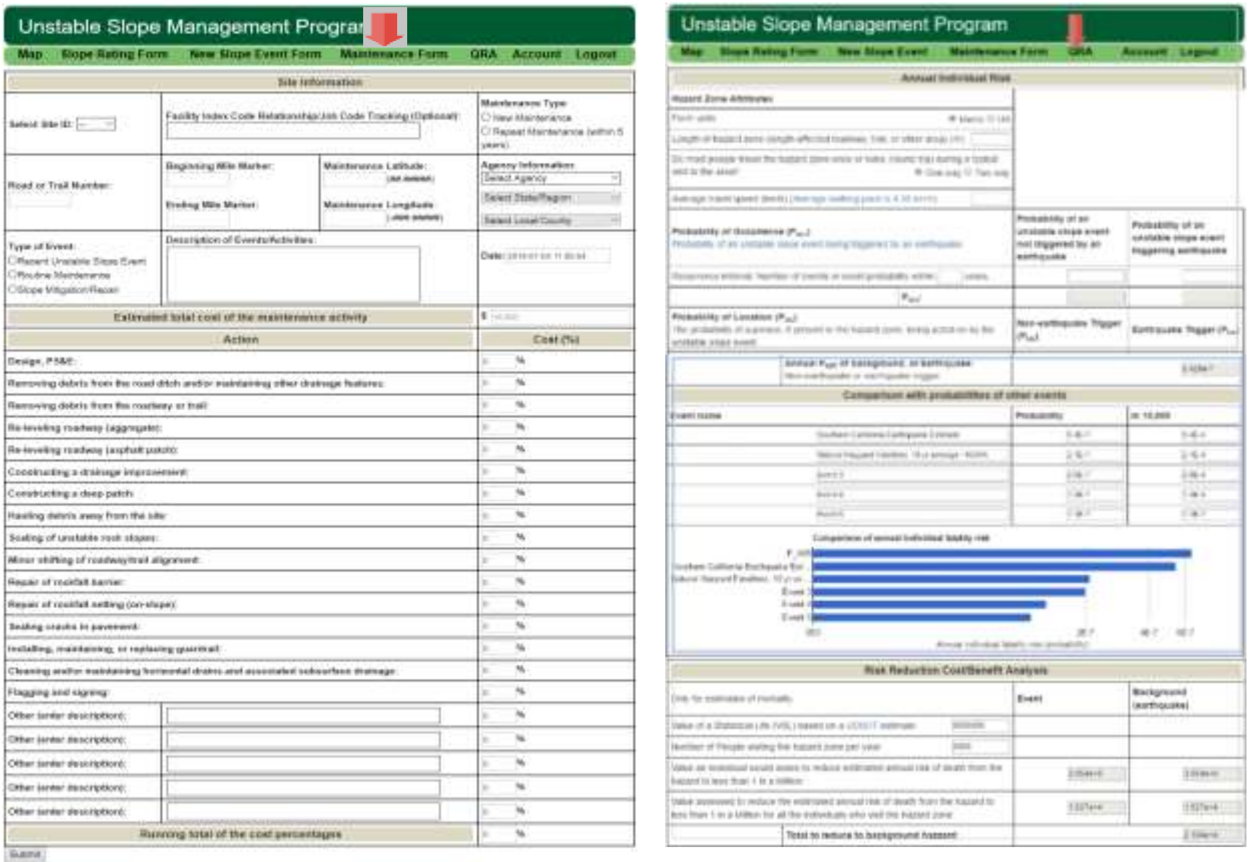

Figure 24: Maintenance form (left) and QRA form (right) of the USMP Web Application. Source: FHWA Federal Lands.

Finally, the USMP incorporates tools for Quantitative Risk Analysis (QRA). These are based on a statistical model to estimate the probability of death associated with the unstable slope's condition, and also features functionality to estimate the level of investment needed to reduce the risk to a certain threshold. These thresholds are referenced with other known societal risks.

After showcasing its features, the speaker now presents the main website for geotechnical resources available at Federal Lands Highways, available through the following link: https://flh.fhwa.dot.gov/resources/geotech

He highlights the latest content, including a new manual published in January 2019, the educational resources available and inclusive of documents, forms, tutorials (field, website and video-based) and presentations, an example of performance measures as developed by the USFS, mobile applications.

