



TEACR Engineering Assessment

Precipitation and Temperature Impacts on Rock and Soil Slope Stability: Interstate I-77 in Carroll County, Virginia

This is one of nine engineering case studies conducted under the Transportation Engineering Approaches to Climate Resiliency (TEACR) Project.¹ This case study focused on the impacts of future changes in precipitation and temperature on rock and soil slope stability.

Overview

Changes in climate affect factors that lead to rockfalls and landslides. For example, freeze-thaw² and wet-dry cycles cause weathering that destabilize rock and can lead to rockfalls; precipitation levels affect soil moisture, which is a factor in the effective stress on slopes that can contribute to landslides. The purpose of this study is to determine if future climate changes could appreciably influence these relationships and, where appropriate, to suggest strategies for monitoring and adapting to changes in the frequency or extent of rockfalls and landslides along highway side slopes.

Key gaps exist in understanding the linkages between changes in climate (in this study precipitation and temperature) and secondary impacts on infrastructure, such as rockfalls and landslides. This assessment aims to inform the relationship between climate

Case Study Snapshot

Purpose: Evaluate potential impacts of projected changes in precipitation and freeze-thaw cycles on slope stability.

Location: Mile Post 1.8 – 6.3 on Interstate I-77 in Carroll County, Virginia

Approach: Perform a soil slope stability analysis by varying soil properties that may be impacted by changes in precipitation and temperature. Assess the potential for rockfall on a rock slope due to changes in freeze-thaw cycles and precipitation.

Key Findings: Projected increases in precipitation projected due to climate change will not have a significant impact to the stability of the existing soil slope. At this site, freeze-thaw event frequency under future climate scenarios is projected to decrease, so no analysis of changes in rock slope stability was required.

Key Lessons: Detailed climate change projections are not necessary to conduct a screening level assessment of the impact of changes in precipitation on soil slope stability. Step 5 of this case study presents an approach to analyzing the “worst case scenario” without specific climate data.

Location-specific climate projections should be developed when freeze-thaw events are expected to have an effect on rock slopes because the timing and amounts of precipitation immediately preceding a freezing event influences the frequency of freeze-thaw events and the two must be considered together when projecting the potential for rock slope failure.

¹ For more information about the project, visit the project website at:

https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/

² The alternation between freezing and thawing of moisture. This is relevant to this study due to its destructive effects on rock when the ice expands and exerts force on the rock material.

changes (e.g., precipitation) and slope stability and to support the consideration of engineering solutions for responding to secondary impacts. In many ways, damage incurred by transportation assets that is associated with secondary events may be far greater than damage associated with the original precipitation event. In order for highways to perform under future conditions, secondary impacts and options for addressing them must be better understood.

This assessment helps bridge gaps in the understanding of secondary impacts, focusing on the stability of a soil slope and rock slopes adjacent to I-77 crossing the Blue Ridge Mountains in southwest Virginia.³ This segment has previously experienced movement and the Virginia Department of Transportation (VDOT) has implemented the first step in its adaptive plan to prevent further significant movement by constructing a soil nail wall at the bottom of the slope. Current monitoring shows that the slope continues to move. See text below in Step 2. This slope was originally chosen because the subsurface conditions have been characterized through subsurface investigations, instrumented with piezometers and inclinometers, and periodically monitored providing additional subsurface data to assist in its analysis. To be instructive to more typical conditions, the analysis was performed considering that the adaptive soil nail wall was not in place.

Each site is unique; however, this analysis can be instructive when considering other slopes (especially high hazard, steepened slopes) that are adjacent to critical transportation infrastructure. The general approach applied in Virginia provides an example of how similar analyses could be conducted in these and other, comparable geologic regions.

Soil Slope Assessment Overview

Increased precipitation on soil slopes could lead to a higher degree of saturation of the residual soils⁴ and higher perched groundwater⁵ levels above the bedrock. This may cause slope instability because the additional water increases the weight of the residual soils and, because of buoyancy effects, decreases the effective stresses and shear strength⁶ along the failure plane.⁷

Although the research team developed detailed projections of future precipitation levels, this information was not required for the engineering assessment of slope stability. Instead, the research team performed a parametric analysis, i.e., varied the key contributors to slope failure at this site – the groundwater elevation and soil unit weight – to determine the response of the

³ The authors acknowledge the support of the Virginia Department of Transportation (VDOT) in this assessment. The team has drawn information from a field visit and meetings conducted in August 2015 and a follow-up memorandum authored by Carl Benson, Geotechnical Engineering Program Manager for VDOT, delivered August 19, 2015.

⁴ Residual soils are those formed from the weathering of parent bedrock.

⁵ Perched groundwater occurs when infiltrating water reaches impermeable rock, is prevented from infiltrating any deeper, and saturates the soil above.

⁶ Shear strength is the peak shear stress a soil can sustain before failure.

⁷ A failure plane is the geometric boundary that differentiates the sliding soil mass from the stable soil mass.

slope under a wide range of conditions. With increased precipitation, one would anticipate higher groundwater levels and higher soil unit weights as they approach saturation, but the threshold at which changes in these variables result in increased slope instability was unknown prior to performing the analysis.

The results showed that, in this case, if the groundwater elevation were significantly increased, well beyond what could be expected from the projected increases in precipitation due to climate change, the factor of safety⁸ of the existing soil slope would only be slightly affected. However, any increase in soil saturation of a slope that has already exhibited some signs of distress would likely lead to an increased risk of slope failure.

The parametric model suggests that, at this particular site, extensive climate modeling is not necessary in advance of the slope failure modeling. This has considerable benefits from a resource standpoint, reinforcing the benefit of doing such a screening level analysis before developing detailed climate projections. In future slope stability assessments, it is recommended that detailed climate modeling be undertaken only when initial parametric analysis indicates that reasonable increases in groundwater levels and soil unit weights are likely to significantly influence the factor of safety. In this case study, the research team has provided details on the climate modeling process to demonstrate how it could be performed in cases where parametric modeling deems it necessary.

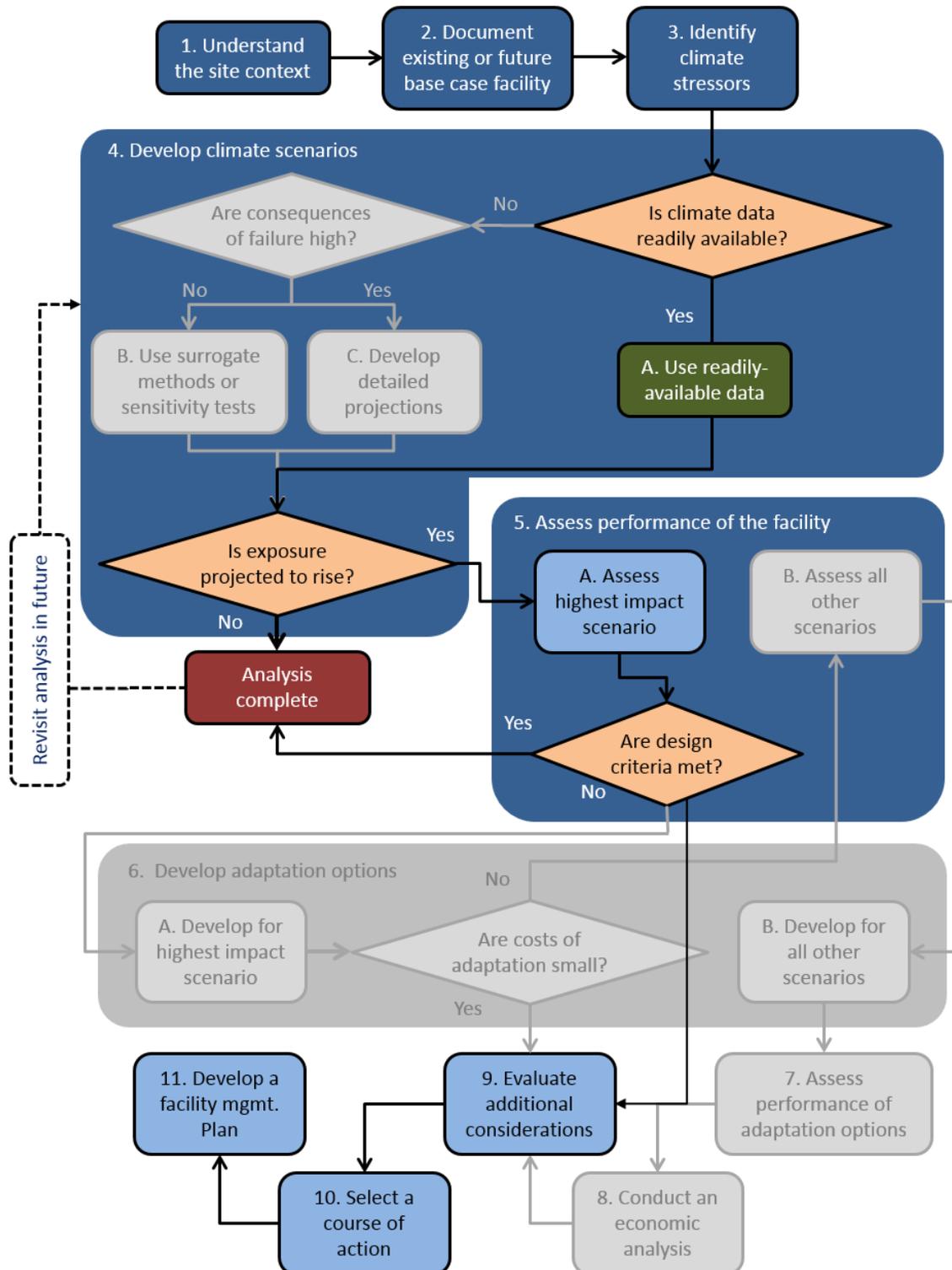
Given the findings in this case study, the research team recommends that VDOT continue to monitor the groundwater levels and movement at this site in order to determine if or when to implement the next portion of their phased adaptation plan. There is no reason to suspect that the timeline for the phased adaptation will need to be accelerated due to climate change but the continued monitoring will ensure that VDOT's implementation is refined and adjusted to accommodate advancements in climate change projections as they become available.

The soil slope assessment followed the Adaptation Decision-Making Assessment Process (ADAP), as outlined in Figure 1. However, the particular slope that is the subject of this analysis does not fit neatly into the ADAP diagram. Step 5 "Assess the performance of the slope" asks "Are the design criteria met?", and although the design criteria are not met (i.e., the factor of safety is less than 1.5, a typical criterion for slope design) the actual analysis need go no further because the magnitude of groundwater level changes due to climate change are insignificant compared to the magnitude of groundwater level change that would cause a significant change to the factor of safety of the soil slope. This modification to the overall process is illustrated by the "grayed-out" portions of Figure 1. It should be noted, however, that there are other measures that can

⁸ Factor of safety in slope stability applications refers to the ratio of shear stress (the force caused by the sliding materials) to available shear strength along a failure plane. Values less than one indicate an unstable slope at high risk of failure. Permanent slopes are typically designed to a factor of safety of 1.5.

be considered and other steps that can be taken (Steps 9 through 11), which are included in this study to help inform other analyses.

Figure 1: Adaptation Decision-Making Assessment Process (ADAP) Used for this Analysis (steps not completed are indicated in gray).



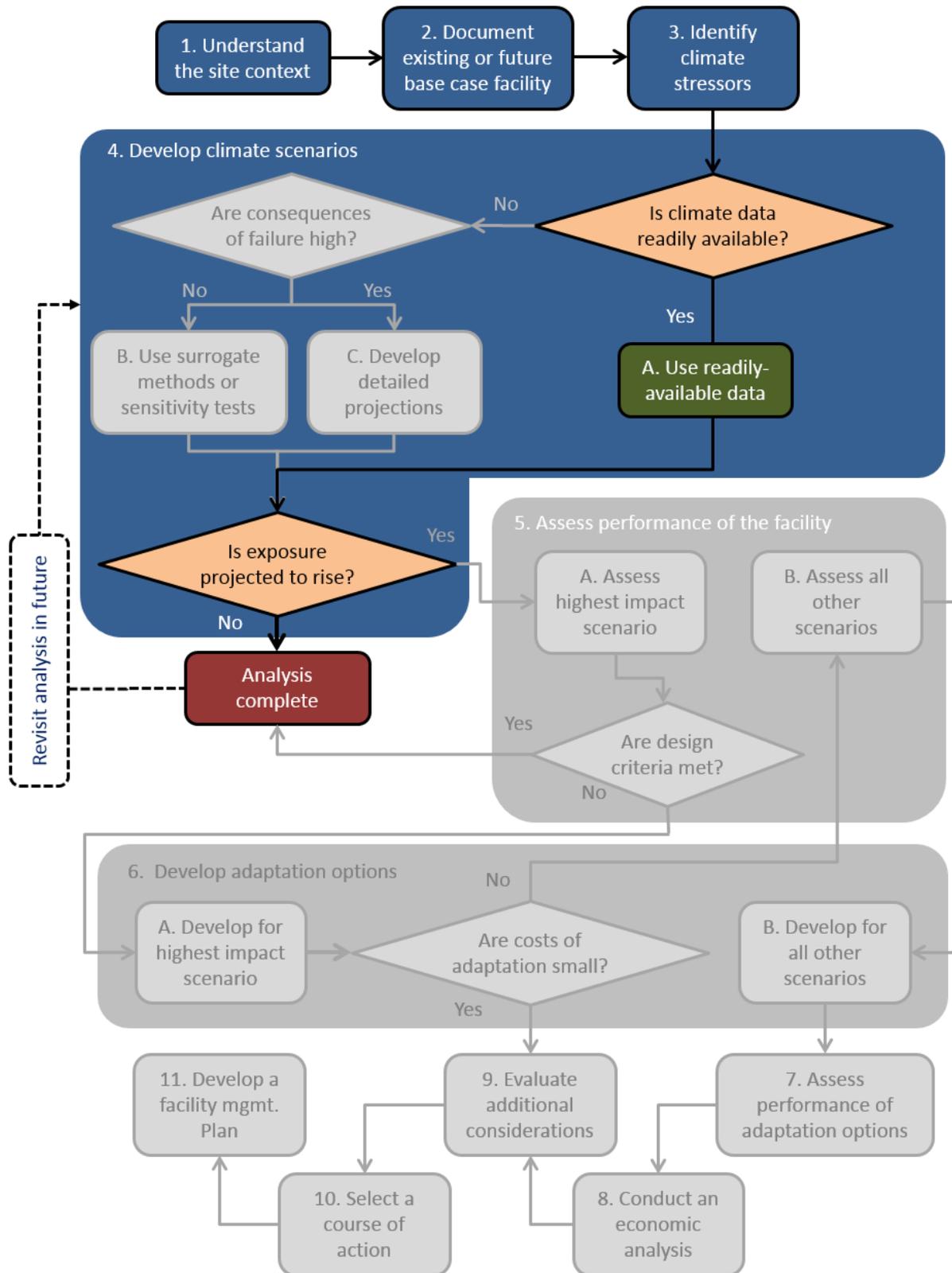
Rock Slope Assessment Overview

Over time, rocks weather and break down from exposure to freeze-thaw cycles. Changes in the frequency of freeze-thaw cycles will affect the rate at which rock weathers. If climate change increases the frequency of freeze-thaw cycles, this will increase the rate at which rocks weather and rockfalls occur. On the other hand, rockfalls will become less frequent if freeze-thaw events decrease.

