Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Effect of climate change on rainfall Induced failures for embankment slopes in Timor-Leste

Effet du changement climatique sur les ruptures induites par les précipitations sur les pentes des remblais au Timor-Leste

Thishani Amarathunga & Kuo Chieh Chao, Ph.D., P.E.
Asian Institute of Technology, Bangkok, Thailand

John D. Nelson, Ph.D., P.E., D.GE
Engineering Analytics, Inc., Fort Collins, Colorado, USA

ABSTRACT: Rainfall-induced slope failure commonly occurs after intensive rainfall events in mountainous areas, particularly in areas covered by residual soils. This type of failure is exacerbated by an excessive amount of infiltration resulted from severe weather conditions. This paper discusses the effect of severe weather conditions on rainfall induced failures for embankment slopes in Timor-Leste. Slope failures repeatedly happened at several locations of mountainous road slopes in Timor-Leste after intensive rainstorm events during severe weather conditions. Climate change analyses were conducted to determine current and future climate data, which were input as boundary conditions in seepage analyses for the determination of timewise pore water pressure changes for the slope. The slope stability analyses were conducted using the results of the pore water pressure analyses to verify the cause of the failure and to assist in the design of proposed remediation plans for the slope under long-term severe weather conditions. It was concluded that the pore water pressure within the fill slope was significantly increased due to the increase of infiltration during the severe weather conditions, resulting in the failure of the slope. Furthermore, the results of the seepage and slope stability analyses indicate that the pore water pressure for the slope could continue to increase during long-term severe weather conditions. Remedial measures including tieback anchors and geogrids were proposed and were demonstrated to be capable of increasing the fill slope stability to an acceptable level during long-term severe weather conditions.

KEYWORDS: Climate change; rainfall induced failure; seepage analysis; slope stability analysis; unsaturated soil.

1. INTRODUCTION

Rainfall-induced slope failure is one of the most damaging natural hazards that commonly occur after intense rainfall events in mountainous areas, particularly in areas covered by residual soils in tropical regions. Rainfall intensity, soil/rock properties, and configuration of the slope have been widely accepted as the primary controlling factors in rainfall-induced slope failure (Brand et al., 1984; Rahardjo et al., 2007; Egeli and Pulat, 2011). The amount of infiltration from the surface water can have a significant influence on the stability of slopes. The increase of infiltration into the soil increases the pore water pressure in the slope, and also reduces the soil's matric suction, resulting in a reduction of the shear strength of the soil, thereby increasing the potential for slope instability (Fredlund et al., 2012; Yeh et al., 2006).

Climate change has been a major concern for people globally as it affects their livelihood and living environments to a considerable extent. It has a significant effect on the statistical distribution of weather patterns over periods of time ranging from decades to millions of years. Climate change affects many factors, such as an increase in the groundwater table, ice melting, changing ecosystems, intense rainfall, high temperature, strong wind, and floods (Varallyay, 2010). Rainfall-induced failure is exacerbated by severe weather conditions which cause an excessive amount of infiltration.

In Timor-Leste, rainfall-induced slope failures that were caused by severe weather conditions were observed in roadways constructed around the year 2012. Cracks and slope failures at some sections of the roadways were observed as early as January 2013. It was reported that the slope failures commonly occurred after heavy rainfall events. Some of the slopes were repaired immediately after the failure. However, failure of the repaired slopes happened again after the next rainy season.

This paper discusses the climate change analyses, seepage analyses, and slope stability analyses conducted for the site to determine the primary cause of the failure and to assist in the determination of appropriate remedial measures for the slope under long-term severe weather conditions. The results of the analyses, findings, and recommendations are presented in the following sections.

2. SITE CONDITIONS

Timor-Leste is a sovereign state in Maritime Southeast Asia near the southern end of Indonesia. Rocks in the northwest part of the country, where this research area is located, have an inbuilt weakness resulting from their metamorphic formation. The Road Network Development Sector Project (RNDSP) in Timor-Leste is funded by the Asian Development Bank (ADB) in rehabilitating its road network to accelerate economic growth and reduce poverty. The project is located in the syn-collisional metamorphic rocks of the Aileu complex. The Aileu formation is of Permian age and can be described as hard metamorphosed deep marine sediments. Berry (1979) indicated that the Aileu complex is mainly composed of phyllite and quartz phyllite grading to schists in the east. These are interpreted as shales, siltstones, and greywackes which were deposited rapidly on an outer shelf or continental slope. It is highly fractured, jointed, and weathered, which potentially causes the slope instability of the rock mass.