Following this demonstration, Engineering Geologist Anderson brought to the attention of the participants a pertinent concept for the prioritization of projects: the tie-breaking rule. State highway agencies can choose to assign priority to projects when either cost or benefit are equal: if the projects have an equal benefit, the agency can choose to do the project with the lower cost; conversely, if they have equal cost, the agency can choose to do first the project with the higher benefit.

Among the next steps for this program is ensuring the continued availability of the USMP rating system web application. At present, the WTI has funding to maintain it until December 31, 2020, after this date Federal Lands is hopeful to deliver the tool they developed for their partners and a maintenance agreement with long-term storage area will be identified. The preferred concept will include the migration of the website to servers protected by a federal firewall. In addition, the USMP will also be available for FHWA partner agencies through the FHWA website for download along with the corresponding system architecture document, scheduled for the end of calendar year 2019.

Prior to transitioning from the USMP web application walkthrough to a case study, a participant asks which elements should be included in a cost analysis. Engineering Geologist Anderson responds by stating the following:

- Direct costs of the geotechnical elements, which are then transferred from the Geotechnical Engineering Division to the Civil Design group.
- Civil design staff incorporate the other project elements along with their cost
- The full cost analysis thus derives from all the included elements: geotechnical, civil, project mobilization, administrative costs and benefits derived from the project.

DAY 2 – WEDNESDAY, AUGUST 28, 2019

Site #1: PR-10, km 57.2, Arecibo

For the second day, Wednesday, August 28, a field trip consisting of five (5) technical site visits around the middle third of the Island was initially scheduled. This field trip was suspended due to adverse weather conditions associated with the declaration of a warning for the potential passage of tropical storm Dorian through Puerto Rico. Some participants of the peer exchange opted to visit the first of five sites of the field trip thanks to a change of the trajectory of Tropical Storm Dorian, which resulted in favorable weather conditions in northern Puerto Rico. Along the way, they traveled from the PRHTA SEO in Bayamón to the site, going along highway PR-22. Along the way, they were able to learn about the karst geology and the construction history of this freeway serving the north coast of the Island.

Figure 25: Final field trip locations visited as part of the Geotechnical Asset Management Peer Exchange.

Once reaching Exit 75, the participants turned southbound to enter PR-10, one of two primary highways connecting the north and south coasts of Puerto Rico through the mountainous interior. Traffic in this area consists of an ADT of 10,000 and trucks associated with agricultural activities in the mountainous interior.

Figure 26: Drainage ditch between filled sinkhole (short grass) and the surrounding natural terrain (tall grass) at PR-10 cuts (image: Douglas A. Anderson, FHWA Federal Lands).

The site in question is located at km 57.2, within the Río Abajo State Forest, a natural preserve administered by the Department of Natural and Environmental Resources (DNER), and traversing limestone belonging to the Montebello Member of the Cibao Formation. This site was selected because it features an unconventional geotechnical asset: a sinkhole with a free-draining fill material. One of the requirements for PR-10's construction was the preservation of karst hydrology, which largely relies on groundwater drainage entering through sinkholes. PRHTA thus had to provide a special fill design capable of both supporting the roadway and its traffic, while at the same time being able to maintain the full drainage capacity of the original sinkhole. This special fill consisted of clearing and grubbing the walls of the sinkhole, which were then lined with a geosynthetic drainage layer, filled in with coarse aggregates and vertical drains, over which the pavement structure and surface drainage elements were installed.

Figure 27: View along PR-10, showing the travel lanes, shoulder, roadside and rock cuts (image: Douglas A. Anderson, FHWA Federal Lands).

Contrasting with the sinkhole is a nearby cut section, showcasing a nearly-vertical rock face excavated to serve two purposes: minimizing the lateral encroachment into the Río Abajo State Forest and removing sufficient material to balance fill at the sinkhole locations. Experience with these rock cuts has also been favorable from a slope stability standpoint: the combination of the near-vertical slope with a wide unpaved clear zone of approximately 8 meters (26 feet) provides an effective catchment area for rock falls. With this design, rock fragments fall vertically and do not roll away from the rock slope and into the travel lanes.

Group discussions highlighted how highway cross-section design practices differ between PRHTA and the other participating DOTs. Along NHS highways, PRHTA generally provides a wide clear zone which acts as a mass movement material catchment area, helping mitigate impacts from smaller magnitude events and providing space for realignments in case of major mass movement occur. This was the case of Site 2, which required a highway realignment when the slope underlying PR-10 began failing during the decade following its construction.

