U.S. Department of Transportation
Federal Highway Administration

Precipitation and Temperature Impacts on Rock and Soil Slope Stability

This study focuses on the impacts of future changes in precipitation and temperature on rock and soil slope stability.[1]

Site Context and Facility Overview

The case study focused on a rural 4.5-mile stretch of Interstate 77 (I-77) in southwestern Virginia that crosses the Blue Ridge Mountains (see Figure 1). The limited-access highway, owned and managed by the Virginia Department of Transportation (VDOT), is a critical north-south transportation artery across the mountains, linking eastern Ohio with the Carolinas.

This segment, which traverses steep terrain, has many known geohazards. The study focused on two geohazards: a rockfall location and an active landslide on a soil slope (see Figure 2).[2]

Figure 1: Map of study area (red star).
Image Source: Google Maps

Environmental Stressors and Scenarios

Increased precipitation (over seasonal timeframes and/or during individual storm events) could decrease the stability of the soil slope and, in conjunction with more frequent freeze-thaw cycles, increase rockfall frequency and severity. To understand how these stressors would change at the project site, future projections were developed for:

- Seasonal precipitation,
- Daily (storm) precipitation (10-, 50-, and 100-year return periods), and
- The number of freeze-thaw days per year.

Because freeze-thaw damage is enhanced by moisture from precipitation, the research team calculated the future annual number of freeze-thaw cycles occurring the day of or the day after a precipitation event.

Projections were developed for 2045, 2065, and 2090 using data from the U.S. Bureau of Reclamation (USBR). Three emissions scenarios (referred to as representative concentration pathway [RCPs]) were used: RCP 4.5 (moderate emissions), 6.0 (moderate emissions), and 8.5 (high emissions).

[1] This snapshot summarizes one of nine engineering-informed adaptation studies conducted under the Transportation Engineering Approaches to Climate Resiliency (TEACR) Project. See https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/ for more about this study and *Synthesis of Approaches for Addressing Resilience in Project Development*.

[2] A concrete wall with embedded soil nails has since been added to the toe of the slide.

Figure 2: Soil slope slide along I-77.
Image Source: VDOT

The projections show a decrease in freeze-thaw days (and freeze-thaw days following precipitation events) under virtually all emissions scenarios. Thus, over the long term, it was concluded that rockfalls would decrease in the area under future environmental conditions and the rockfall analysis was concluded.

Precipitation, on the other hand, was generally found to increase, both seasonally (except during summer) and with storms, raising concerns over the long-term stability of the soil slope. Samples of the seasonal and storm precipitation projections are shown in Table 1 and Table 2, respectively.

Season	Obs.	2080–2099		
		RCP 4.5	RCP 6.0	RCP 8.5
Winter	10.16	+2.04	+0.74	+1.13
Spring	12.24	+0.80	+0.31	+0.04
Summer	13.43	-2.12	-0.81	-1.24
Fall	11.18	+0.87	+0.32	+0.88
Annual	47.01	+1.58	+0.56	+0.80

Table 1: Projected change (in inches) in seasonal precipitation for 2080–2090 (relative to a 1990–2009 baseline, obs.).

Return Period	Obs. (NOAA)	2080–2099		
		RCP 4.5	RCP 6.0	RCP 8.5
10-Year	4.80	+0.20	+0.22	+0.24
50-Year	6.61	+0.18	+0.20	+0.22
100-Year	7.44	+0.18	+0.17	+0.20

Table 2: Projected changes (in inches) in the daily 10-, 50-, and 100-year storm events for 2080–2090 (relative to the NOAA baseline).

Analytical Approach

Overview

Soil slope stability is assessed by computing a slope factor of safety. This factor of safety is the ratio of the forces holding a slope in place to those causing movement. A factor of safety below one indicates an unstable slope. Engineers typically aim to keep the factor of safety for a slope at or above 1.5.