This project comprises two main components, namely the Road Rehabilitation component and the Road Maintenance component. This study focuses on the issues occurring in the Road Rehabilitation section starting from Maubara (Km 62+567) to MotaAin road (Km 114+213.69), which is an area consisting of mostly sand, gravel, and highly weathered rock. Personnel from the Asian Institute of Technology conducted site visits to inspect the conditions of the Road Rehabilitation section and identified ten locations with slope instability and drainage issues within the section (AIT, 2018). The authors concluded that the slope failures commonly occurred after heavy rainfall events, either at fill slopes with tension cracks observed at the pavement surface or at cut slopes with highly weathered rocks (Morya et al., 2019). Examples of the fill and rock slope failures that occurred at the location of Km 66+900 are shown in Figure 1.

3 SITE CONDITIONS

Timor-Leste is a sovereign state in Maritime Southeast Asia near the southern end of Indonesia. Rocks in the northwest part of the country, where this research area is located, have an inbuilt weakness resulting from their metamorphic formation. The Road Network Development Sector Project (RNDSP) in Timor-Leste is funded by the Asian Development Bank (ADB) in rehabilitating its road network to accelerate economic growth and reduce poverty. The project is located in the syn-collisional metamorphic rocks of the Aileu complex. The Aileu formation is of Permian age and can be described as hard metamorphosed deep marine sediments. Berry (1979) indicated that the Aileu complex is mainly composed of phyllite and quartz phyllite grading to schists in the east. These are interpreted as shales, siltstones, and greywackes which were deposited rapidly on an outer shelf or continental slope. It is highly fractured, jointed, and weathered, which potentially causes the slope instability of the rock mass.

This project comprises two main components, namely the Road Rehabilitation component and the Road Maintenance component. This study focuses on the issues occurring in the Road Rehabilitation section starting from Maubara (Km 62+567) to MotaAin road (Km 114+213.69), which is an area consisting of mostly sand, gravel, and highly weathered rock. Personnel from the Asian Institute of Technology conducted site visits to inspect the conditions of the Road Rehabilitation section and identified ten locations with slope instability and drainage issues within the section (AIT, 2018). The authors concluded that the slope failures commonly occurred after heavy rainfall events, either at fill slopes with tension cracks observed at the pavement surface or at cut slopes with highly weathered rocks (Morya et al., 2019). Examples of the fill and rock slope failures that occurred at the location of Km 66+900 are shown in Figure 1.

Based on the severity and the type of failure conditions, the location at Km 66+900 was chosen to be considered in this study. Cracks and slope failures along this road section started to occur in 2013. A slip failure on the ocean side of the roadway was observed, as shown in Figure 1(a). Tension cracks measuring up to approximately 400 mm wide can be seen on the roadway surface. A shear failure happened again at the same location around the end of 2015 to early 2016 and was repaired in August 2016. The failure happened again during the rainy season between January to February 2017. Intense rill erosion was observed at the surface of the cut slope.

4 CLIMATE CHANGE ANALYSES

4.1 *Introduction*

As discussed in Section 1, rainfall intensity, soil/rock properties, and slope configuration have been widely accepted as primary controlling factors in rainfall induced slope failures. The amount of infiltration from the surface water increases the pore water pressure in the slope, and thus, reduces the soil shear strength. The reduction of shear strength reduces the resisting force in the slope, thereby increasing the potential for slope instability. As discussed in the previous section, slope failures at the site were often observed after heavy rainfall events. The slope failure at the location of Km 66+900 initially occurred in 2013. This location had recorded annual precipitation much higher than the average annual precipitation within the region. This will be discussed more fully in Section 3.3.3. It was therefore considered important to evaluate the climate change data to estimate the amount of infiltration into the slopes for use in the seepage and slope stability analyses.

(a) Fill slope failure at Km 66+900

(b) Weathered rock slope failure at Km 66+900

Figure 1. Failure conditions of fill and rock slopes.

4.2 Methods of Climate Change Projection

Recent evidence and future predictions indicate that the future climate could have significant changes. Because of the significant effects of infiltration due to rainfall, the slope and embankment are highly climate-dependent engineering infrastructures (Pk, 2017). Therefore, it is important to assess how the slopes at the site would behave under a variety of future climate scenarios.