DAY 3 – THURSDAY, AUGUST 29, 2019

RE-SCHEDULED FIELD TRIP TO SITES #4 AND #5

The third day started with its revised agenda, with the morning portion dedicated to two of the remaining field trip sites and the afternoon to the discussion and closing remarks session.

Site #4: PR-52, km 68.3, Salinas

The full group attended and traveled from the PRHTA SEO in Bayamón to the municipality of Salinas, located in the semiarid southern coast of the Island. The fourth site of interest, located in km 68.3 at the western side of Salinas, consists of a benched rock cut of the Cuevas Limestone formation along the Esmeralda fault line. Contrasting with the limestone formations at the Río Abajo State Forest, rock at this site has degraded more and thus the slope generates more rock fall events. These characteristics have resulted in a slope rating of A, as per the RHRS methodology.

Figure 28: Benched rock cut along PR-52, km 68.3. Wildfire remnants can be observed towards the upper left side of the image, along with the semiarid climate vegetation cover, consisting of grasses, cacti and shrubs.

Between 2011-2020, the east and south areas of Puerto Rico have experienced abnormally dry weather, including a major drought event in 2015 and numerous wildfires since. These wildfires have burned and scorched the vegetation of the area, damaging the root system holding together the soils. Additionally, thermal stresses induced by the fire cause expansion and fragmentation of soil and rock particles, further increasing propensity to earth mass movements. These mass movements, consisting mainly of rock falls and debris flows, threaten intercity traffic consisting of an ADT of 35,000 and trucks carrying imported goods from San Juan to the nearby city of Ponce and the more distant city of Mayagüez in western Puerto Rico. At the time of the site visit, no protection beyond modular concrete barriers was provided at this slope.

Figure 29: GAMPE attendees during site visits on Day 3.

Group discussions at the site centered about the right-of-way challenges with mitigation of rock fall sources, as the rocks may be originating beyond the right-of-way owned by the DOT. In these cases, a trade-off is made between frequency of fall events and the required effort to gain authorization from neighboring landowners to remove loose material uphill of the agency's slope.

Site #5: PR-52, km 52.3, Salinas

The fifth and last field trip site was along PR-52, km 52.3, towards the northeast side of the municipality. The site in question is located along the mountainous portion of the freeway's alignment, traversing igneous formations made of andesitic breccia and flows. The site in question consists of a tall slope, whose total height reaches up to 130 meters with slopes ranging from 60 to 80 degrees. Owing to the steeper topography, the clear zone in front of the cut rock face has a much narrower unpaved roadside of approximately 4 meters instead of the more typical 10 to 12 meters elsewhere along the freeway. Protecting this slope is an aging rock fall mesh, which exhibits corrosion, punctures and small trees piercing through it as they grow.

Figure 30: View of Site 5, with the relevant slope to the left. Notice how the clear zone opposite to the slope exceeds 10 meters (33 feet) of width between the shoulder and the forested area, while the clear zone at the toe of the slope can barely be distinguished.

Much like Site 4, traffic traversing Site 5 consists of an ADT of 35,000 and intercity truck traffic transporting imported goods towards Ponce and Mayagüez; climate and vegetation are also semiarid and prone to wildfire impacts. However, unlike site 4, the mountainous topography is associated with detour routes less capable of accommodating the large trucks, and as such, rock falls cause major disruptions to traffic along this corridor.

Figure 31: Roadside vegetation at PR-52, Km. 68.3, representative of semiarid slopes in southern Puerto Rico, consisting of cacti, shrubs and grasses. From top to bottom: Engineering Geologist Marc Fish (WSDOT), Eng. Cecilia Barbosa (PRHTA), Engineering Geologist Krystle Pelham (NHDOT), Engineering Geologist Douglas A. Anderson (FHWA Federal Lands) and Dr. Benjamín Colucci (PRLTAP).

Discussions on the challenges of this site revolved around the best maintenance practices to use for this kind of rock slope. One of the most significant of these was the use of rock scaling, where loose rock fragments are removed from the slope face to prevent their fall into the roadway's right-of-way, as well as the best ways to repair and replace the mesh. Recommendations for this site include the addition of mesh sheets to stitch together portions which have opened along the seams whenever rock falls have occurred, as well as the possibility of removing small trees due to their roots separating rock fragments as they grow.