To analyze slope stability, the research team intended to build a detailed SLOPE/W computer model of the soil slope, calculate its current factor of safety, and then determine how the factor of safety might change in the future under the different precipitation projections. Unfortunately, there was insufficient data relating precipitation amounts to the local groundwater table height and soil unit weights to enable this type of analysis given the resources and timeframe available for the case study. This is an issue many practitioners are likely to encounter when doing these types of analyses since gathering the necessary data often requires instrumentation of the slope which takes time and money.

To work around this issue, the research team performed a parametric analysis instead. The parametric analysis also involved building a detailed model of the slope using SLOPE/W software (see Figure 3). The model incorporated available data on the location and shape of the failure surface, the engineering properties of the soils, the shear strength of the soil, and an assumption on the depth to bedrock at the slide location (assumed to be in the worst possible spot, just below the failure plane). In the parametric analysis, instead of trying to model how much the projected increases in precipitation would raise the groundwater table or increase soil unit weights, very high groundwater elevations and soil unit weights (much higher than the projected precipitation changes could ever induce) were selected a priori and run through the model (using the limit equilibrium method) to see if they would adversely affect the factor of safety.

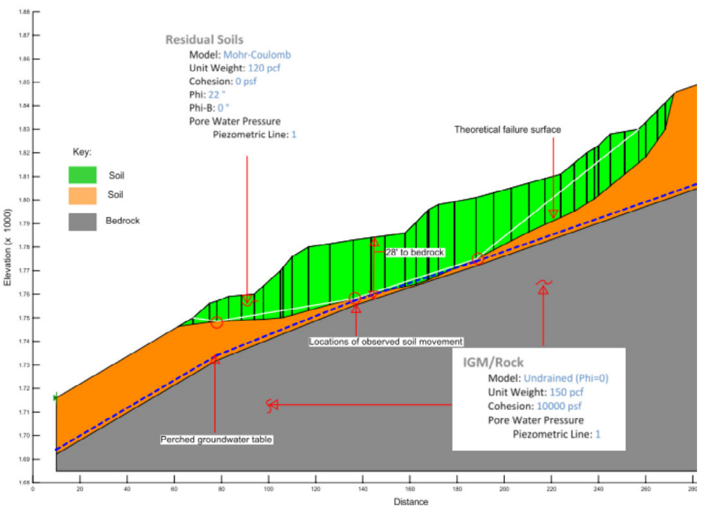

Figure 3: Model representation of the soil slope using SLOPE/W software.

Results

The research team found that the soil slope currently has a factor of safety of only 1.05. This low value, close to the critical value of one, is consistent with a slope exhibiting slow movement like the one that was analyzed. Surprisingly, the parametric analysis revealed that increasing the groundwater table height and soil unit weights, even by an unreasonably large amount (beyond what projected precipitation changes could induce), did not appreciably decrease the factor of safety. Thus, the research team concluded that future precipitation patterns would not have a significant effect on the long-term stability of this particular soil slope. Note that this conclusion is very site specific; other slopes may exhibit very different behavior.

Overcoming Challenges

Parametric analysis proved to be a useful approach for working around the lack of detailed data on groundwater heights and soil unit weights. Thus, such analyses could be used as an initial screening of slope stability. Where impacts are found to be insignificant, as in this case study, the analysis can be concluded. If, on the other hand, the parametric analysis indicates a possibility for adverse effects, then additional resources can be spent on data collection to enable a more detailed modeling analysis using an empirical relationship between local water table levels, soil unit weight, and precipitation.

Adaptation Options

Since the soil slope was found to be unaffected by projected precipitation changes, adaptation options were not developed for this case study. However, in response to historical slope movements, VDOT has developed a plan to mitigate any future movements of the slope on an as needed basis with the installation of additional soil nails farther up the slope and grading work to create terraces (see Figure 4). This plan exemplifies an adaptive management approach because it addresses problems over time as they occur rather than trying to mitigate all potential issues (some of which may never actually happen) at once.