General Circulation Models (GCMs) are a widely used tool to project future climate change under different greenhouse gas emission scenarios (Rashid, Beecham, and Chowdhury, 2015). Regional Climate Model (RCM) is another climate model that considers ocean conditions from a general circulation model. RCMs have a higher resolution than the GCMs, and they tend to provide more reliable information. A process termed "bias correction" has been developed to derive climate projections at scales that decision-makers desire. Downscaling is one of the methods that can be used for the process of bias correction.

Downscaling methods are divided into two groups: (1) dynamic downscaling and (2) statistical downscaling (Rashid, Beecham, and Chowdhury, 2015). Dynamical downscaling depends on the use of a regional climate model (RCM). Dynamical downscaling approaches use a one-way nested modeling technique. This method is computationally intensive and requires large volumes of data as well as a high level of expertise to implement and interpret results, which is often beyond the capacities of institutions in developing countries (Trzaska and Schnarr, 2014). Statistical downscaling requires the establishment of empirical relationships between historical and/or current large-scale atmospheric and local climate variables. When a relationship has been determined and validated, future atmospheric variables that GCMs project are used to predict future local climate variables. Statistical downscaling consists of various methods that vary in sophistication and applicability, such as linear scaling and quantile mapping. Linear scaling aims to match the monthly mean of the values to be corrected with that of the observed means. Quantile mapping is a nonparametric method that is applicable for all possible distributions of precipitation.

Many factors must be considered when trying to predict how future global warming will contribute to climate change. There are Representative Concentration Pathways (RCPs) whose primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. Four pathways, including RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5, have been selected for climate modeling and research, which describe different climate futures. These pathways depend on how many greenhouse gases are emitted in the years to come (IPCC, 2019). The RCP 4.5 and RCP 8.5 were considered in this study because the RCP 4.5 is the average case scenario, and the RCP 8.5 is the worst-case scenario. RCP 4.5 depicts that stabilization without exceeding 4.5 W/m^2 by 2100 and RCP 8.5 interpret increasing in radiative forcing to 8.5 W/m^2 by 2100 (IPCC, 2019)

4.3 Observed and Future Climate Data Analysis

4.3.1 *Input Parameters*

Observed climate data for precipitation and temperature from 2001 to 2013 were collected from the National Oceanic and Atmospheric Administration (NOAA) global climate data portal. In addition, monthly relative humidity, wind speed, and net radiation data were obtained from various online resources and were assumed to be constant throughout the particular month.

Future climate data for precipitation and temperature from 2006 to 2099 were collected by using the Regional Climate Model (RCM) data portal. The RCM data sets were obtained from the Coordinated Regional Climate Downscaling Experiment (CORDEX). Based on data available in the CORDEX data portal, six RCMs including CNRM-CERFACS-CNRM-CM5, CSIRO-BOM-ACCESS, MPI-M-MPI-ESM-LR, NCAR-CCM4, NCC-NorESM1M, and NOAA-GFDL-GFDL were selected. These RCMs were compared using the R^2 statistical values to determine the best RCMs for the site. It was determined that CNRM-CERFACS-CNRM-CM5, MPI-M-MPI-ESM-LR, and NOAA-GFDL-GFDL have the best R^2 values, and thus, were selected in the study.

4.3.2 Climate Data Analysis

The NOAA data were interpreted as global climate data, and the RCM data were predicted using regional climate models. Therefore, it was required to extract both NOAA and RCM data to location-based data using ArcGIS Software. As noted in Section 3.3.1, the CNRM-CERFACS-CNRM-CM5, MPI-M-MPI-ESM-LR, and NOAA-GFDL-GFDL regional climate models were selected for future climate data analysis. The linear scaling method was conducted to obtain future corrected climate data for both RCP 4.5 and RCP 8.5 scenarios. Due to the space limitations of the paper, only the results of the MPI-M-MPI-ESM-LR regional climate model are presented and discussed in this paper.

4.3.3 Results of Analysis

During La Niña years, above-normal rainfall amount leads to increase potential for flooding and landslides. Bacon et al. (2013) showed that during the La Niña years from 1914 to 1988, the amount of rainfall that was observed in Timor-Leste was 19% more than the average. Therefore, it was considered in this study that "severe precipitation" is defined as 19% more rain than the average amount.