For this study, a daily freeze-thaw event was defined as a day when the minimum temperature drops below freezing (32° Fahrenheit) and the maximum temperature is above freezing; in other words, a freeze-thaw event occurs when the freezing mark has been crossed during the day. Based on an analysis of the climate model data, the research team found that all future projections suggest a reduction in freeze-thaw days between 14% and close to 50% below historic conditions. Upon inspection of a few scenarios/models, this appears to be primarily due to the projected daily minimum temperatures warming to above freezing conditions. Therefore, it can be assumed that there will be no increase in rockfalls influenced by climate change in the future.

The ADAP approach for the rock analysis follows the truncated ADAP approach outlined in Figure 2.

Figure 2: Adaptation Decision-Making Assessment Process (ADAP) Used for this Analysis (steps not completed are indicated in gray).



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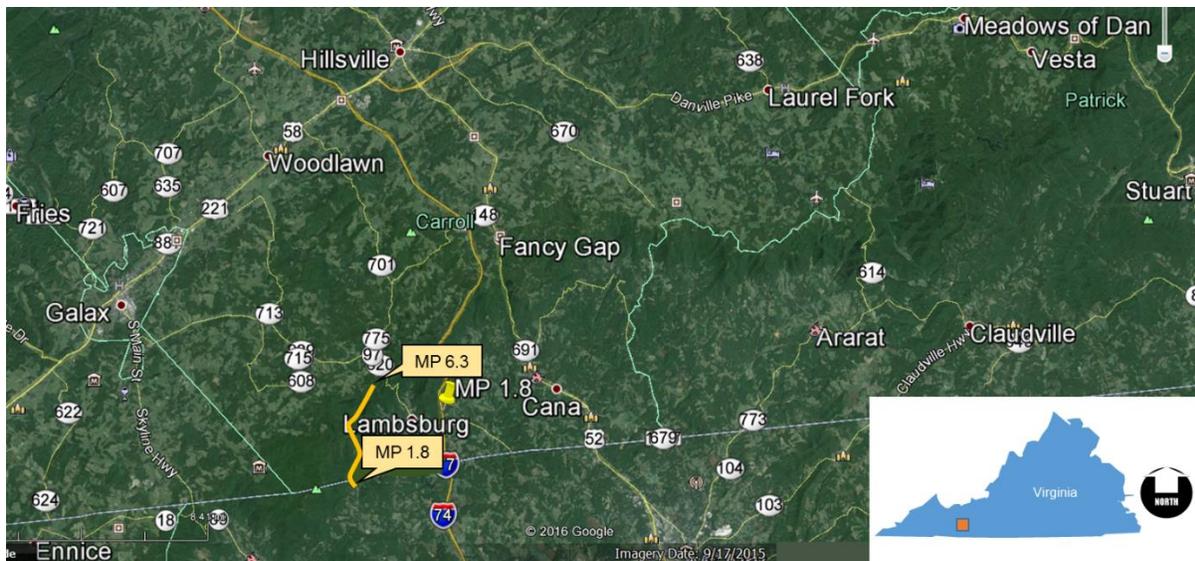
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Details of the Analysis

Step 1. Understand the Site Context

The general study area is an approximately four and one-half-mile long segment of I-77 (mile post [MP] 1.8 to 6.3) crossing the Blue Ridge Mountains in Carroll County in southwest Virginia (see Figure 3). This section of I-77 was built in the early 1970's and the slopes along the highway between the North Carolina state border and Fancy Gap, Virginia have been prone to rockfall throughout the highway's lifetime. Three major rockfalls on this section have closed highway lanes and resulted in one fatality. Figure 4 shows a map of the area and a history of rockfalls in the area.

Figure 3: Vicinity Map of the Mile Post 1.8 to 6.3 Study Area.⁹

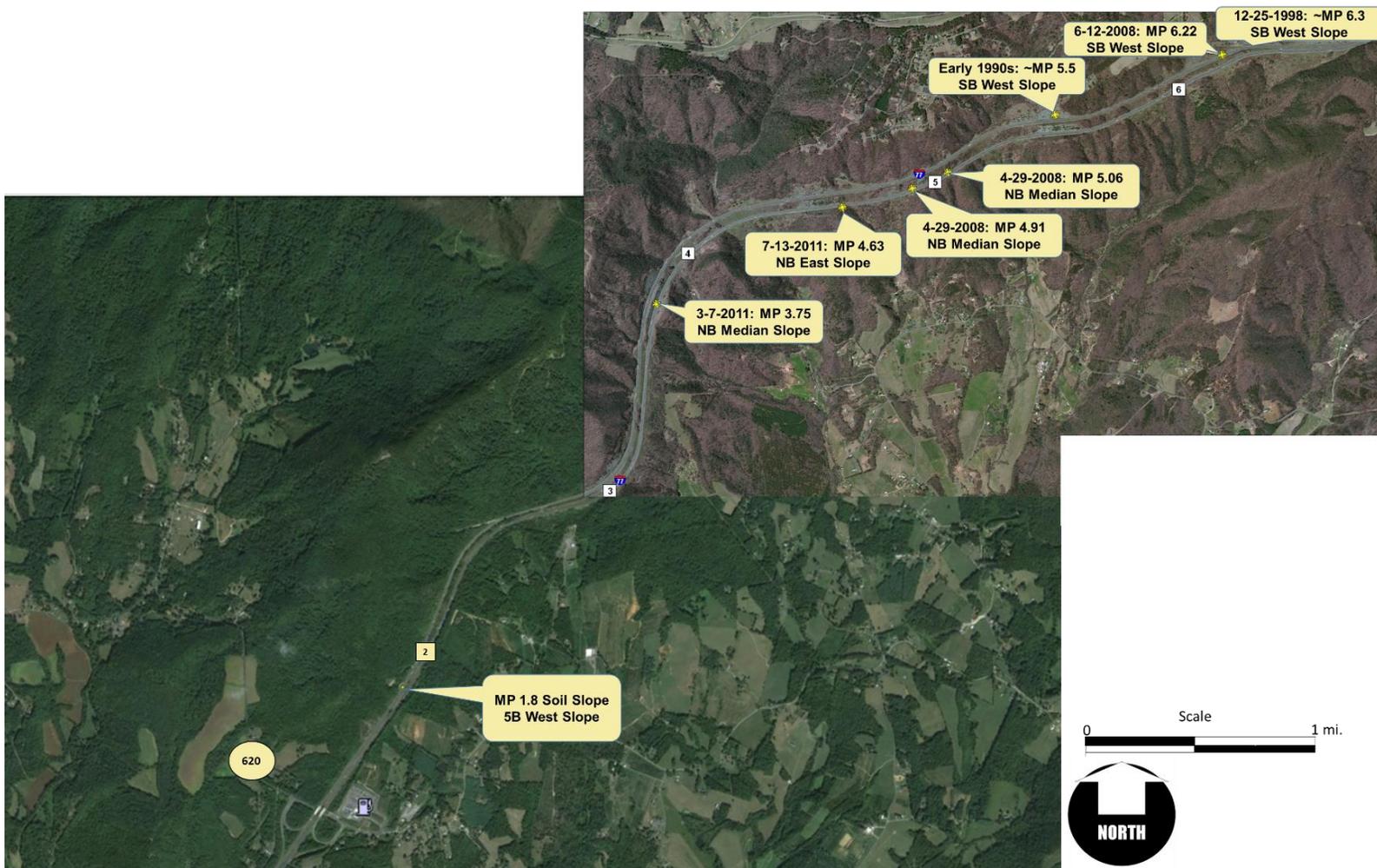


The soil slope stability analysis focused on a specific soil slope on the west side of the highway (affecting the southbound lanes) at MP 1.8 (see Figure 4). The rockfall analysis applies to all rock slopes along the length of the corridor. This roadway segment is particularly prone to rockfalls and soil movement due to steep cut slopes and has experienced both phenomena in the recent past.

Figure 5 and Figure 6 show the topography of the area. The remainder of this section discusses the transportation network and environmental context of the study area.

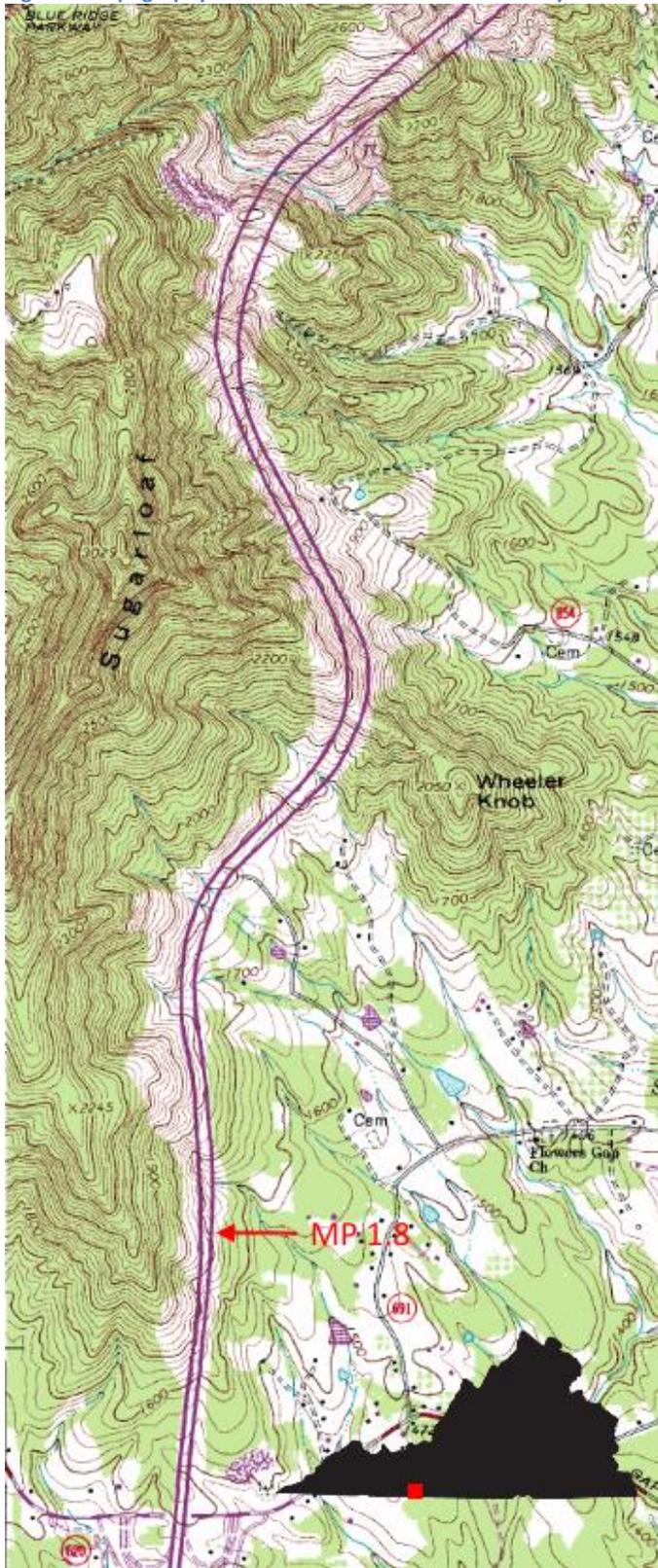
⁹ Image source: Google Earth (as modified).