Figure 32: View of slope covered in steel mesh with a torn seam, along with a typical heavy vehicle traversing PR-52 northbound.

PEER EXCHANGE DISCUSSION SESSION

Following the field trip visits during the morning of August 29, 2019, the GAMPE participants returned to the Headquarters of the CIAPR to partake in the last activity of the exchange. Here they exchanged and discussed their observations, ideas and goals for the refinement of their respective agencies' GAM plans and policies.

Main Points Presented in the Discussion Session

During the peer exchange session, the participant representatives of the various agencies exchanged ideas and identified opportunities for improvement of the geotechnical asset management plans presented. Here they are listed in the order in which they were mentioned throughout the discussion:

1. **Adopt technologies and methodologies to facilitate GAM activities:** All participants agreed on the importance of adopting appropriate hardware, software and methodologies to feed in the data required to make decisions. Imaging instrumentation such as LiDAR, photogrammetry, unmanned aerial systems (UAS), together with geographic information system (GIS) software, efficient inspection protocols and rating systems, help establish priorities for maintenance and rehabilitation of the growing body of assets of the agency.
2. **Leverage capacity-building events and funding:** A consensus position established in the exchange was the pertinence of seeking and leveraging the plethora of programs, funds and events aimed at capacity building, with emphasis in field-oriented practice. This will help ensure the preparation of agency staff and contractors to successfully implement GAM practices, as well as helping the agency communicate and enforce the associated requirements. Pertinent capacity-building programs mentioned include the Geotechnical Committees of the Transportation Research Board (TRB), the National Highway Institute (NHI), the State Planning and Research (SPR) program, the State Transportation Innovation Council (STIC), Accelerated Innovation Deployment (AID) grants, funds and technical expertise from the *FHWA Resource Center*, *Every Day Counts 5 (EDC-5)* initiatives *(14) Advanced Geotechnical Methods in Exploration (A-GaME), Project*

Bundling, and the regional geotechnical conferences for DOTs, in particular those of the southwest and northwest regions of the United States. The pertinence of the southwest and northwest geotechnical conferences is intimately associated to geography: states within these regions possess mountainous topography, resulting in greater experience with slopes and which can benefit PRHTA in the adoption of best practices suitable for the mountainous topography of Puerto Rico. Other resources available from entities beyond those directly involved in transportation infrastructure include training for landslide emergency response training from the NPS supporting FLH staff.

3. **Communicate the importance of GAM to agency leadership:** Participants unanimously recognized that geotechnical staff of the agency must make sure to communicate effectively the benefits, consequences and importance of adopting said practices, using the appropriate language and perspective to make it relevant to agency leaders (DOT secretaries, executive directors and lawmakers) and to ensure they make it a priority in the agency's agenda. This communication must be adapted to the target audiences and to the prevailing administrative culture within the agency and how GAM contributes to the attainment of the leadership's priorities.
4. **Be ahead of federal regulations:** As research progresses, technical staff at DOTs must identify the upcoming technologies and strategies which might be adopted as standard practice. Such early adoption confers both earlier benefits of employing such practices while also reducing the burden of compliance, and especially the consequences of being penalized financially, by the time they become federal transportation regulations. Outstanding examples of this kind include the application of GAM by NHDOT for over 40 years and CDOT's comprehensive GAM encompassing 12 classes of assets.
5. **It's not just about the money**: The successful adoption of innovations like GAM is not only about money, it must consider other equally important aspects for implementation. These other aspects include having the appropriate experts, education, tools and methods. Additionally, recognizing the synergy between GAM and other innovations is crucial to maximize the benefit derived from each. One example is combining three of the EDC-5 initiatives, *A-GaME*, *Project Bundling* and *Unmanned Aerial Systems.* Project bundling can be utilized to accelerate the design, construction and rehabilitation of geotechnical projects, while A-GaME and UAS can feed in the information to guide both the project

prioritization and the designs. These combination of innovations has the potential to reduce the amount of agency staff and resources required to implement them.