Figure 2 depicts the annual precipitation data obtained from NOAA from 2001 to 2013 during the wet seasons of December to March at the Loes Weather Station in Timor-Leste. Figure 2 indicates that the annual precipitation ranges from approximately 700 to 1,500 mm with an average value of 1,100 mm. It is observed that the annual precipitation values after 2008 are generally higher than those from 2001 to 2008. The precipitation data for 2009, 2010, and 2013 can be classified as a severe precipitation condition, because it is more than 19% of the average precipitation. The failure of the selected slope that happened in 2013 had a "severe precipitation" condition.

Figure 3 shows the predicted annual precipitation data up to the year 2095 along with the observed annual precipitation data in the study area. It is shown in Figure 3 that the predicted precipitation data for the RCP 4.5 and RCP 8.5 scenarios exhibit the same general trend as that for the observed precipitation data. However, the predicted precipitation data have higher spikes compared to the observed precipitation data. Also, the RCP 8.5 scenario predicts higher predicted precipitation data compared to those predicted for the RCP 4.5 scenario.

5 SEEPAGE ANALYSES

5.1 General

It was reported that slope failures at the site frequently happened after several heavy rainfall events. Therefore, two-dimensional (2-D) seepage analyses were performed to evaluate the change in pore water pressure for the fill slopes from the dry season to the wet season during the year 2013 to verify the causes of the slope failure. In addition, the seepage analyses were also conducted using the predicted future climate data to determine predicted pore water pressure changes in the future to assist in the determination of the proposed remediation plan for the slope.

The seepage analyses were conducted for three scenarios, including (1) as-built slope with the observed climate data from 2001 to 2013; (2) current slope with proposed repair plans using the predicted RCP 4.5 climate data from 2014 to 2090; and (3) current slope with proposed repair plans using the predicted RCP 8.5 climate data from 2014 to 2090.

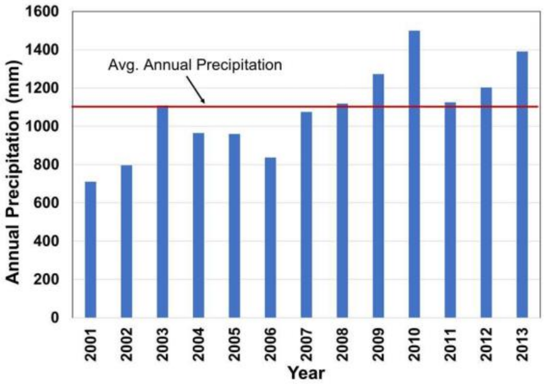

Figure 2. Annual Precipitation Data from 2001-2013 (NOAA Data).

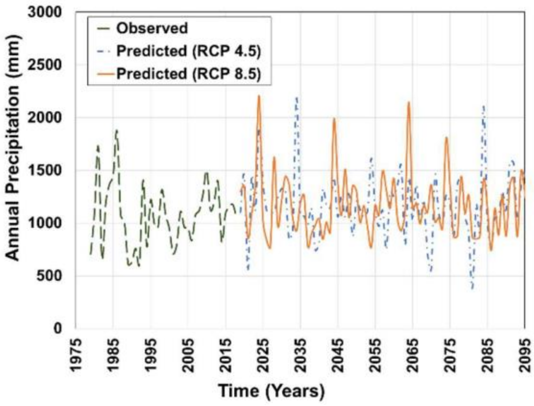

Figure 3. Observed and Predicted Annual Precipitation.

5.2 Method of Analyses

The seepage analyses were conducted using the computer program SEEP/W (GEOSLOPE, 2020). SEEP/W is a finite-element program that can be used to model flow through soil and bedrock and distribution of pore water pressures. The program can consider the effects of infiltration, surface seepage, runoff and ponding, and groundwater recharge.

The cross-section at the location of Km 66+900 was selected for both seepage and slope stability analyses because of the severity and type of the failure condition observed at that location. The geometry of the cross-section is presented in Figure 4. The cross-section was generated using the information obtained from the results of the field investigations conducted by AIT (AIT, 2018). The daily climate data obtained from the climate change analyses were specified as a boundary condition at the ground surface and the sea water level was specified as a constant water level boundary condition in the models for the seepage analyses, as shown in Figure 4.

The soil parameters used in seepage analyses are presented in Table 1. The soil/bedrock properties were obtained from laboratory tests or typical values shown in the literature.