Figure 4: Location of Historical Slope Failures and Rockfalls within the Study Area.¹⁰



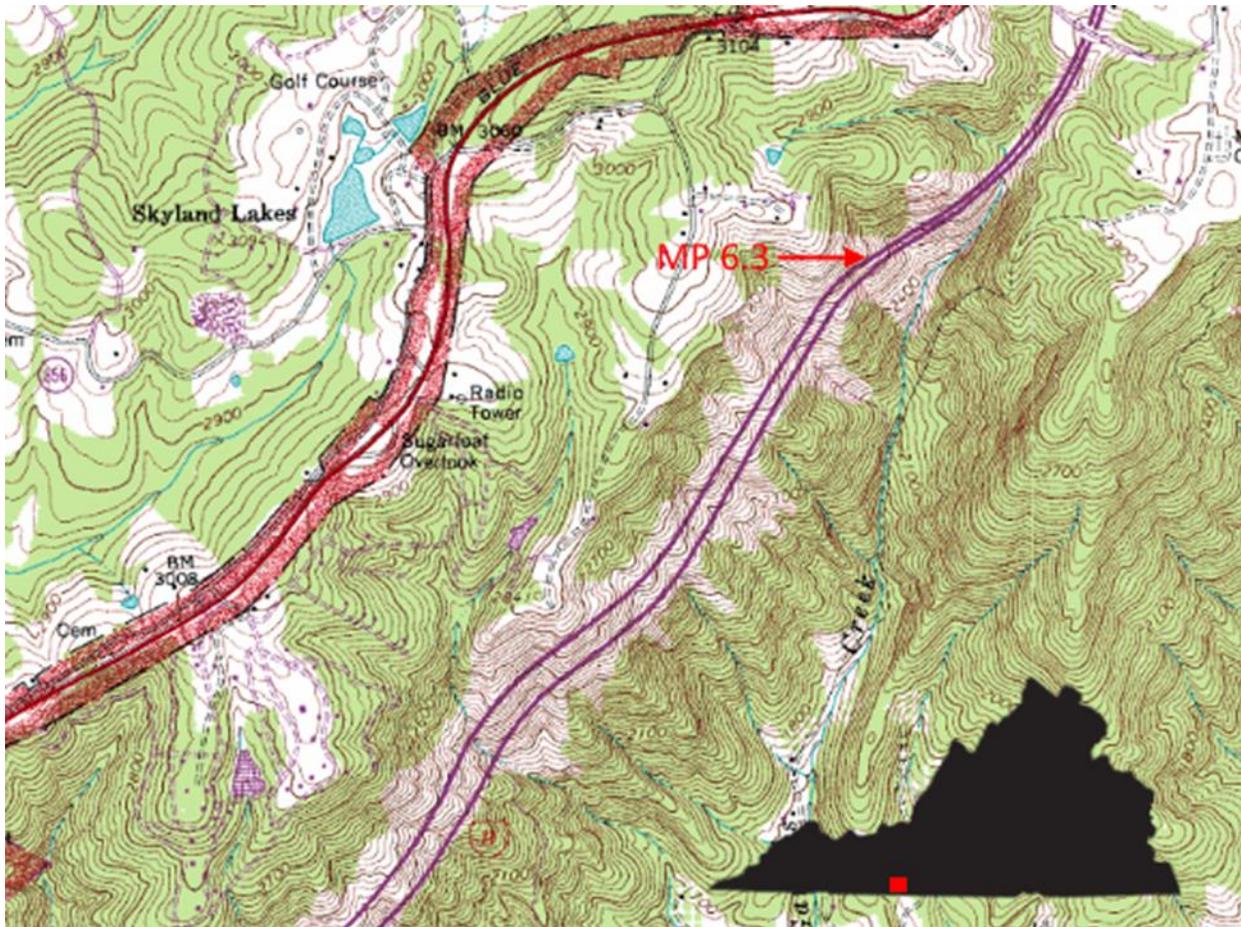
¹⁰ Image source: VDOT.

Figure 5: Topography of the Southern Portion of the Study Area.¹¹



¹¹ Image source: United States Geological Survey (as modified).

Figure 6: Topography of the Northern Portion of the Study Area.¹²



Transportation Network Context

This section of I-77 was originally constructed in the late 1960's to early 1970's. The highway is an important north-south connection running between Cleveland, Ohio and Columbia, South Carolina. Major cities along the route include Akron, Ohio; Charleston, West Virginia; and Charlotte, North Carolina. In 2014, 34,000 vehicles per day traveled along this stretch of interstate highway.¹³ Applying the current growth rate of 1.47% increase per year, it is estimated that approximately 105,000 vehicles per day with approximately 23% trucks (current percentage assumed to remain constant) will use this corridor in 2090 (the end of the study's climate change projection forecasts).

¹² Image source: United States Geological Survey (as modified).

¹³ Virginia Department of Transportation. (2014). Annual Average Daily Traffic Volume Estimates By Section of Route, Primary and Interstate Routes. Retrieved from http://www.virginia.gov/info/resources/Traffic_2014/AADT_PrimaryInterstate_2014.xls, August 11, 2015.

If a major failure were to occur, such as a major rockfall or slope failure, it would be reasonable to assume the corridor would need to temporarily close to allow for slope rehabilitation and construction. If the obstruction required closure of both southbound lanes, the traffic would need to be diverted to one of the north bound lanes (if possible) as there are no reasonable high-volume detour options.

Environmental Context: Site Geologic Conditions

The project is located in the Tugaloo terrane¹⁴ of the Blue Ridge Physiographic Province. The principal rock type within the cut slopes is biotite (commonly, “black mica”) gneiss.¹⁵ The rock is a light to medium gray, with thin to very thinly laminated fine-to medium-grained quartzofeldspathic gneiss with thin partings of biotite and muscovite that define the layering.¹⁶ The soil slope at MP 1.8 is generally comprised of brown, fine to coarse, silty sand with gravel traces and mica.¹⁷

At the soil slope site, the natural slope extends approximately 1,100 feet west of and approximately 400 feet vertically above the highway at MP 1.8. to a ridge line (drainage divide) that generally parallels the highway alignment. The area up-slope from the study area is wooded. Wooded land cover affects the rate of rainfall runoff and helps stabilize the soil.

Step 2. Document Base Case Facility

The base case facilities in this study are the existing soil slope located at MP 1.8 and the existing rock slopes along the 4.5-mile corridor. The cut slopes in the study area, be they rock or soil cuts, are roughly 40 to 45 years old. While slopes are not designed to a specific service life, VDOT indicated that a 75-year service life is representative of their expectations. Although the study slopes are less than 75-years old, VDOT considers these “legacy” slopes because they have become weakened over time. This section discusses the basic design characteristics of each slope studied and highlights some of the recent geotechnical issues experienced.

Soil Slope

The existing soil slopes were cut to form the western slope of the southbound lanes of I-77. On October 21st, 2013, a landslide was first observed at this location. During the slide, the toe (bottom of the slope) encroached on the drainage ditch bordering the highway but did not enter the traffic lanes. The presence of moss on the slide scarp¹⁸ indicates this slide was progressing as

¹⁴ The Tugaloo terrane is a fault-bounded area with distinctive rock layers and layering, structure, and geological history.

¹⁵ Biotite gneiss is a metamorphic rock form characterized by banding caused by segregation of different types of rock, typically light and dark silicates.

¹⁶ Technical Memorandum, Final Phase 2, Task 1, HDR Engineering, Inc., June 11, 2012.

¹⁷ Geotechnical Data Memorandum, Interstate 77 at Mile Post 1.8, Phase I, Schnabel Engineering, July 24, 2014, Courtesy, Virginia Department of Transportation.

¹⁸ A scarp is a highly steepened or vertical face located at the top of a failing soil mass caused by rotational or sliding movements of a slope.

a slow creep failure rather than as a sudden slope failure. Additionally, while there are no true tension cracks,¹⁹ there are multiple scarps within the slide material. VDOT believes that the slope's strength gradually diminished leading to the slide of residual soils weathered from the parent bedrock. Based on the bulge at the bottom of the sliding mass (the toe) and a 20-foot upper scarp, it is reasonable to assume that the slide moved approximately 20 feet in almost 40 years before remediation occurred in the winter of 2013/2014. Figure 7 shows the area prior to the slope failure and Figure 8 shows the toe of the slope after failure.

Figure 7: MP 1.8 Slope Prior to Failure October 1, 2011.²⁰



¹⁹ A tension crack is an opening in the soil surface that results from physical forces within the soil.

²⁰ Image source: Google Street View.

Figure 8: Toe of the Slope in October 2013.²¹



The slopes were constructed in accordance with the design criteria for interstate highways established at the time. Aerial photographs of the area from the current day back through 1993 show moderately dense tree cover. There appears to be no major ditches that would intercept precipitation runoff before it reached the slope study area.

A construction road is located north of the slide area. Numerous older logging roads are evident in the area around the failed slope area.

Figure 9 and Figure 10 show the slide perimeter scarp and one of the internal scarps, respectively. Figure 11 shows the topographic detail of the slide area.

²¹ Image source: VDOT.

Figure 9: Upper Scarp Looking North.²²



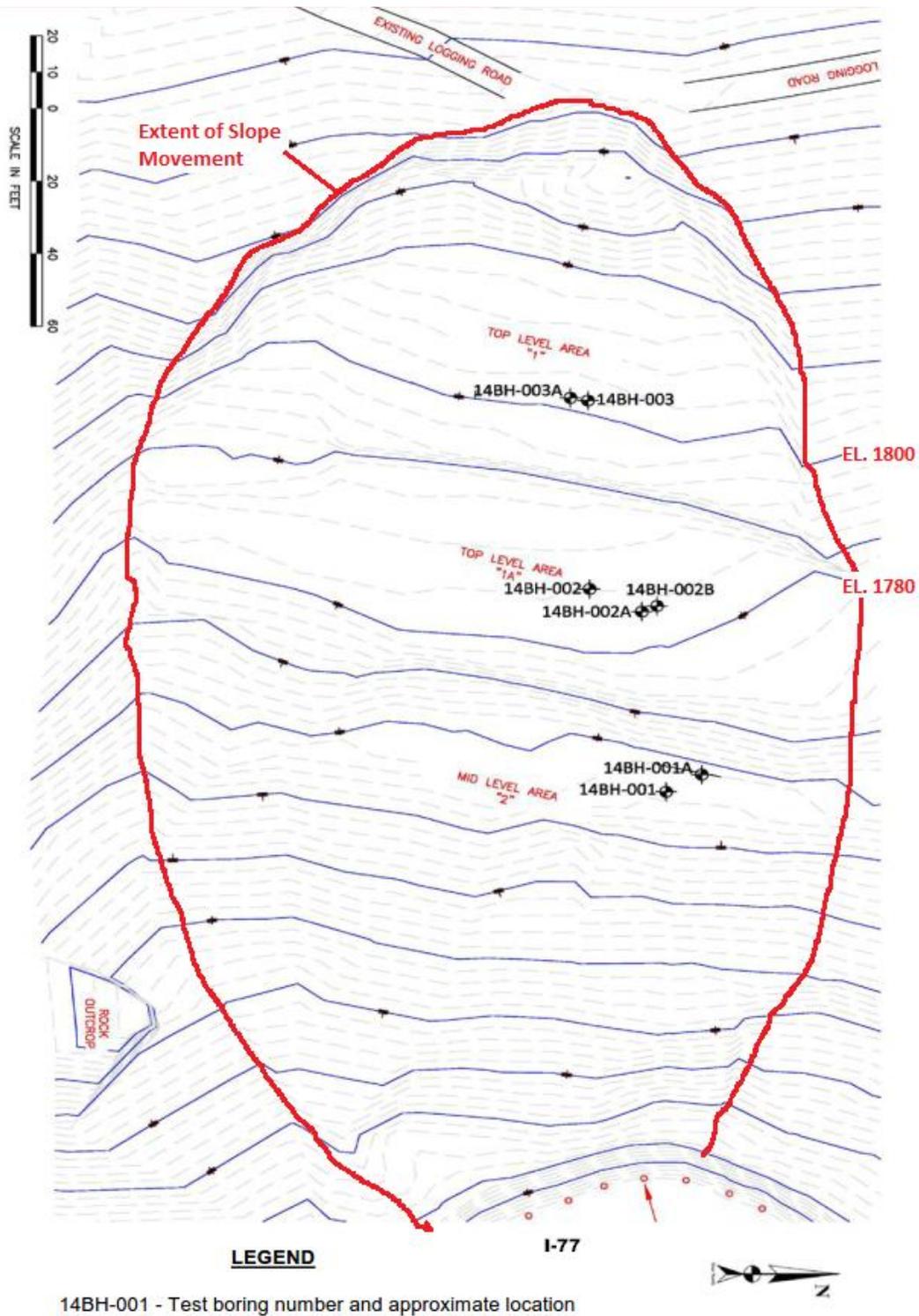
Figure 10: Scarp within the Slide Material.²³



²² Image source: WSP | Parsons Brinckerhoff.

²³ Image source: WSP | Parsons Brinckerhoff.

Figure 11: Topographic Detail of the Soil Slope.²⁴



²⁴ Base map data: Schnabel Engineering, "Geotechnical Data Memorandum" Interstate 77 at Mile Post 1.8 Landslide Exploration and Monitoring, Carroll County Virginia, Phase I – Field Engineering and Lab Testing, July 24, 2014.

Although precipitation may or may not have initially *triggered* the October 2013 soil movement, precipitation did occur a few days earlier at Fancy Gap, Virginia, 6.2 miles north-northeast of the study site as shown in Table 1.

Table 1: Precipitation Recorded Prior to October 21, 2013.²⁵

Date	Rainfall Amount (Inches)
October 6, 2013	1.44
October 7, 2013	0.37
October 10, 2013	0.07
October 17, 2013	0.18
October 19, 2013	0.04

Another possible mechanism that may have triggered the initial slide may be related to seismic events. The Blue Ridge region has historically experienced minor earthquakes along active fault lines. The influence of seismic events on this slope is unlikely, but should be considered when implying causation to slope failure events within seismic regions.

To contain the slide, VDOT built a soil nail²⁶ supported toe wall, at the base of the slide in January 2014 (see Figure 12 and Figure 13). This was the first step in an adaptive response to the slide that includes building additional walls, higher on the slope, if needed. Figure 14 shows the full extent of the long-term, phased response plan. By stepping forward one phase and monitoring the results before committing more funds to the next phase, VDOT is addressing the uncertainty of the future but not risking expending funds that may not be necessary to protect the slope.

²⁵ Data provided courtesy of VDOT.

²⁶ Soil nailing consists of inserting slender reinforcing elements into the slope and installing a rigid facing of pneumatically applied concrete creating a wall at the toe of the slope – a “toe wall.”