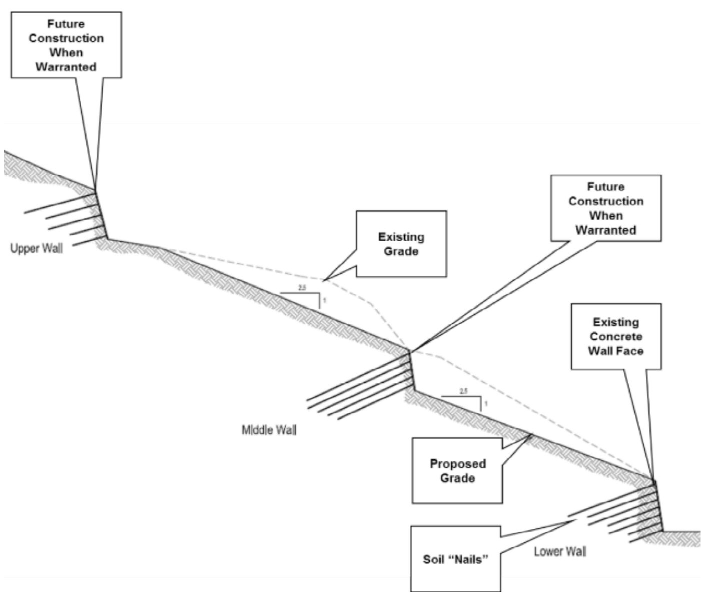

Figure 4: Long-term phased slope instability remediation plan.

Image Source: VDOT

The research team also recommended the installation of a geotextile and stone lined drainage ditch above the slope scarp (top of the slope) to intercept water and prevent infiltration which may hasten further slope movement (see Figure 5).

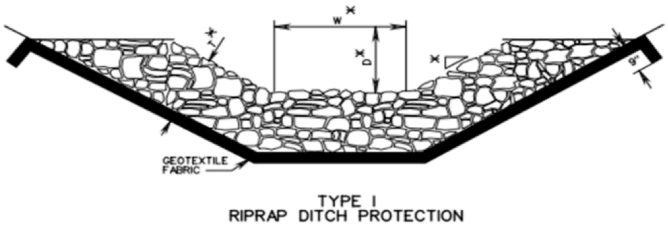

Figure 5: Typical section for the proposed interceptor ditch.

Recommended Course of Action

The recommended course of action for the soil slope is for VDOT to continue following the remediation plan that had already been developed prior to the case study, as no new risks were identified during the analysis. VDOT may also consider adding the interceptor ditch above the slope scarp. Existing instrumentation installed to measure movement and the groundwater table height should be maintained and, perhaps, augmented to allow for real time remote monitoring.

Lessons Learned

- An adaptive management approach may be appropriate for addressing slow-moving landslides without overspending.
- Increases in precipitation, even large increases, will not necessarily lead to decreases in slope stability on every slope. Nonetheless, many slopes may be adversely affected. Each slope is unique and analyses should be performed before conclusions are drawn.
- A parametric analysis can be a useful low-cost and time-efficient screening tool to determine if a soil slope is responsive to changes in precipitation. The parametric approach may be inappropriate for use on soil slopes or embankments with soft soils or whose groundwater tables are influenced by tidal fluctuations or surface flooding.
- For rock slopes, it is important to consider the timing of freeze-thaw cycles vis-à-vis precipitation events. Freeze-thaw cycles that occur concurrently or after precipitation events may be more impactful than those that occur during drier conditions. Snow cover can complicate this analysis of precipitation timing and should be considered when performing these analyses in colder regions.

For More Information

Resources:

Transportation Engineering Approaches to Climate Resiliency (TEACR) project website
www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/index.cfm

HEC 25 Volume 2: Assessing Extreme Events
www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=192&id=158

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