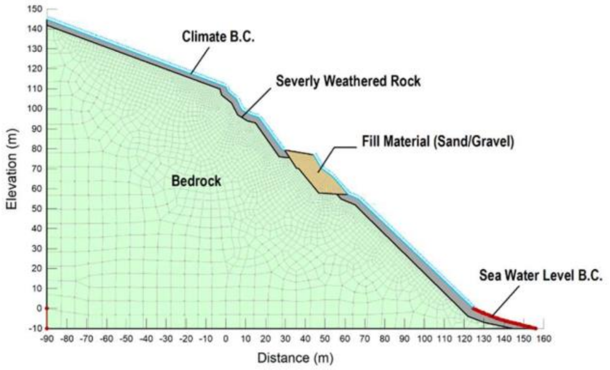

Figure 4. Geometry and Boundary Conditions for Seepage and Slope Stability Analyses.

Table 1. Summary of Input Parameters

Parameters	Fill Material (sand)	Weathered Rock	Bedrock
Porosity	0.21(1)	0.39(2)	0.2(2)
Permeability, K_x (m/s)	1×10^{-2}(2)	1×10^{-6}(2)	1×10^{-7}(2)
K_x/K_y Ratio	1(2)	1(2)	1(2)

Notes: (1) Values obtained from laboratory tests
(2) Assumed typical values (Earle, 2015)

5.3 *Results of Analyses*

5.3.1 Scenario 1

Scenario 1 was conducted for the as-built slope with the observed daily climate data from 2001 to 2013 to verify the cause of the slope failure. Figure 5 shows the pore water pressure profiles from 2001 to 2013 for Scenario 1. The figure indicates that the pore water pressure continued to increase with time above an elevation of approximately 60 m. The maximum pore water pressure within the zone of pore water pressure change was predicted to be approximately -110 kPa near the ground surface in 2013. The predicted pore water pressure distributions shown in Figure 5 were used in the slope stability analyses.

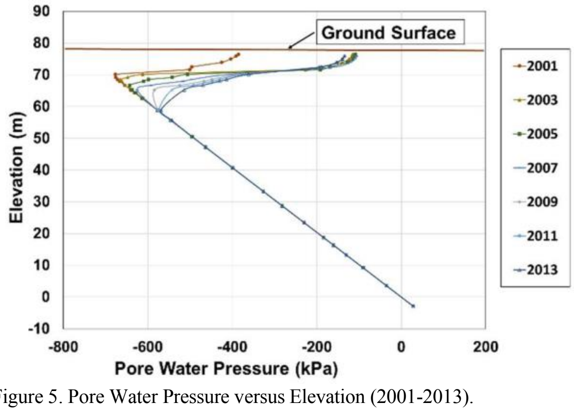

Figure 5. Pore Water Pressure versus Elevation (2001-2013).

4.3.2 Scenario 2

Scenario 2 was conducted for the current slope with proposed repair plans using the predicted RCP 4.5 daily climate data from 2014 to 2090 to estimate the long-term pore water pressure conditions of the slope considering the climate change. Figure 6 shows the pore water pressure profiles from 2014 to 2090 for Scenario 2. Figure 6 indicates that the pore water pressure continues to increase with time under severe weather conditions. However, it is observed that the pore water pressure profile does not change significantly after 2085. Comparison of Figure 6 to Figure 5 indicates that the pore water pressure of the slope could continue to increase under long-term severe weather conditions. The pore water pressure profile in 2085 represents the most conservative pore water pressure conditions considering the severe weather conditions. Thus, it was used in the slope stability analyses to determine adequate remediation plans for the slope.