Figure 12: Slide at MP 1.8 and Installation of Toe Wall.²⁷



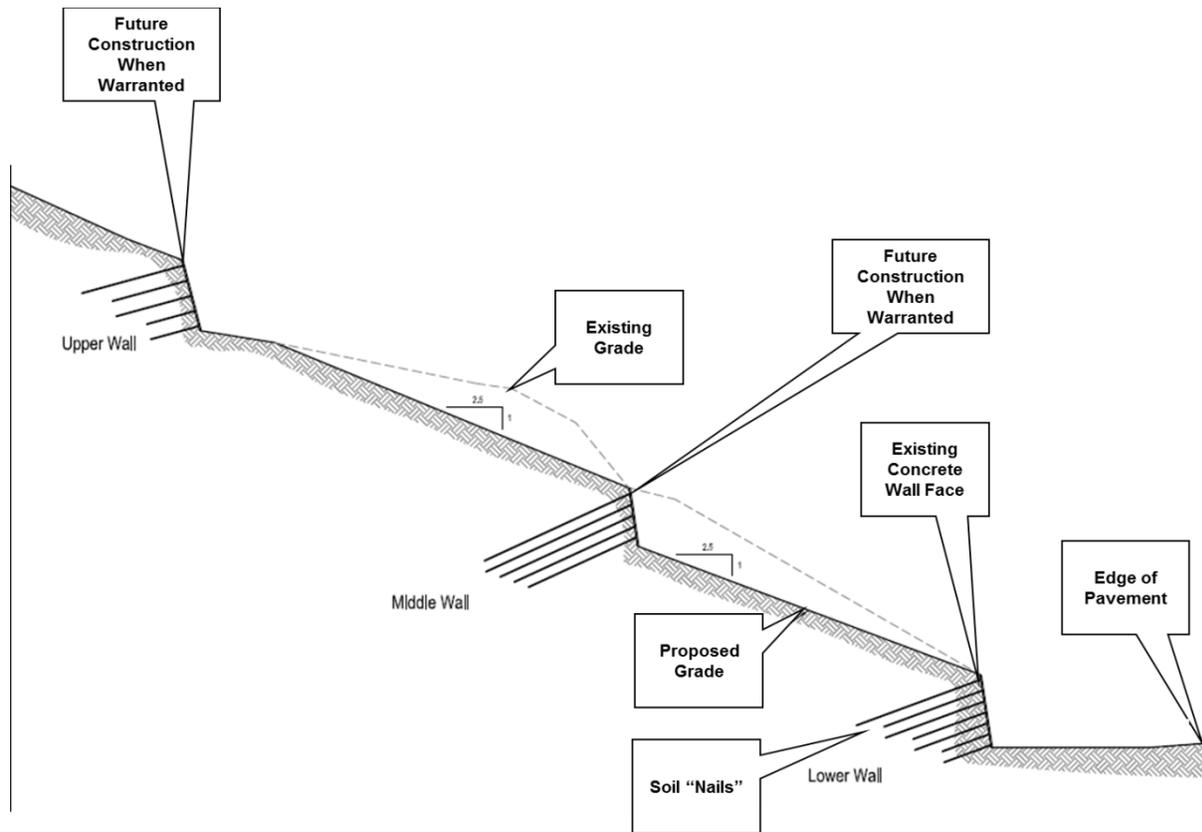
Figure 13: Completed Toe Wall at the Base of the Sliding Mass at MP 1.8.²⁸



²⁷ Image Source: Google Street View.

²⁸ Image Source: WSP | Parsons Brinckerhoff.

Figure 14: MP 1.8 Long-Term Phased Slope Instability Remediation Plan.



In summer 2014, VDOT installed inclinometers²⁹ and piezometers³⁰ to measure the movement of the slope and to monitor groundwater levels. Over 18 months of measurements, the inclinometer data revealed ongoing progressive slope movement of approximately 2.25 inches, which equates roughly to 0.125 inches of downslope movement per month. The highest magnitude of movement occurred during a wet period in the spring of 2015, equal to approximately one inch; however, there was relatively little movement during another period of wet conditions in the fall of 2015. Currently, there is not enough data to correlate slope movement and precipitation levels.

The piezometers installed to monitor groundwater levels did not encounter a groundwater table at the elevations at which they were installed. A geotechnical report dated April 14, 2015 concluded that additional slope stabilization measures were not necessary at that time because the movement had been relatively minor and that data should be collected bi-monthly or on a more frequent basis and reviewed for further assessment and recommendations.³¹ VDOT has

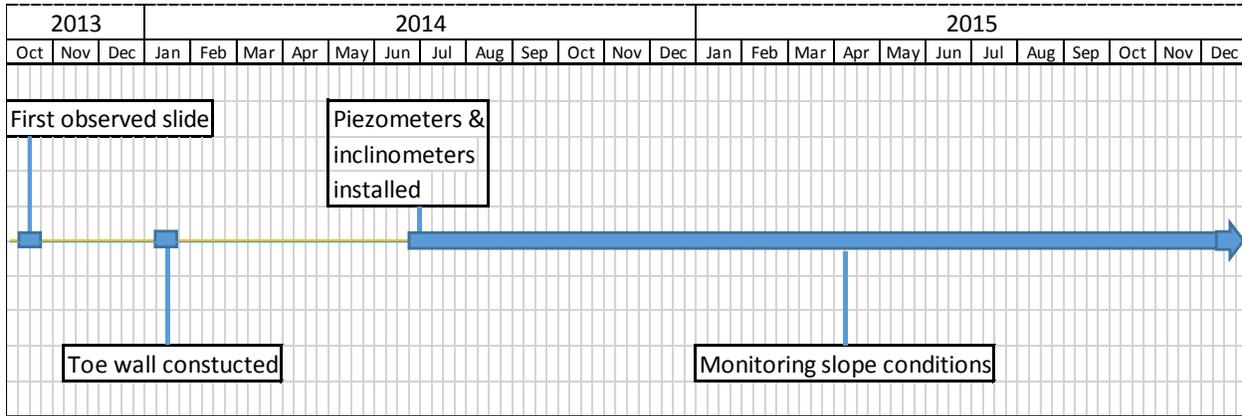
²⁹ Inclinometers are instruments used for measuring soil movement. The inclinometer is suspended on a string within a casing and confined in a drilled borehole. The instruments measure the deformation of the casing caused by soil movement.

³⁰ Piezometers are instruments used for measuring the depth of the groundwater table.

³¹ Geotechnical Engineering Report, Interstate 77 at Mile Post 1.8, Phase IV, Schnabel Engineering, April 14, 2015.

made regular observations since the soil nail wall has been in place and they indicate that the soil creep has slowed. Figure 15 provides a timeline of events summarizing VDOT actions after the first report of a slide at MP 1.8.

Figure 15: Timeline of VDOT Actions after the First Reported Observation of the MP 1.8 Soil Slide.



Rock Slopes

The native soils along the length of the study segment of highway contain intermittent sections of exposed bedrock. All of the rock slopes in the study area are cut into the biotite gneiss bedrock which is highly foliated (i.e., characterized by repetitive layering) in flat sheets, making it prone to weathering (see Figure 16 (a) and (b) for visual examples of the rock slopes). The rock cut slopes vary in height from 40 feet to over 250 feet.

The section of highway (MP 0 to MP 8 near Fancy Gap) has been prone to rockfalls throughout its lifetime. Three major rockfalls have closed highway lanes and resulted in one fatality. Figure 17 shows a map of the area between MP 3.75 and MP 6.3, where the rock slopes are primarily located, and includes locations of recent rockfalls along the corridor. Existing rockfalls protection measures in place over this 8-mile section of I-77 consist of rockfall barrier fences at two cut slopes on the west side of the southbound lanes at approximately MP 5.45 and 6.3. Additional rockfall protection, consisting of draped wire mesh, was installed on the rock slope faces at approximately MP 3, 3.8, and 5 during 2016.

Rockfalls have generally been planar, with large sheets of rock becoming unstable and separating along foliation planes. These rockfalls predominantly occur on the western slopes affecting the southbound travel lanes. Ruptures have also occurred where faults or cracks in the bedrock intercept the foliated layers, forming a wedge where moisture can collect. When this moisture is subjected to repetitive freeze-thaw cycles, the freezing force can break the weaker foliation bonds and trigger rockfalls (see Figure 16(c) for an example of an old rockfall site).

Figure 16: Rock Slopes Along I-77.³²



(a)



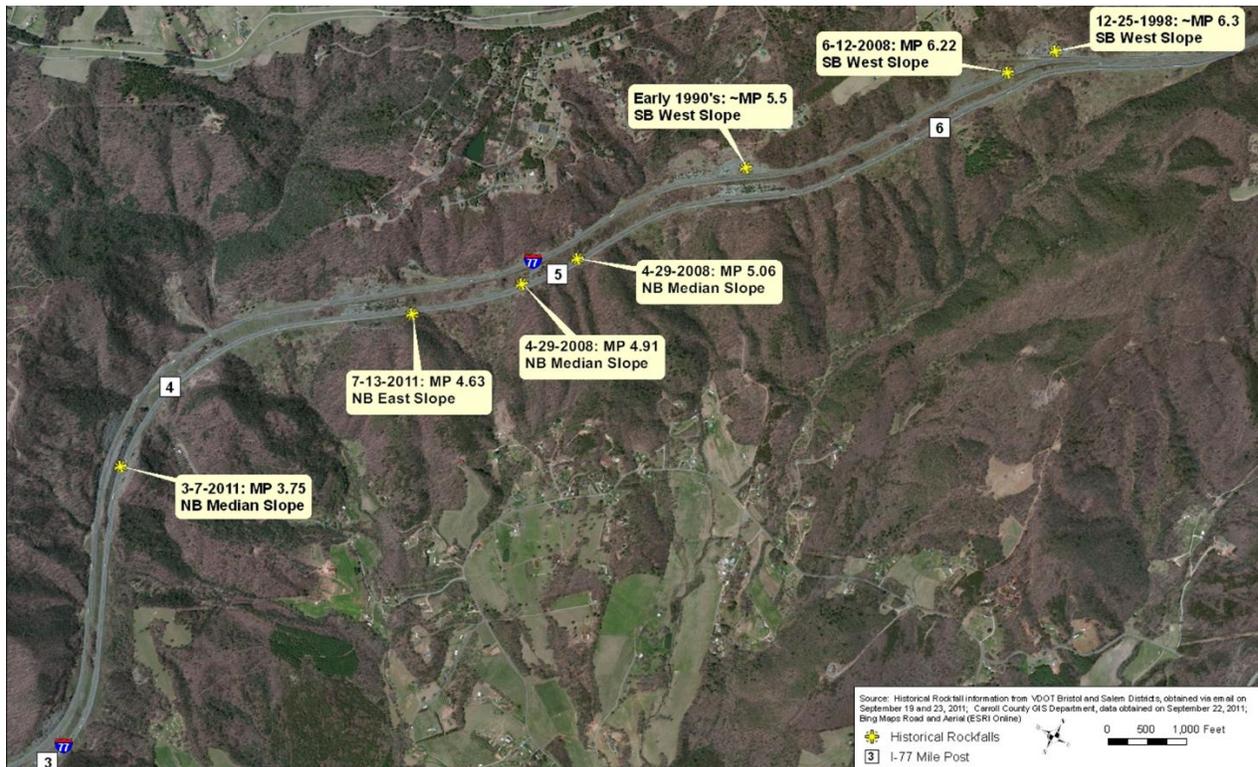
(b)



(c)

³² Image Source: WSP | Parsons Brinckerhoff.

Figure 17: Significant Recent Rockfall Locations, I-77 MP 3-6.3.³³



Step 3. Identify Climate Stressors

Slope failures and rockfalls along cut slopes can be sensitive to changes in the following climate stressors:

- Changing precipitation patterns:** Changes in precipitation affect soil saturation and groundwater levels that can change the risk of landslides in soil slopes. Both seasonal and storm event precipitation amounts impact slope stability. Changes in precipitation can also affect the rate of rockfalls by providing more moisture for freeze-thaw processes.

Climate Stressors

- Changes in precipitation (relevant to rock and soil slopes)
- Changes in temperature and in free-thaw cycles (relevant to rock slopes)

- Changes in temperature:** Changes in temperature, particularly increases in freeze-thaw cycles, can trigger rock falls along rock slopes.

Although erosion from precipitation runoff can alter slope geometry, it is generally not a primary factor in triggering rockfalls in this geologic setting so it is not included in this assessment.

³³ Source: Virginia Department of Transportation, Power Point® presentation: “I-77 Rockfall History.”

The geotechnical mechanisms through which changes in precipitation and temperature affect slope stability are discussed in more depth below.

Precipitation Impacts to Soil Slopes

Soil slope movement of the type occurring at MP 1.8 occurs when the gravitational forces acting on the soil overcome the soil's ability to resist movement. The soil generally weakens along a curved surface or plane that engineers term the "subsurface failure plane."³⁴ Figure 23, in Step 5, below, shows the shape of this plane at MP 1.8.

Changes in precipitation frequency, duration, and intensity can affect surface runoff (increasing erosion potential) and water infiltration, which in turn affects soil saturation, soil weight, groundwater table position, pore water pressures,³⁵ and, to a lesser extent, soil suction.³⁶ These factors influence the effective stresses³⁷ along the subsurface failure plane of a sliding soil mass, such as the one at MP 1.8, and affect the shear strength³⁸ needed to resist a slide. Increases in precipitation can increase the likelihood of soil slope failure through two general mechanisms:

- One mechanism is through **wetter conditions increasing the rate of water infiltration** into the soils, thereby increasing the total unit weight of the soils as they approach saturation. Heavier soils on steep slopes typically increase the driving force of the sliding soil mass above a nascent failure plane.
- A second mechanism is an **increase in groundwater table height** caused by infiltration of precipitation. If the water table height increases above the failure surface there will be a decrease in the effective stresses as the soil becomes buoyant, thereby reducing the shear strength along the failure plane.