6. **Maintain current asset inventories**: A challenge faced by PRHTA officials throughout the decades is the difficulty of managing the highway network due to the numerous assets which are not inventoried. When emergency response is required, the agency loses valuable time when discovering damaged assets which were not inventoried, causing delays due to the required inspections and documentation prior to the development of the rehabilitation and reconstruction projects associated with the emergency. Proper asset inventories facilitate emergency response and the everyday operation, maintenance and rehabilitation activities needed to maintain the state of good repair, which ultimately tie into developing a resilient highway network. The three priority tasks of their GAM, 621, 649 and 674, all contribute to this main point.
7. **Incorporate system resilience into the asset management plan**: Participants agreed on how the application of GAM to the highway network contributes to the physical integrity of assets, ease of response to incidents, traffic safety and mobility. By reducing threats from geological and geotechnical phenomena, vital links for emergency response activities can be kept open more easily, saving lives, money and time when authorities and other responders have to face extreme events. CDOT provided a clear example of this by showcasing a corridor-level resilience analysis methodology applied through their GAM.

Level of Resilience (LOR) Index Total Annual Risk		
LOR Index	No. of 1-Mile Roadway Segments	% of Total 1-Mile Roadway Segments
A	129	68
B	12	6
C	27	14
D	17	9
E	5	3
TOTAL	191	100

Figure 33: Level of Resilience index mapping applied to US-40. Source: CDOT.

8. **Incorporate transparency and accountability:** When an agency has a formal and all-encompassing methodology for asset management, its leadership is empowered to make the data based decisions and can justify why certain actions were or were not undertaken. This can help face issues such as liability, where the agency can demonstrate that it is indeed undertaking the proper measures to address particular situations.
9. **Develop objective and consistent rating methodologies:** A challenge participants recognized widely was the qualitative nature of geotechnical asset rating methodologies currently in use. Secondly, the lack of a general standard for these can result in difficulty communicating just what is happening at a particular slope of interest. Additionally, rating methodologies which rely on qualitative assessment of slope characteristics can reduce the effectiveness of slope management programs—if two evaluators disagree on the condition of a slope, it may be possible for a slope in poor condition to be overlooked by being categorized at a better condition, while a slope in a good or fair condition can receive unnecessary interventions if it was classified as poor, resulting in a waste of agency resources.
10. **Having a good plan is better than a perfect plan:** Development of a GAM should not fall prey of a perfectionist mindset. As long as the GAM plan contains sufficient elements to get started, it can start providing benefits to the agency and to road users much sooner. As time goes by, the agency can continue improving upon the plan as they learn from implementing the original version. A pertinent element of a successful plan is defining "big picture" goals: the agency should start with data collection, but it must also define activities and milestones it wants to achieve into the future, this way it becomes possible to adjust the initial plan more seamlessly to attain said goals.
11. **Adopt low-maintenance and fast-repair countermeasures:** Participants of the exchange recognized the benefits of this type of countermeasure, which results in benefits such as maintenance of mobility, lower lifecycle costs, faster emergency response and ease of implementation in financially-constrained agencies. Vertical rock cuts with catchment areas of at least 2.4 meters or 8 feet of width are of interest due to lower maintenance costs from reduced rock fragment encroachment into the travel lanes and due to reduced costs associated to liability lawsuits from vehicle damage caused by smaller rock fragments.

12. **Address water infiltration:** A prevailing challenge in slope stability mentioned by all agencies was that of water infiltration into slopes and embankments. This water, originating either from the water table, small streams, intense rain/snowmelt events or drainage deficiencies increases pore pressure and erodes soil materials, triggering mass movements and their associated damage to assets and disruptions to traffic operations. Slope stabilization countermeasures should emphasize installation and maintenance of drainage systems, while slope inspections should use investigation methods capable of identifying infiltrated water. One innovative example of water infiltration related countermeasures was conducted by PRHTA, along PR-10. As the highway traverses the Río Abajo State Forest, the DNER required among the environmental impact mitigation activities the maintenance of drainage capacity of sinkholes. This led to the formation of a new class of geotechnical assets, filled sinkholes capable of maintaining their full drainage capacity due to a combination of geotextiles and free-draining crush stone gradations.

13. **Recognize when full mitigation is not possible:** Given the resource constraints and the vastness of the highway networks of each agency, along with the variability in frequency and severity of geological hazards associated with roadside slopes, care must be taken when determining which sites to protect, to what extent and with which countermeasures to do so. One example, presented by Engineering Geologist Anderson from WFL, was covering only the upper portion of a rock slope with rock fall mesh, such that only the lower 50 feet of the slope was exposed, resulting in a reduction of 90% of falling rock fragments encroaching into the travel lanes, based on the rockfall analyses with a software such as Rocscience's RocFall. A second example pertains to PRHTA, whose experience with rock cuts indicates that a vertical cut geometry may be more beneficial in certain contexts. Their limitation was due to minimizing PR-10's encroachment into the Río Abajo State Forest, and in 25 years of experience, the limestone cuts along this highway have shown small rock fragments falling, with no major rock fall events since its construction.