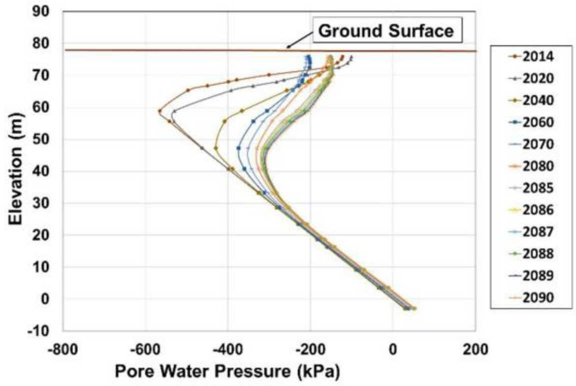

Figure 6. Pore Water Pressure versus Elevation for the RCP 4.5 Scenario

4.3.3 Scenario 3

Scenario 3 was conducted for the current slope with proposed repair plans using the predicted RCP 8.5 daily climate data from 2014 to 2090 to estimate the long-term pore water pressure conditions of the slope considering the climate change. The pore water pressure profiles from 2014 to 2090 for Scenario 3 are presented in Figure 7. Similar to the results for Scenario 2, the pore water pressure continued to increase with time under severe weather conditions and reaches a relatively constant condition in 2085. The pore water pressure profile in 2085 was used in the slope stability analyses to determine adequate remediation plans for the slope.

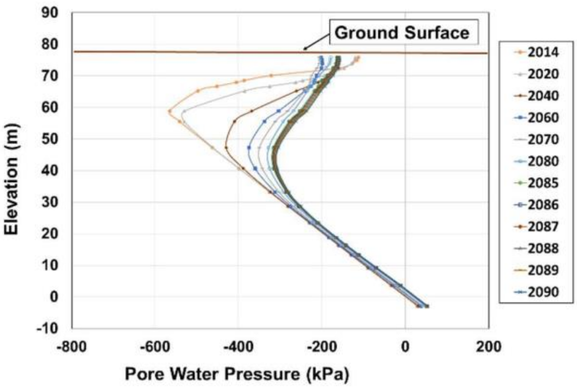

Figure 7. Pore Water Pressure versus Elevation for the RCP 8.5 Scenario (2014-2090

6 SLOPE STABILITY ANALYSIS

5.1 General

Slope stability analyses were performed using the pore water pressure conditions obtained from the seepage analyses to evaluate the factor of safety of the fill slope for Scenarios 1 to 3. The results of the slope stability analyses for Scenario 1 were utilized to verify the cause of the slope failure. The results of the slope stability analyses for Scenarios 2 and 3 were used to assist in the design of proposed remediation plans for the slope. Options for the proposed conceptual repair plans analyzed in the slope stability analyses include (1) installation of tieback anchors and (2) installation of geogrids.

5.2 Method of Analyses

The slope stability analyses were performed using the computer program SLOPE/W (GEOSLOPE, 2020). SLOPE/W solves limit equilibrium slope stability problems by several different methods. The Morgenstern-Price method was chosen for this study. This method considers both force equilibrium and moment equilibrium.

Fill slope failures occurred repeatedly after heavy rainfall events during the wet season. At that point, the slopes had a factor of safety of 1.0 or less at the time of the failure. Results of the field investigation indicated that the majority of the slopes contain sand, gravel, and severely weathered rock. The material properties for the sand, gravel, and severely weathered rock were back-calculated in SLOPE/W to obtain a factor of safety of 1.0 for the slope. In the back-calculations, the pore water pressure data obtained from the seepage analyses for 2013 were used. A factor of safety of 1.5 was used as a design criterion for the proposed remedial measures under the static loading conditions. Table 2 summarizes the soil/bedrock properties that were used in the slope stability analyses. The soil/bedrock properties were obtained from laboratory tests, back-calculated values, or typical values shown in the literature. A cohesion of 0 kPa was used for the sand/gravel fill material. The cohesion in residual strength for the residual materials is typically zero (Nelson and Thompson, 1977). Thus, a cohesion of zero (0) was assumed for the severely weathered rock in the analyses.

Table 2. Summary of Input Parameters for Slope Stability Analyses

Parameters	Fill Material	Weathered Rock	Bedrock
Unit Weight (kN/m^3)	26.4$^{(1)}$	26.4$^{(1)}$	Impenetrable
Cohesion (kPa)	0$^{(2)}$	0$^{(2)}$	
ϕ' (Degrees)	25.0$^{(3)}$	15.0$^{(3)}$	
ϕ^b (Degrees)	16.7$^{(4)}$	10.0$^{(4)}$	

Notes: (1) Values obtained from laboratory tests (AIT, 2018)
(2) Assumed values
(3) Back-calculated values
(4) Assume that $\phi^b = 2/3\phi'$

5.3 Results of Analyses

5.3.1 As-Built Slope

The slope stability analyses for the as-built slope were performed using the pore water pressure conditions obtained from Scenario 1. In Timor-Leste, the dry season starts around May and June, and the wet season is from December to March. The failure of the slope was observed in the wet season (around February) of 2013. Therefore, the slope stability analyses were conducted using the monthly pore water pressure conditions for one year starting in June 2012 (beginning of the dry season) obtained from the seepage analyses.