Two additional mechanisms that may increase the likelihood of a sliding failure are increased pore pressures and/or reduction of soil suction along the failure plane. Neither of these mechanisms were considered in this analysis because groundwater pressurization cannot be determined without determining if soil suction is artificially increasing the shear strength along the failure plane and this is nearly impossible to determine due to the amount of variability at

³⁴ A failure plane is the geometric boundary that differentiates the sliding soil mass from the stable soil mass.

³⁵ Pore water pressure refers to the pressure exerted by water on its surroundings when held in pore spaces in rock or soil. The pressure is positive when the soil is fully saturated and is proportional to the height of the water measured in an open tube (a piezometer) above the point of interest. A buoyancy effect is achieved in this situation because the pressure and the shear strength of the soil is reduced. The pressure is zero when the soil voids are filled with air and is negative when the voids are partly filled with water (in which case surface-tension forces operate to achieve a suction effect and the shear strength of the soil is increased).

³⁶ Soil suction is the process by which moisture is drawn upward through the soil through capillary action just like a wick draws up liquid from a vessel below.

³⁷ Effective stress and neutral stress are geotechnical engineering terms describing the forces acting on a soil mass. A relative higher effective stress indicates a higher resistance to shear stress.

³⁸ Shear strength is the ability of the soil to resist sliding or "shear" movement.

this site. In addition, typical slope stability analyses in practice do not account for these mechanisms. Nonetheless, these two mechanisms are described in more detail:

- **Increased pore pressures** can be caused by subsurface hydraulically connected perched or trapped groundwater,³⁹ located upslope from the failure plane, in porous soils, tension cracks, or fissures in which precipitation can collect. This perched or trapped water can have a high hydraulic head⁴⁰ that can pressurize the groundwater, reducing the effective stress, and thus reducing the shear strength along the failure plane.
- **Reduction of soil suction** occurs when infiltrating water breaks the existing capillary forces, present just above the water table, and reduces the shear strength along the failure plane if it is located just above the water table.

Freeze-Thaw Impacts to Rock Slopes

Over time, rocks weather and break down from exposure to freeze-thaw cycles. As water enters the natural fissures in the rock and freezes (expands) then thaws (contracts), immense internal pressure is exerted within the rock until it ruptures. This weathering process generally occurs gradually over multiple decades. Depending on the rock type and its exposure to freeze-thaw cycles, rocks can weather within 20-40 years, which is within the life expectancy of highway slopes. Changes in the frequency of freeze-thaw cycles and the amount of moisture available (due to changes in precipitation) will affect the rate at which rock weathers. If climate change increases both the frequency of freeze-thaw cycles and the amount of moisture present due to increased precipitation, this could increase the rate at which rocks weather and rockfalls occur. Without additional freeze-thaw cycles, it is unlikely that additional precipitation alone would cause an increase in rockfalls.

Step 4. Develop Climate Scenarios

Before the completion of the parametric analysis, described in Step 5A, below, the research team analyzed both of the climate stressors (changes in precipitation and freeze-thaw cycles) to determine the magnitude of the changes in these two stressors. However, as is discussed in more detail in the lessons learned, this level of detail was ultimately determined unnecessary for the assessment of the soil slope stability. What is required, at least initially for screening, is simply a general understanding of the direction of change in the climate variables (i.e., increasing or decreasing precipitation levels and increasing or decreasing frequency of freeze-thaw events).

Historically, Carroll County is within a region that experiences a marine coastal climate with wintertime snowfall and warm summers. The annual average mean temperature is 53.1°

³⁹ Perched groundwater is subsurface water contained in a dish-shaped stratum or impervious soil.

⁴⁰ Hydraulic head refers to the vertical pressure from the weight of the water.

Fahrenheit and average annual total precipitation is 44.6 inches.⁴¹ Significant levels of precipitation are observed throughout the year with average monthly precipitation ranging between 2.7 and 4.6 inches. From 1895 to 2015, this region has shown no change in average temperature but a slight upward trend in precipitation (0.05 inches per decade).

This section begins with a description of the climate change scenarios used in this case study followed by discussion of the projected climate change variables.

Greenhouse Gas Scenarios

The research team used three climate scenarios based on plausible trajectories of future greenhouse gas emissions (GHGs), referred to as representative concentration pathways (RCPs).⁴² The RCPs describe how global society may evolve in its use of fossil fuels, technology, population growth, etc. and the resulting GHG concentration levels in the atmosphere. The three scenarios used include:

- **RCP 4.5** with a radiative forcing⁴³ of 4.5 watts per square meter indicating a low to moderate increase in the total greenhouse gas concentration levels in the atmosphere
- **RCP 6.0** with a radiative forcing of six watts per square meter indicating a moderate increase in the total GHG concentration levels in the atmosphere
- **RCP 8.5** with a radiative forcing of 8.5 watts per square meter indicating a high or unabated increase in the total GHG concentration levels in the atmosphere

Figure 18 presents the equivalent carbon dioxide⁴⁴ concentrations and radiative forcing trajectories of different RCPs. As shown in the graphs, RCP 4.5 annual GHG emissions rise quickly but then stabilize with time. After about 2060, RCP 6.0 GHG emissions exceed RCP 4.5 GHG emissions and then stabilize. Finally RCP 8.5 GHG emissions rise steadily at a greater rate

Climate Data Overview

Level of Detail: Developed detailed projections of future temperature and precipitation

Data Source: Global Historical Climatology Network (GHCN), U.S. Bureau of Reclamation (2013) which provides peer-reviewed statistically downscaled data of the World Climate Research Programme's Coupled Model Intercomparison Project 5

Scenarios: Representative Concentration Pathways (RCPs) 4.5, 6.0, and 8.5

Is exposure projected to change in the future? Fall, winter, and spring precipitation are projected to increase along with small increases in the intensity of storm events. Number of freeze-thaw days are projected to decrease.

⁴¹ Source: National Oceanic and Atmospheric Administration. Climate at a glance. <http://www.ncdc.noaa.gov/cag/> for the Southwestern Mountain region within the state of Virginia. Based on 1990 to 2010 data.

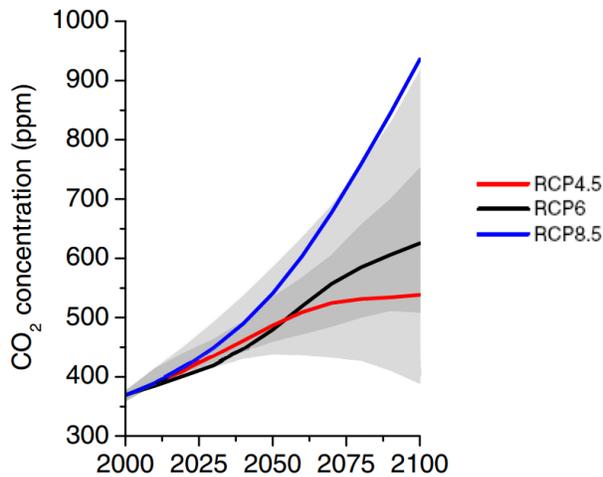
⁴² Van Vuuren, et al. (2011). The representative concentration pathways: an overview. Climatic Change

⁴³ Radiative forcing causes a change in the energy balance leading to a net warming or cooling of climate. For example, a change in the concentration of carbon dioxide or the output of the sun can cause a radiative forcing (IPCC 2014 WGIII).

⁴⁴ Carbon dioxide equivalent is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential.

compared to the other RCPs and do not stabilize at the end of the century. It is important to note that the global radiative forcing does not reflect local changes in precipitation (i.e., more global radiative forcing does not necessarily consistently indicate more or less precipitation for a given area).

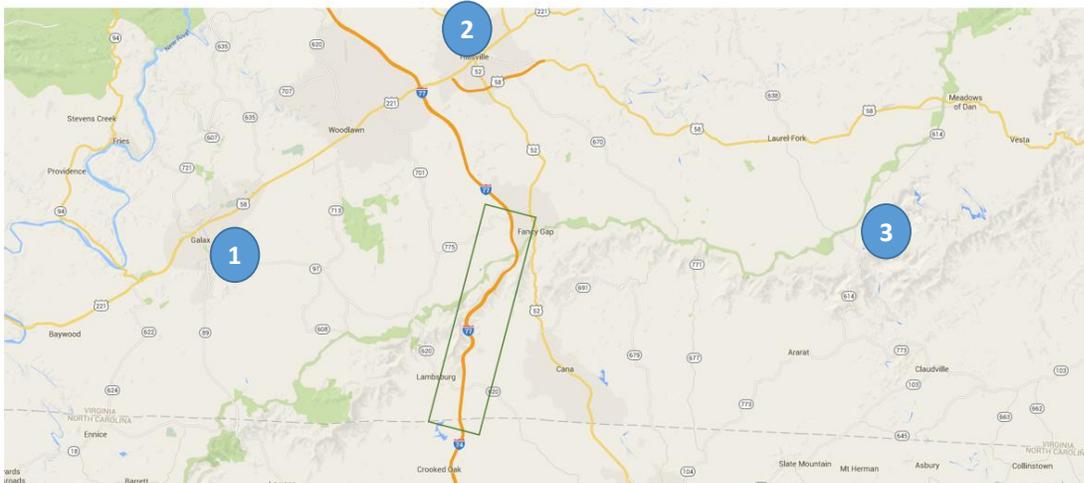
Figure 18: Radiative Forcing Trajectories of Different Representative Concentration Pathways.



Climate Projections

The research team collected historical observations and developed projections of future changes in seasonal precipitation, storm event precipitation, and freeze-thaw cycles. The research team obtained historical observations from three Global Historical Climatology Network (GHCND) observation stations: USC00443267, USC00443991, and USC00445453 (see Figure 19). All three stations provided precipitation data; temperature data was available only from station USC00443267.

Figure 19: Locations of GHCND Observation Stations (1) USC00443267, (2) USC00443991, and (3) USC00445453 relative to the Project Area (Green Box).⁴⁵



The research team used publicly available statistically downscaled⁴⁶ climate change data from the U.S. Bureau of Reclamation (USBR) to develop the climate data projections.⁴⁷ The USBR's website provides downscaled data from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Five (CMIP5) that was used to inform the Intergovernmental Panel on Climate Change (IPCC) Assessment reports. These projections, originally available at a spatial resolution of approximately one degree,⁴⁸ have been statistically downscaled to 1/8 degree resolution grid cells for the United States by USBR. The research team downloaded daily values for minimum temperature, maximum temperature, and precipitation for 11 global climate models, four USBR grid cells,⁴⁹ and the three RCPs from 1950 to 2099 (see Table 2).⁵⁰ This analysis averages across the four grid cells for each model/scenario combination for three future time periods (2035-2054 termed "2045", 2055-2074 termed "2065", 2080-2099 termed "2090").

⁴⁵ Underlying map from Google Maps.

⁴⁶ Statistical downscaling is a technique for improving the spatial resolution of climate projections based on historical climate observations.

⁴⁷ Reclamation (2013). Downscaled CMIP 3 and CMIP 5 Climate and Hydrology Projections. Retrieved from: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

⁴⁸ The one-degree value is approximate because each climate model's spatial resolution varies and may be smaller or larger than one degree.

⁴⁹ Four grid cells were chosen based on the center of the study location with latitude of 36.639571° North and longitude of 80.717160° West.

⁵⁰ The research team acknowledges the WCRP's Working Group on Coupled Modelling, which is responsible for CMIP, and thanks the climate modeling groups for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provided coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Table 2: Global Climate Models and Scenarios used for this Study.

Global Climate Models	Scenarios
▪ bcc-csm1-1	▪ RCP4.5
▪ ccsm4	▪ RCP6.0
▪ gfdl-esm2g	▪ RCP8.5
▪ gfdl-esm2m	
▪ ipsl-cm5a-lr	
▪ ipsl-cm5a-mr	
▪ miroc-esm	
▪ miroc-esm-chem	
▪ miroc5	
▪ mri-cgcm3	
▪ noresm1-m	

The remainder of this section discusses the historical data and future projections of seasonal and annual precipitation, storm event precipitation, and freeze-thaw cycles.

Seasonal and Annual Precipitation

Historically, the project site has experienced the heaviest rainfall during the summer months and the lowest precipitation levels during the winter months.⁵¹ Table 3 below shows the observed seasonal precipitation from 1990 to 2009. There is some variability across these stations, particularly between USC00445453 and the other two stations. There are a number of factors that may contribute to station-to-station variability, including the presence of small-scale atmospheric processes that affect precipitation amounts or potential errors in precipitation collection. The research team calculated the average seasonal rainfall across the three weather stations to represent the observed values for comparison with the future projections.

⁵¹ For the purposes of this analysis, the seasons are defined as follows: winter consists of December, January, and February; spring is March, April, and May; summer is June, July, and August; and fall is September, October, and November.

Table 3: Observed Seasonal Precipitation for Study Area Stations, 1990 to 2009.

Season	Observed Precipitation (inches)			Average (inches)
	USC00443267	USC00443991	USC00445453	
Winter	9.49	8.58	12.36	10.16
Spring	10.94	11.54	14.21	12.24
Summer	12.13	11.46	16.73	13.43
Fall	9.88	10.35	13.27	11.18
Annual Total	42.44	41.93	56.57	47.01

For developing the future seasonal precipitation projections, the research team coded the following approach in Microsoft Excel:

- For each climate model and scenario, averaged the daily precipitation across the four grid cells from 1980 to 2099;
- For each climate model and scenario, summed the daily precipitation to obtain seasonal precipitation from 1980 to 2099;
- For each climate model and scenario, averaged seasonal precipitation for each time period;
- For each climate model, scenario, and time period, calculated the future change by subtracting the future model projection from the baseline model simulation; and
- For each climate model, scenario, and time period, calculated the ensemble averages (i.e., average across all climate models for each scenario) of future change.