Demonstration of GAM Software and Technological Tools

During the first day of technical presentations, representatives from the participant agencies mentioned the different software and technological tools they use for their respective programs. These tools can be grouped into three major categories: terrain imaging and measurement, GIS databases, and digitalized slope rating methods. These are further explained below:

1. **Terrain imaging and measurement:** This category encompasses all the tools involved in this activity, including technologies such as LiDAR, photogrammetry, rangefinders, and UAS. Each agency showcased the digital output of their tools and explained the strengths and limitations of each. A summary of these is shown below:
    a. **LiDAR:** This system uses laser beams to create point clouds of a surface of interest. It can be deployed either through ground mounting, such as with surveying tripods (ground-based LiDAR), or it can be deployed through UAS (aerial LiDAR). It has the advantage of constructing precise images, even as far as allowing for the filtering of groundcover to map out only the base terrain, with the methods of *first return* and *last return* filtering of points. It does, however, face the limitation of being more expensive due requiring of specialized equipment.

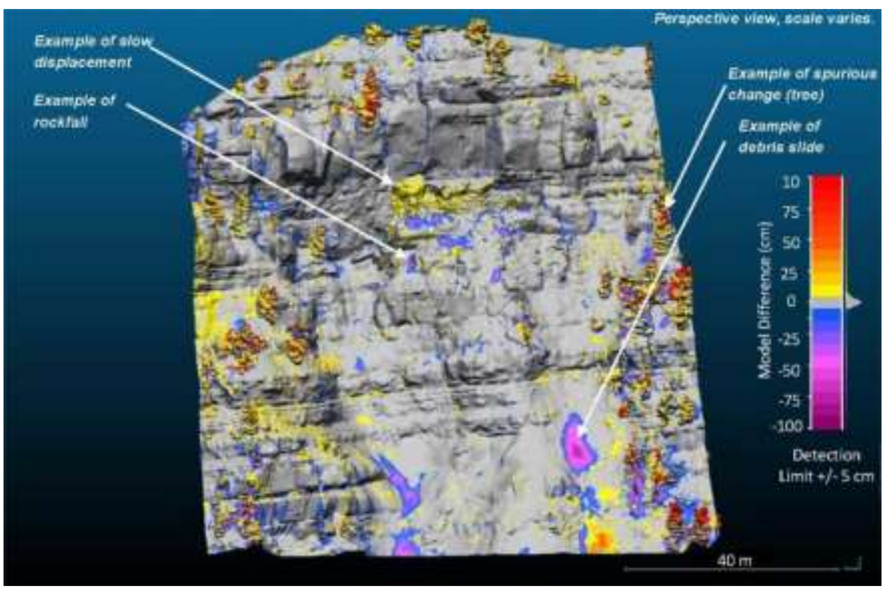

Figure 34: LiDAR-derived 3D model used for change detection. Source: CDOT.

b. **Photogrammetry:** This system creates tridimensional images through the mathematical analysis of overlapping photographs of a surface. Among its advantages is its cheaper implementation, as any digital camera whose position is known can be used to generate said images, whereas its limitation is the inability to observe the base terrain below groundcover elements, such as vegetation and infrastructure. NHDOT and CDOT make use of photogrammetry for *before and after* comparisons of suspected unstable slopes. Images derived through LiDAR are then analyzed with **structure from motion** software packages, which can them compare consecutive terrain models to identify areas where terrain movement occurs. As a strategy to overcome the groundcover limitation, NHDOT applies the method during the late autumn period, as leaves have fallen and snow has not yet accumulated. A similar strategy can be applied in warm regions, during the dry season when foliage is least dense. Engineering Geologist Pelham also pointed out that, in the case of highly unstable slopes with active movement, soil and/or rock particles are not exposed by vegetation and can be mapped through photogrammetry. CDOT takes a more sophisticated approach by incorporating infrared images, enabling them to detect presence of water seepage in potentially unstable slopes.