Figure 8 shows the reduction of the factor of safety with time (from the dry season in June 2012 to the wet season in March

2013) for the fill slope at Km 66+900. The results of the back- calculation analyses indicated a friction angle of 25 degrees for the fill material and a friction angle of 15 degrees for the severely weathered rock for a factor of safety of unity during the wet season in 2013. Figure 8 indicates that the factor of safety of the slope does not reach unity until the wet season of 2013, which is consistent with the observation of the failure at the site. It should be noted that the as-built slope at the dry season had an initial factor of safety of only about 1.23, which is lower than the generally accepted factor of safety of 1.5 in the geotechnical engineering practice.

5.3.2 Proposed Conceptual Repair Plans

The stability of the proposed conceptual repair plans was analyzed using the worst pore water pressure conditions in 2085 obtained from the seepage analyses for Scenarios 2 and 3 to ensure the remediated slope remains stable under severe weather conditions. The slope stability analyses were conducted under static loading conditions.

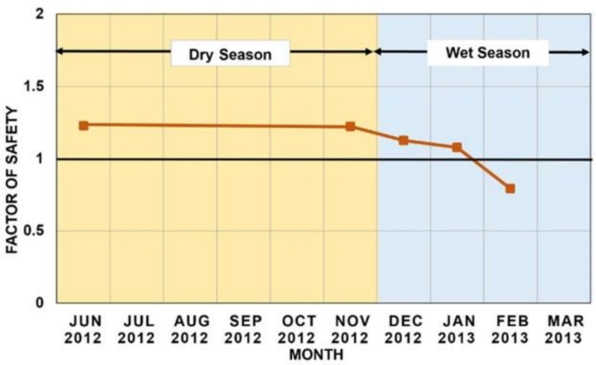

Figure 8. Reduction of Factor of Safety with Time for the Fill Slope.

The proposed remediation plans for the slope include (1) tieback anchors and (2) geogrids. For the option of the tieback anchors, five rows of the tieback anchors with a spacing of 2 m and a length of 13 m were proposed to be installed onto the fill slope. For the option of the geogrids, 16 rows of the geogrids with lengths of 11 to 13 m were proposed to be installed onto in the fill slope. The material properties of the tieback anchors and the geogrids were obtained from typical values of the materials and are shown in Table 3.

Table 3. Summary of Material Properties of Tieback Anchors and Geogrids

Material	Material Properties		
Tieback Anchor	Pullout Resistance (kPa)	Tensile Capacity (kN)	Bond Length (m)
	400	2,000	3
Geogrid	Pullout Resistance (kPa)	Tensile Capacity (kN)	Spacing Between Layers (m)
	75	200	1.0 – 1.5

Table 4 summarizes the results of the factor of safety for the remediated slope with tieback anchors and geogrids for Scenarios 2 and 3. Table 4 indicates that the factor of safety was increased to approximately 1.7 for the option of the tieback anchors for both scenarios, and the factor of safety was increased to approximately 1.5 for the option of geogrids for both scenarios. The results shown in Table 4 indicate that both of the remedial measures could effectively increase the fill slope stability to an acceptable level during severe weather conditions.

Table 4. Summary of Factor of Safety for Remediated Slope

Scenario No.	RCP No.	Repair Option	Factor of Safety with Remediation
2	RCP 4.5	Tieback Anchors	1.68
		Geogrids	1.45
3	RCP 8.5	Tieback Anchors	1.72
		Geogrids	1.48

6. CONCLUSIONS

Heavy rainstorm events were the leading cause for the slope failure that happened at the location of Km 66+900. It was reported that the slope failures repeatedly happened after intense rainstorm events during the wet seasons. The failure of the slope occurred again even after the initial repair of the slope. A review of the annual precipitation data collected at the site indicates that the annual precipitation data for 2009, 2010, and 2013 can be classified as a severe precipitation condition compared to the annual precipitation data from previous years. The failure of the selected slope that happened in 2013 had a “severe precipitation” condition.