The results are presented in tabular form in Table 4 and graphically in Figure 20. In the graphical figure, the ensemble means are represented by rectangles and the range across the models is shown by error bars. As one can see, changes in seasonal precipitation generally suggest an increase in winter, spring, and fall precipitation and a decrease in summer precipitation. For the end of century, seasonal precipitation based on the ensemble averages of RCP 4.5 varies from a decrease of 14% in summer to an increase of 15% in winter. All scenarios show an increase in the annual total precipitation with the greatest increases in annual precipitation projected in the early to mid-century periods.

It is likely that in some cases, the increase in annual precipitation is within the natural variability (i.e., year-to-year change) experienced today. The annual precipitation increase is not as large for the end-of-century time period, largely due to the projected significant decrease in precipitation during the summer months. Unlike simulating future temperatures that tend to warm with increasing greenhouse gas concentrations and the associated radiative forcing, precipitation is affected by many variables particularly at the local scale. For example, changes in pollution where particles act as a surface for condensation and cloud formation, vertical

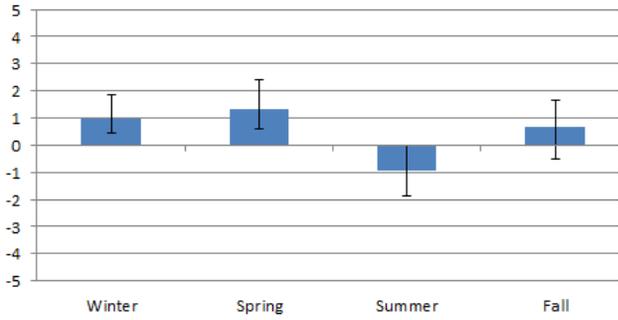
temperatures, atmospheric circulation patterns, and sea surface temperatures can all play a role in whether a cloud is formed and then develops into a precipitation-producing cloud.

Table 4: Projected Change in Seasonal Precipitation Relative to a 1990-2009 Baseline.

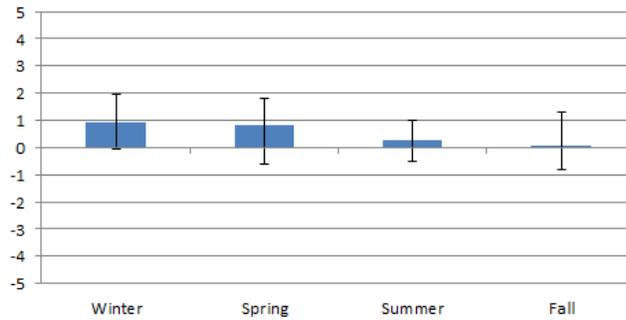
Season	Obs (inches)	2035-2054			2055-2074			2080-2099		
		RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5
Winter	10.16	+1.00	+0.91	+0.97	+0.57	+0.82	+1.45	+2.04	+0.74	+1.13
Spring	12.24	+1.35	+0.82	+0.19	+0.43	+1.24	+1.72	+0.80	+0.31	+0.04
Summer	13.43	-0.94	+0.29	+1.04	-0.37	-0.87	-0.56	-2.12	-0.81	-1.24
Fall	11.18	+0.67	+0.09	+0.39	+1.32	+0.27	+1.22	+0.87	+0.32	+0.88
Annual Totals	47.01	+2.08	+2.11	+2.58	+1.95	+2.46	+3.82	+1.58	+0.56	+0.80

Figure 20: Projected Changes in Seasonal Precipitation (in Inches) by Scenario and Future Time Period.

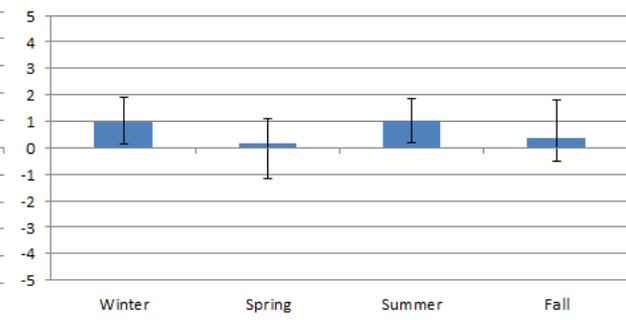
2035-2054, RCP4.5



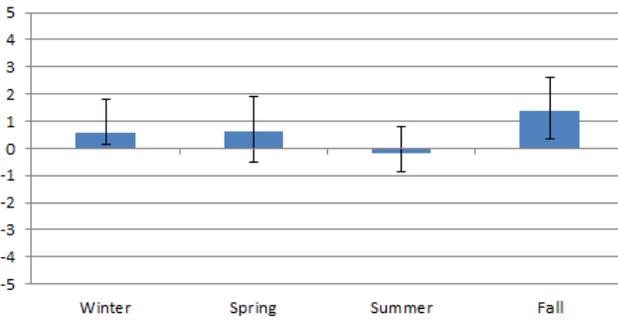
2035-2054, RCP6.0



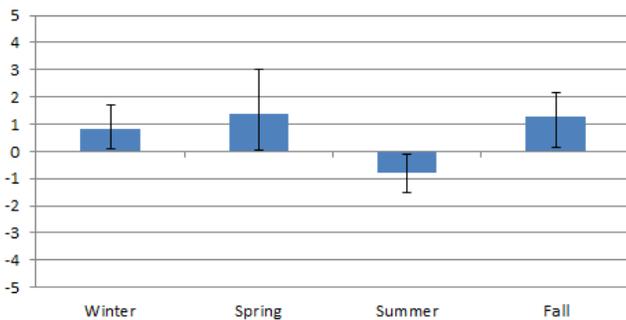
2035-2054, RCP8.5



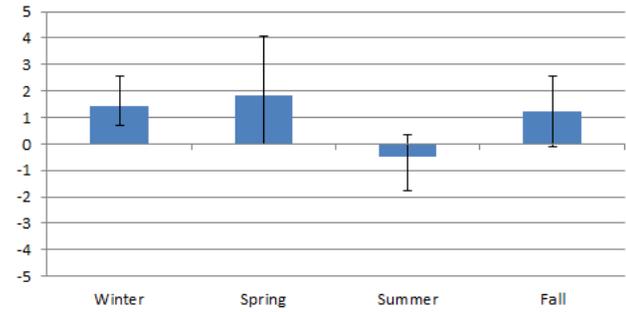
2055-2074, RCP4.5



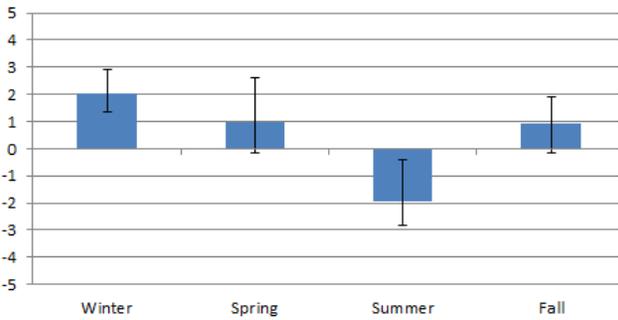
2055-2074, RCP6.0



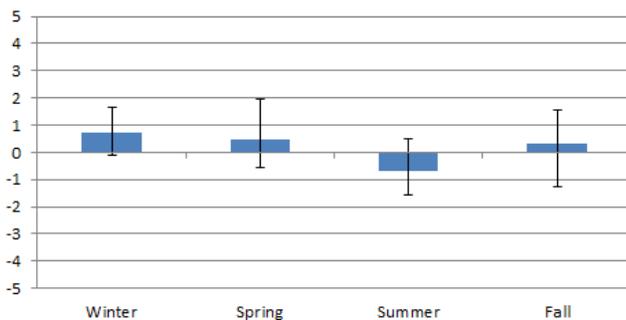
2055-2074, RCP8.5



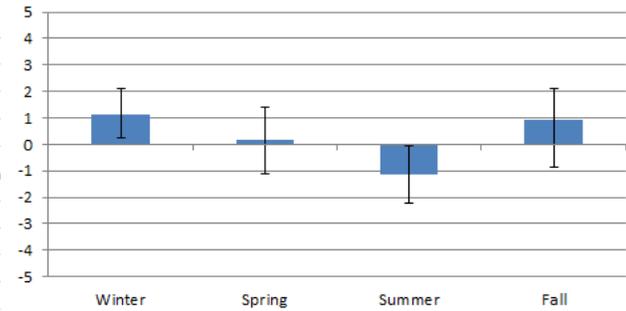
2080-2099, RCP4.5



2080-2099, RCP6.0



2080-2099, RCP8.5



Storm Event Precipitation

Heavy precipitation from storm events have the potential to trigger landslides that can damage transportation infrastructure and interrupt traffic. The research team used a generalized extreme value distribution (GEV)⁵² to create a theoretical fit for each station's annual maximum daily precipitation (i.e., the highest amount of daily precipitation for a given year) to estimate the total daily precipitation associated with the 1-in-10, 1-in-50, and 1-in-100 year return period⁵³ storms. The research team developed daily precipitation projections for return periods for modeled baseline and future time periods and for baseline conditions. National Oceanographic and Atmospheric Administration (NOAA) Atlas 14, Volume 2, Version 3 was used for baseline conditions.

The research team developed the change in future return periods using the following steps:

- The maximum daily precipitation for each year from 1980 to 2099 was determined for each emissions scenario, climate model, and grid cell;
- The GEV was fitted to each set of maximum annual precipitation data for each 20-year time period,⁵⁴ emissions scenario, climate model, and grid cell;
- The return periods were then calculated based on the GEV fit for each emissions scenario, climate model, grid cell, and time period;
- Return periods were then averaged across the four grid cells for each time period, emissions scenario, and climate model;
- For each emissions scenario and climate model, the projected change was then calculated by subtracting the baseline average from the future average; and
- For each emissions scenario, the projected change across the climate models was averaged to obtain the ensemble average value.

Projected changes in the magnitude of recurrence intervals are provided in the Table 5 for the climate model ensemble by scenario and future time period.⁵⁵ The magnitude of the storm

⁵²The choice of GEV is consistent with the best fit for precipitation in Virginia as described in NOAA Atlas 14 (2004): http://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume2.pdf. This is also consistent with the choice of extreme value distributions used in the other TEACR case studies.

⁵³ A return period describes how frequently a storm with a given magnitude occurs in that location. For example, a 1-in-100 year return period is a storm that has a 1 percent chance of occurring in any given year.

⁵⁴ When fitting a distribution and then extrapolating to obtain values at the tails (e.g., the 100-year storm), a 30-year or longer time period may be preferred so that a sufficient amount of data points are used. However, this study needed to provide projections for the end of the century when climate may be changing more rapidly and the beginning and end of the 30-year period could be in two statistically different climate periods. Because of this, 20-year time periods were chosen for this distribution instead of the 30-year minimum period typically used.

⁵⁵ In a very limited number of cases, the GEV distribution did not do a good job representing specific climate simulations at a specific grid cell (due to the poor fit between the GEV distribution curve and the climate simulation data). This poor fit included the following climate simulations: (1) the miroc-esm-chem climate model

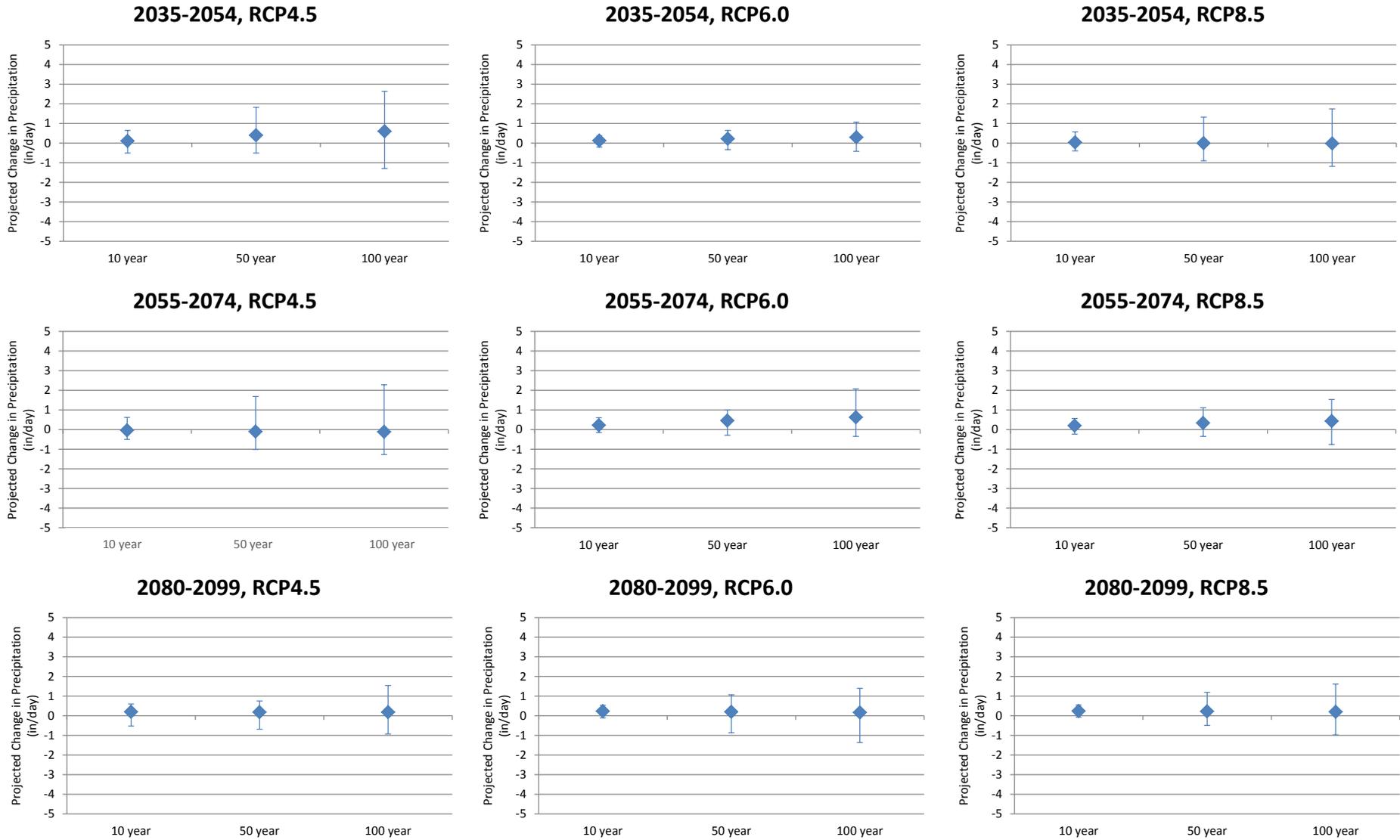
events is largely projected to increase, suggesting the severity of storms will increase for the study location, though not dramatically so. Figure 21 illustrates the ensemble means by diamonds and the range across the models by error bars.