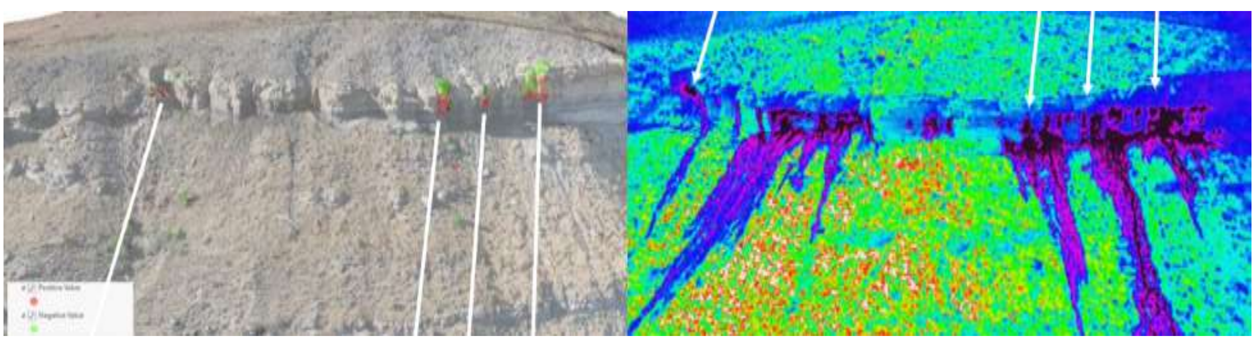

Figure 35: Water seepage infrared mapping correlated with change detection mapping. Source: CDOT.

c. **Rangefinders:** PRHTA uses rangefinders due to the portability and ease of use, as they help make quick measurements of slopes without deploying dedicated survey crews or placing personnel in a possibly dangerous location to collect data with trip and fall hazards. These devices use laser and a digital level to measure out the distance and vertical angle from the observer's location to a point of interest. With trigonometric calculations and these measurements, basic slope properties such as height and angle of inclination can be derived and included in inspection reports.

Figure 36: Rangefinders are a small and portable tool which aids in the measurement of roadside slopes. Source: PRHTA.

d. **Structure from motion and change detection:** This analysis method is applied to LiDAR, photogrammetry and other imaging methods, using a computer algorithm to conduct change detection, highlighting areas where the shape of the surface, or the placement of features, changes but is not necessarily noticeable to a human observer. This technique provides the benefit of accurately identifying the occurrence of changes, removing bias from the analysis and allowing for targeted intervention at the specific areas of the slope experiencing significant changes. Additional analysis can be conducted, such as quantitative estimates of falling material or affected surface area, which can later be used for detailed design and construction cost estimation. This technique is being used by NHDOT using the *Pix40* software package.
e. **Unmanned Aerial Systems (UAS):** A majority of the participant agencies support this technology, with the exception of NHDOT. The latter considers the deployment of UAS as impractical for their program due to the combination of cost of the equipment, cost and delay of contracting UAS surveying services and regulatory barriers of licensing for operators and permitting for use in slopes adjacent to the highways. Instead, it has been faster and more practical for NHDOT to use tools

and software compatible with equipment the agency already possesses or which is easily obtainable, as is the case with photogrammetry and consumer-grade / "point and shoot" digital cameras. Conversely, PRHTA, WSDOT and CDOT currently make in-house use of UAVs for their respective GAMs, thanks to their flexibility for inspection in rugged terrain and hazardous conditions

f. **Use of instrumented vehicles for right-of-way analysis:** Four agencies, NHDOT, WSDOT, National Park Service and FLH, use images collected from these instrumented vehicles, such as the *SRView, Automated Road ANalyzer (ARAN)* or the *PathRunner,* for desk analysis of geotechnical assets. The benefit derived from these images is that they are likely already collected by the agency for other purposes along much of the highway network, are of high resolution and allow for initial slope ratings without requiring dedicated field visits. Among its limitations are the inability to collect images on slopes significantly above the roadway, or slopes below the roadway level, and as such cannot be used for detailed analysis of sites of concern.

g. **Virtual dynamic slope analysis and instrumented rocks:** NHDOT uses a niche methodology for slope analysis, in which two software packages, *Rockfall* and *SmartRock,* analyze rock fall events in virtual 3D models derived from photogrammetry to estimate the efficacy of countermeasures, dimensions of catchment areas and hazard posed to adjacent highways by slopes of interest. These virtual analyses are validated with the use of instrumented rocks which are made to fall along the real slopes of interest.