Table 5: Projected Changes in the Daily 10-Year, 50-Year, and 100-Year Storm Events Relative to a 1990-2009 Baseline.

NOAA Atlas (inches)		2035-2054			2055-2074			2080-2099		
		RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5
10 year	4.80	+0.11	+0.12	+0.04	-0.03	+0.22	+0.19	+0.20	+0.22	+0.24
50 year	6.61	+0.39	+0.22	-0.00	-0.10	+0.45	+0.34	+0.18	+0.20	+0.22
100 year	7.44	+0.60	+0.29	-0.02	-0.12	+0.62	+0.43	+0.18	+0.17	+0.20

under the RCP 4.5 scenario for two grid cells, and (2) the mri-cgcm3 model under the RCP 8.5 scenario and RCP 6.0 scenarios for one grid cell. These poor data fits were not included in the analysis.

Figure 21: Projected Changes in Storm Precipitation (in Inches) By Scenario and Future Time Period.



Freeze-Thaw Cycles

For this study, a daily freeze-thaw event is defined as a day when the minimum temperature drops below freezing (32° Fahrenheit) and the maximum temperature is above freezing; in other words, a freeze-thaw event occurs when the freezing mark has been crossed during the day. The research team used Station GHCND USC00443267, the only station nearby with temperature data (minimum and maximum daily values), to calculate the average number of freeze-thaw events per year from 1980 to 2009.

For projecting future changes in daily freeze-thaw events, the research team undertook the following process:

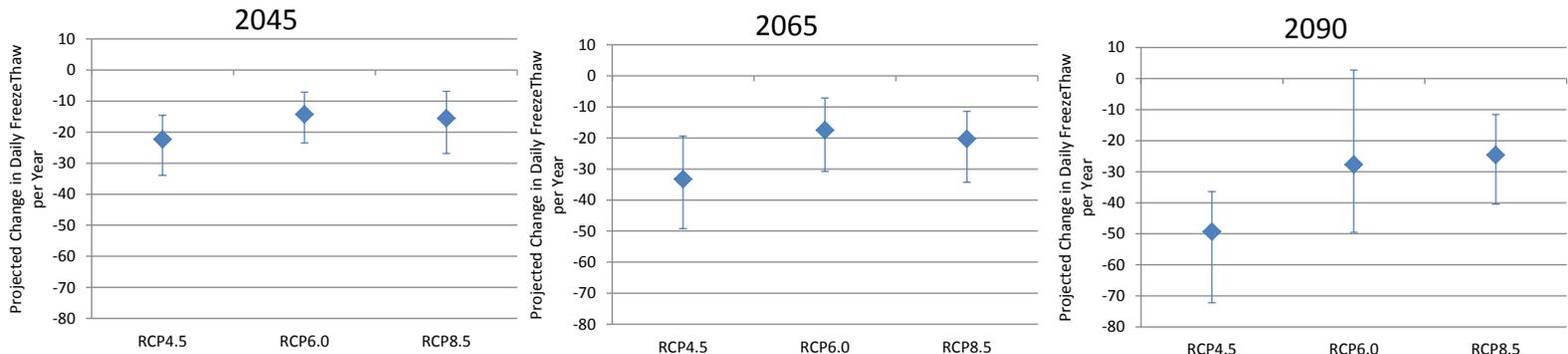
- For each climate model, emissions scenario, and grid cell, the research team summed the number of days per year where the daily minimum temperature was below 32° Fahrenheit and the daily maximum temperature was above 32° Fahrenheit;
- The total number of freeze-thaw days per year was then averaged for each time period, climate model, emissions scenario, and grid cell;
- Next, the research team averaged across grid cells for each time period, climate model, and emissions scenario;
- The ensemble average of daily freeze-thaw was calculated for each time period and emissions scenario; and
- For each emissions scenario, the projected change was calculated by subtracting the baseline average from the future average for both the ensemble and by climate model.

Table 6 summarizes the projected changes in freeze-thaw events. All future projections suggest a reduction in freeze-thaw days from 14% to close to 50%. Upon inspection of a few scenarios/models, this appears to be primarily due to the projected daily minimum temperatures warming to above freezing conditions. Figure 22 illustrates the ensemble means by diamonds and the range across the models by error bars.

Table 6: Projected Change in Daily Freeze-Thaw Events per Year Relative to a 1990-2009 Baseline.

	Obs	2045			2065			2090		
		RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5	RCP4.5	RCP6.0	RCP8.5
Days per year	101	-22	-14	-16	-33	-18	-20	-49	-28	-25

Figure 22: Projected Changes in Daily Freeze-Thaw Events per Year.



The research team also explored the change in freeze-thaw events per year that occur the day of or the day after a precipitation event. This provided some insight as to how the frequency of potentially dangerous expansion of water within the rock slope might change under future conditions. The research team investigated future changes in the following six conditions for each climate model, scenario, and time period averaged over the four grid cells:

1. Number of days with precipitation at or above 0.01 inches and a freeze-thaw cycle occurs;
2. Number of days with precipitation at or above 0.05 inches and below 0.1 inches and a freeze-thaw cycle occurs;
3. Number of days with precipitation at or above 0.1 inches and below 0.5 inches and a freeze-thaw cycle occurs;
4. Number of days with precipitation at or above 0.01 inches and a freeze-thaw cycle occurs the next day;
5. Number of days with precipitation at or above 0.05 inches and below 0.1 inches and a freeze-thaw cycle occurs the next day; and
6. Number of days with precipitation at or above 0.1 inches and below 0.5 inches and a freeze-thaw cycle occurs the next day.

The results suggest a reduction in the future number of days for all six conditions for all time periods, scenarios, and climate models. The exception was condition 6 for the RCP 6.5 scenario where the ensemble average suggested an additional day or two of this condition in the near-term and mid-century.

Summary

The projected increases in seasonal precipitation in fall, winter, and spring along with the small increases in the intensity of storm events indicate increasing exposure for the soil slope. Thus, the soil slope analysis will proceed to Step 5A.

Climate exposure for the rock slopes due to freeze-thaw events, however, is expected to decrease in the future under all climate change scenarios (although changes in precipitation may still affect the rock slopes). Thus, consistent with ADAP, no further analyses are necessary for the rock slopes since exposure to freeze-thaw events is not expected to rise with climate change.

Steps 5 through 11 (Rock Slopes)

These steps are not required for this analysis because the climate stress of more frequent and/or severe freeze-thaw cycles are not projected to increase. However, other climate factors may still affect the slopes, such as an increase in precipitation. These factors might have an effect on the frequency of rockfalls in the future. VDOT should continue to monitor the slopes and follow established protocols for managing cut rock slopes.

Step 5A. Assess Asset Performance under the Highest Impact Scenario (Soil Slope)

As previously mentioned, the research team approached the assessment of the highest impact scenario by determining how the soil slope would perform under a range of extreme conditions, rather than assessing how it would perform under the specific climate change scenarios developed in Step 4. The team ran a parametric analysis⁵⁶ that varied the groundwater elevation parameter well beyond the level that could be expected to infiltrate from precipitation and varied the

soil unit weights to determine if these extreme values would affect the tendency of the slope to fail. A parametric analysis was determined to be an efficient initial screening approach to the problem since undertaking the modeling necessary to tie projected changes in precipitation under a given scenario to soil unit weights and the groundwater table is a larger effort that should only be undertaken if the parametric screening analysis indicates slope sensitivity to precipitation. The presence of the discrete soil nail elements were not included in the analysis; however, the geometry created from the soil nail walls was modeled.

Methodology

The research team followed the following basic steps to conduct the engineering assessment:

Facility Performance Overview

Highest Impact Scenario: Elevated perched groundwater conditions and higher soil unit weights.

Asset Design Standards: Allowable Stress Design standard practice.

Key models, tools, and assumptions: SLOPE/W, cross section geometry, soil properties, groundwater conditions.

Is the structure resilient? Yes.

⁵⁶ A parametric analysis is one that, in general, varies a constant or variable term in a function that determines the specific form of the function but not its general nature. For example, altering a in $f(x) = ax$ to see the effect on $f(x)$ where a determines the slope of the line described by $f(x)$.

- Calculated the slope factor of safety⁵⁷ under current conditions, which required the following inputs:
 - Location and shape of the failure surface
 - Depth to bedrock at the slide location
 - Engineering properties of the residual soils
 - Shear strength of the soil
- Calculated the slope factor of safety under a range of future groundwater levels and soil unit weights
- Determined the magnitude of the change in factor of safety that would be caused by future precipitation projections.

To calculate the slope factor of safety under current conditions, the research team used a limit equilibrium method of slope stability analysis with SLOPE/W⁵⁸ computer software. The limit equilibrium method looks at the balance of forces within a soil mass--the balance between forces that tend to cause the slope to slide down under the influence of gravity versus those forces that tend to hold it in place. The following paragraphs go through the assumptions and methods for obtaining the inputs to the SLOPE/W software.

The first required input is the location and shape of the slip surface which can be measured directly with instrumentation or approximated using limit equilibrium analysis. The research team obtained subsurface (e.g., stratigraphy⁵⁹ and material properties) and topographic data for the slope from VDOT's April 2015 Geotechnical Engineering Report.⁶⁰ With this information, the research team estimated the physical location of the failure plane using the inclinometer data obtained from beneath the surface of the slope and the existing topography. Figure 23 depicts the theoretical failure surface adapted from inclinometer data and topography and optimized using Spencer's procedure.

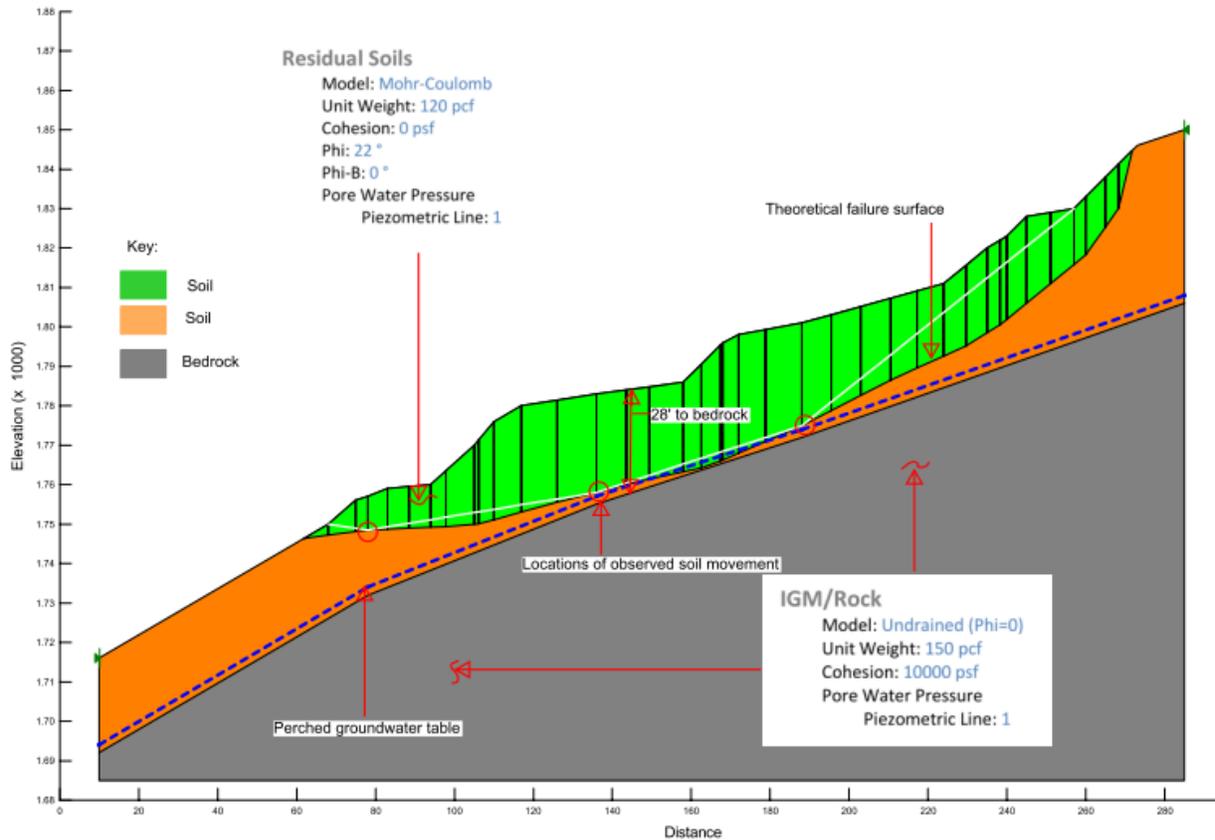
⁵⁷ The factor of safety is the ratio of the shear strength (resistance to sliding) to the shear stress (force tending to cause a slide) required for equilibrium. If the value of the factor of safety is less than 1.0, the slope is unstable.

⁵⁸ SLOPE/W is a geotechnical engineering software developed by GEO-SLOPE International. SLOPE/W employs limit equilibrium to model slope stability and compute the factor of safety.

⁵⁹ Stratigraphy relates to the order and relative position of strata and their relationship to the geological time scale.

⁶⁰ Geotechnical Engineering Report, Interstate 77 at Mile Post 1.8, Phase IV, Schnabel Engineering, April 14, 2015.

Figure 23: Approximate Location of the Theoretical Failure Surface at MP 1.8.



The next required input is the depth to bedrock below the slip surface. The depth to bedrock is difficult to determine in this geologic setting because the bedrock is highly foliated, characterized by alternating rock layers that vary in durability to weathering. When the rock mass is tilted by geologic forces, the exploratory soil borings may extend into the weathered layers or abruptly encounter a more durable layer. An example of bedrock near this slope that was tilted by geologic forces can be seen in Figure 16(a) and Figure 16(b) in Step 2.

For this analysis, the research team modeled the intact bedrock at the most conservative depth below the ground surface--just below the failure plane measured by the inclinometers. At this location, the model will produce the most dramatic changes to the factor of safety caused by a rising perched ground water table, which directly increases the pore water pressures along the failure plane. In turn, the increase in pore pressures results in lower effective stresses and lower shear strength.

Another required input to the SLOPE/W software is the engineering properties of the residual soils. The research team determined the engineering properties of the residual soils necessary for the analysis based on the boring logs and laboratory testing included in the report cited above.

For this assessment, the research team used a current, typical soil (wet sand) unit weight of 120 pounds per cubic foot.

Since slope failure is the result of forces resisting sliding (shear resistance) being overcome by the forces working to cause sliding (shear forces), it is necessary to compute the resisting forces (i.e., the shear strength of the soil). The general equation, below, for calculating available shear strength within a soil (for this case, along the theoretical failure plane) relates moisture from precipitation and groundwater to slope failure:

$$\tau = c + \sigma \tan\phi$$

Where,

- τ = the available shear strength along the failure plane
- c = cohesion intercept⁶¹ of the soil, which is equal to zero for the cohesionless soils at this site
- ϕ = angle of internal friction within the soil
- σ = vertical effective stress on the failure plane, which is a function of soil unit weight and buoyancy effects caused by the location of the groundwater table⁶²

A key element in this equation is the angle of internal friction – a measure of a soil's tendency to fail under shear forces. The higher the internal angle of friction, the more resistant a soil is to sliding. For this slope, an angle of internal friction (ϕ')⁶³ of 22 degrees⁶⁴ was used and coincides

⁶¹ Cohesion intercept is a value of shear strength that is present in cohesive soils that is not influenced by changes in external stresses.

⁶² The equation shows that the vertical effective stress has a direct effect on the available shear strength along the failure plane. Vertical effective stress is calculated using soil unit weights and height of the water table above the point of interest or, in this case, the failure plane of the sliding soil mass. The impact of increases in precipitation is analyzed using the vertical effective stress variable in the shear strength equation.

⁶³ A measure of the ability of a unit of rock or soil to withstand a shear stress. It is the angle (ϕ), measured between the normal force (N) and resultant force (R), that is attained when failure just occurs in response to a shearing stress (S). Its tangent (S/N) is the coefficient of sliding friction. (Ailsa Allaby and Michael Allaby. "Angle of internal friction." *A Dictionary of Earth Sciences*. 1999. *Encyclopedia.com*. (January 25, 2016). <http://www.encyclopedia.com/doc/1O13-angleofinternalfriction.html>.

⁶⁴ Although this ϕ' value is considerably lower than the nearly 36 degrees measured with lab testing, the model more accurately reflects the observed field conditions using the lower, back-calibrated ϕ' value of 22 degrees. This lower ϕ' value may provide more accurate results in the model due to gradual soil softening or creep along the failure plane. Creep and soil softening occurs when soil shearing is very slow and soil particles begin to rearrange along the failure plane. This particle rearrangement can dilate the soil, cause excess water to enter, and further lubricate the soils along the failure plane. This is supported by the measured soil moisture contents near the observed failure plane which were generally higher than the surrounding soils, suggesting soil creep and softening may be or have occurred in the past. In addition, the presence of mica minerals in the residual soils may contribute to the decrease in shear strength.

with a factor of safety under current conditions to be approximately 1.05. A factor of safety just above one coincides with the progressive slope movement being observed at the site.

To understand the impact of increased precipitation on the factor of safety, the research team performed a parametric study that calculated the changes in the factor of safety under a range of potential future variations in soil unit weights and higher perched groundwater levels. As previously discussed, these variables affect slope stability due to the increased weight of residual soils that approach saturation and decreased shear strength along the failure plane caused by buoyancy effects. The research team used a parametric study rather than directly using the climate change scenario data developed in Step 4 because rainfall impacts on soil unit weights are unknown and the groundwater table height is unknown.

The research team used a range of future soil unit weights varying from a typical minimum of 105 pounds per cubic foot to 130 pounds per cubic foot and assumed perched groundwater table height varied from zero feet to seven feet (arbitrarily stopped at seven feet as it is an extreme value to expect the height to reach from precipitation infiltration) above the soil-rock interface. A multitude of values within the ranges specified were modeled to produce a corresponding approximate range of factors of safety.

Results

Based on initial sensitivity analyses, variations in soil unit weight did not have an appreciable impact on the factor of safety. The resulting general impact to the factor of safety caused by an increase of perched water table height above bedrock is depicted in Figure 24.

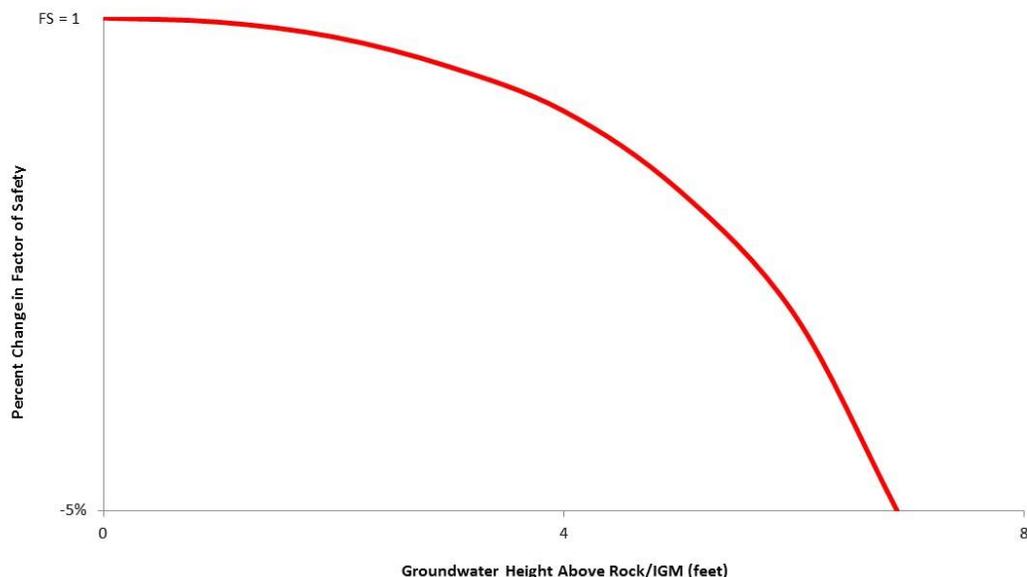


Figure 24: Generalized Estimated Changes in the Factor of Safety with Increasing Groundwater Levels/Precipitation.

The results suggest that when the slope is already at a factor of safety close to one, increased precipitation on slopes in residual soils does not significantly affect the overall factor of safety to a degree of accuracy and precision to which slope stability analyses can be performed.

For context, the projected precipitation increase for the 100-year storm in 2065 is approximately half an inch from baseline conditions, which could not produce an increase in the groundwater level of seven feet. Although antecedent moisture conditions and seasonal variations could increase the groundwater table height, it would not reasonably be expected to reach the extreme level modeled in the analysis and, therefore, would not significantly affect the existing factor of safety. Nonetheless, for existing slopes that have a known factor of safety close to one, and considering the uncertainty inherent in climate projections, controlling groundwater levels by reducing infiltration associated with increased precipitation could reduce the risk of slope failure and should be further investigated to extend the “life” of the slope.

Steps 5B, 6, 7, and 8 (Soil Slope)

These steps are not required for this analysis because additional precipitation from climate change is not expected to be an issue for this particular slope and the fact that VDOT has initiated an adaptive design approach to mitigating future significant slope movement.

Step 9. Additional Considerations (Soil Slope)

Typically, Step 9 includes broader considerations such as environmental impacts, the agency’s tolerance for risk, and budget concerns for both maintenance and capital expenditures on adaptation measures. VDOT has taken an adaptive design approach (i.e., they are taking adaptive action in phases, monitoring the results and the environmental projections, and adapting accordingly). The adaptive design approach is strongly recommended when the level of uncertainty is high and budgets are constrained.

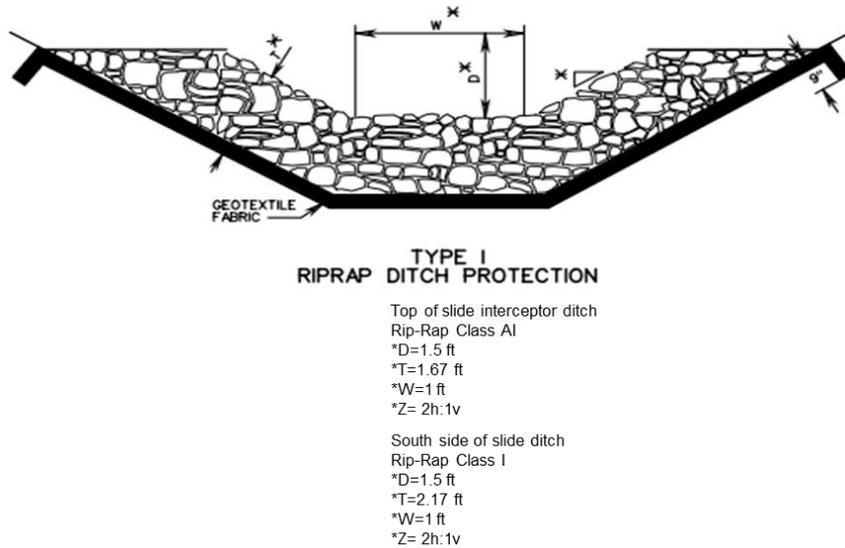
Step 10. Select a Course of Action (Soil Slope)

The results of this limited analysis indicates that higher groundwater levels caused by increased precipitation are having a negative effect on the slope stability; however, the slope is not projected to become significantly more unstable over time due to increases in precipitation.

This step typically requires selection of a specific adaptation solution to the existing or potential issues with an asset under study. This site is unique in that an adaption plan is under way and being followed. However, due to the current instability of the slope, in addition to the terracing measures proposed by VDOT, consideration could be given to one additional measure that would further reduce the amount of surface runoff infiltrating the perched groundwater area and, for relatively small cost, help extend the “life” of the slope. This additional measure would be to construct a small ditch, lined with impermeable geotextile and stone rip-rap above the scarp. Figure 25 shows a typical section of the suggested ditch. One ditch would run along the top of

the slide area and down the slope on the north side and another on the south side. These ditches would intercept the overland flow before it reaches the slide area and convey it to the highway drainage ditch.

Figure 25: Typical Section of Interceptor Ditch.⁶⁵



Step 11. Develop a Facility Management Plan

VDOT has installed instrumentation to monitor the slope movement and water table height with inclinometer casings and piezometers, respectively. Although the piezometers do not encounter any groundwater, the inclinometers should continue to be monitored on a regular basis in case this changes in the future. Consideration could be given to automating the readings using a data logger powered by solar panels or other permanent power source coupled with permanently installed inclinometer strings or ShapeAccelArrays (SAA). The data could then be collected in real-time and serve as an early warning system for slope movement.

Installation of additional, deeper piezometers could also be considered to accurately measure the water table depth and potential pore pressure increases associated with precipitation events. Installation of an automated rain gauge at the site would also be helpful in determining if correlations exist between precipitation events and soil movement, water table height, and pore pressure increases near the failure surface.

⁶⁵ Image Source: WSP | Parsons Brinckerhoff.

Lessons Learned

The lessons learned are divided into those related to soil slopes and those related to rock slopes.

Soil Slopes

- While it seemed intuitive that increased precipitation resulting from climate change would increase the likelihood of more frequent slope failure, that is not necessarily the case and a slope that is suspected of being vulnerable should be analyzed before drawing conclusions about its effects.
- An economical first step in analyzing a slope suspected of being vulnerable to increased precipitation would be to conduct a preliminary investigation that would include:
 - Determine the steepness of the slope. Slopes steeper than 2 (horizontal) to 1 (vertical) should be initially suspect.
 - Perform a field inspection to detect physical clues such as soil bulges at the toe of the slope, deformed tree trunk growth, depressed elevation of the slope face.
 - Perform a parametric analysis such as used in this analysis. Doing so could save considerable time and expense in instrumentation and data collection.
- If the parametric analysis indicates the possibility of failure, a detailed analysis of a slope's vulnerability to increased precipitation is needed. This requires collecting data as early as possible in such a way that can correlate dates with rainfall amounts, rates of infiltration and groundwater elevations.
- The parametric analysis process, as used in this analysis, is adequate to determine the impact of increased precipitation on slope stability when dealing with slopes that have similar geologic and topographic characteristics. The methodology used in this study is not necessarily applicable to soil slopes and embankments over soft soils or slopes that have water levels influenced more significantly by such events as tidal surges or flooding of several feet in depth.

Rock Slopes

- Projections of the future frequency of freeze-thaw cycles are needed to determine if climate change will increase the exposure of the slope to freeze-thaw cycles and the resultant increase in weathering. For this study, freeze-thaw events were defined as a day when the minimum temperature drops below freezing (32° Fahrenheit) and the maximum temperature is above freezing.
- It is also important to analyze the relationship between the timing and amount of precipitation, and the projected temperatures because freeze-thaw events that occur within a day or two of a precipitation event are likely to have a more severe negative impact on the rock slope.

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