2. **GIS databases:** Participant State DOTs make use of one family of GIS applications of the ArcGIS Family, developed and published by the Environmental Systems Research Institute (ESRI). These use commercial and proprietary licensing, which, although expensive, has multiple benefits for the agencies: dedicated professional technical support, ease of development of custom forms for field data collection, compatibility with other GIS applications within the agency and complete documentation of the software. These benefits help the agencies focus on using the software for geotechnical asset management, as

opposed to losing time with troubleshooting and solving incompatibility issues between software tools.

3. **Digital slope rating forms:** All participant agencies make use of some kind of digital form to collect field data about the slopes and other geotechnical assets of interest. These forms are designed to collect information on the location, dimensions, materials, condition, impacts, applied countermeasures and photographs of these assets.
    a. **PRHTA**: This agency's form has been treated as a living document, receiving frequent adjustments along the way to fine-tune the specifics on how it is utilized. This update process has focused on optimizing the form structure for simplified data entry, increased objectivity and support of reference documents. Development at the time of the peer exchange focuses on *ArcGIS Survey123*, a mobile app platform for direct use with *ArcGIS Online*, and in substitution of ArcGIS Collector. Rock slopes are rated following three categories defined by their instability behavior: A slopes corresponds to the highest probability of rock fall; B slopes, B slopes corresponds to moderate risk and low probability of rocks reaching the roadway; and C slopes corresponds to Low risk, and in case of a rock fall, it is unlikely that its reach the roadway.
    b. **CDOT**: Slope rating forms used by this agency incorporate resilience analysis and corridor-level analysis. Data collected with these is used to rate the condition of 1-mile segments, which are then further analyzed to rate corridors in terms of four resilience components: rapidity, robustness, resourcefulness and redundancy.
    c. **WSDOT**: Their rating form collects attributes of the slopes of interest, and assigns numeric values to categorize them. These values are then processed through a matrix to calculate a score rating indicating risk associated to the DOT's slopes. This valuation estimates the likelihood and the severity of geotechnical hazards with a score from 1 to 5 for each, which then define the consequences of not mitigating the slope.

Likelihood Ranking (1-5)						
	Very Likely	Low	Medium	Medium	Very High	Very High
	Likely	Low	Medium	Medium	High	Very High
	Possible	Very Low	Low	Medium	Medium	High
	Unlikely	Very Low	Low	Medium	Medium	High
	Very Unlikely	Very Low	Very Low	Low	Medium	High
		Minimal	Minor	Moderate	Significant	Major
		Severity Ranking (1-5)				

Figure 37: Matrix for weighted risk rating, used for the Unstable Slope Management Program. Source: WSDOT Transportation Safety, Quality, and Enterprise Risk Division.

d. **NHDOT**: The Geotechnical Asset Management efforts of the New Hampshire DOT was presented within the current Organization & Infrastructure division.

e. **FLH and Partners**: FLH has developed an application tool with the rating, new slope event, and maintenance forms in Android and iOS versions. They are hopeful that the federal land management agencies will use these as a standardized set of forms. This tool is open sourced and is also available to State and Territory DOTs. Among its distinctive features, this form makes a distinction between geotechnical assets and features, as the latter are those physical elements that do not belong to the agency and thus are beyond their control. Secondly, the slope rating form has two variants: one for rapid screening, which allows filtering out slopes in good condition, and a detailed form in which slopes in fair and poor condition can be rated more rigorously. Finally, in terms of its software licensing for the website, it uses a MySQL database, which uses open-sourced licensing, paired with a proprietary component in the form of Google Maps as the base map. The USMP Android and iOS applications are built in ReactNative software and provide an efficient field entry platform in an offline format. Information from the application can be uploaded to the USMP website upon making connection with the internet, and take the redundancy and possible human error out of having to input data into the website upon returning to the office.

APPENDIX A: GAMPE AGENDA

APPENDIX B: GAMPE PARTICIPANTS PACKAGE

APPENDIX C: GAMPE FIELD TRIP GUIDE

APPENDIX D: PROFILES OF PARTICIPANT AGENCIES

APPENDIX E: PEER EXCHANGE PRESENTATIONS

APPENDIX F: GAMPE PARTICIPANTS

APPENDIX G: REFERENCES

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