Seepage and slope stability analyses were conducted to evaluate the effect of an increase in the pore water pressures during severe weather conditions. The results of seepage analyses demonstrated that the pore water pressure within the fill slope was significantly increased due to the increase of infiltration during severe weather conditions. The results of slope stability analyses indicated that the factor of safety of the fill slope was reduced from 1.23 to unity at the wet season. The increase of the pore water pressures in the fill slope during the wet season reduced the shear strength of the fill material and caused the instability of the fill slope. This finding confirmed the cause of the slope failure observed at the site. Furthermore, it was found that the as-built slope had an initial factor of safety of only about 1.23, which is lower than the generally accepted value of 1.5 normally used in geotechnical engineering practice.

It should be noted that tension cracks could have a significant effect on the reduction of slope stability at this location. Tension cracks were observed on the roadways during the site visits. Some of the tension cracks were sealed but reopened after the additional movement of the slopes. The tension cracks provided a means for increased infiltration into the slope that resulted in an adverse impact on the stability of the fill slope.

The results of the climate change analyses indicate that the predicted precipitation data until the year 2095 for the RCP 4.5 and RCP 8.5 scenarios exhibit the same general trend as that for the observed precipitation data at the site. However, the predicted precipitation data exhibit higher spikes compared to the observed precipitation data, which indicates that an excessive amount of precipitation could continue to happen at the site.

The results of the seepage analyses using the long-term weather data predicted in the climate change analyses show that the pore water pressure in the slope could continue to increase during severe weather conditions. After the year 2085, the pore water pressure reaches a fairly constant condition. Therefore, the pore water pressure conditions in 2085 were used in the slope stability analyses to determine the remedial measures for the slope. It was concluded that both of the proposed remedial measures including tieback anchors and geogrids could be effectively used to increase the fill slope stability to an acceptable level during the long-term severe weather conditions.

7. ACKNOWLEDGEMENTS

The authors would like to thank Asian Development Bank for giving us permission to use the data collected for the project site to conduct the research. In addition, the authors would like to extend our appreciation to GEOSLOPE International Ltd. for providing us the academic license of the GeoStudio program.

8. REFERENCES

Asian Institute of Technology (AIT). 2018. Results of Geotechnical Investigation, Road Network Development Sector Project, Package R-2, Democratic Republic of Timor-Leste. Bangkok, Thailand.

Bacon, S., Neto, F.M., Pereira, I.S., and Williams, R. 2013. The Impact of the El Niño Southern Oscillation on Rainfall Variability in Timor-Leste. TLSA Conference, Timor-Leste. 1-17.

Berry, R.F. 1979. Deformation and Metamorphism of the Aileu Formation, East Timor. Ph.D. Dissertation, School of Earth Sciences, Flinders University of South Australia, Australia.

Brand, E.W., Premchit, J., and Phillipson, H.B. 1984. Relationship Between Rainfall and Landslides in Hong Kong. The 4th International Symposium on Landslides, 377-384.

Egeli, I. and Pulat, H.F. 2011. Mechanism and Modeling of Shallow Soil Slope Stability During High Intensity and Short Duration Rainfall. Journal of Scientia Iranica,18(6), 1179-1180.

Earle, S. 2015. Physical Geology. Victoria: BCCAMPUS.

Fredlund, D.G., Rahardjo, H., and Fredlund, M.D. 2012. Unsaturated Soil Mechanics in Engineering Practice. John Wiley & Sons, New York, NY.

GEOSLOPE International Ltd. 2020. GeoStudio. Alberta, Canada.

Intergovernmental Panel on Climate Change (IPCC) 2019. Retrieved from the Data Distribution Centre.

Morya, R., Kongpanickul, S., Chao, K.C., and Ishenaliev, R. 2019. Rainfall-Induced Failure on Unsaturated Fill and Highly Weathered Schist Slopes. The 7th Asia-Pacific Unsaturated Soils Conference, Nagoya, Japan.

Nelson, J.D. and Thompson, E.G. 1977. A Theory of Creep Failure in Overconsolidated Clay. Journal of the Geotechnical Engineering Division, 103(11), 1281-1294.

Pk, S. 2017. Effects of Climate Change on Soil Embankments. York University, Canada.

Rahardjo, H., Ong, T.H., Rezaur, R.B., and Leong, E.C. 2007. Factors Controlling Instability of Homogeneous Soil Slopes During Rainfall. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 1532-1543.

Rashid, M.M., Beecham, S., Chowdhury, R.K. 2015. Statistical Downscaling of CMIP5 Outputs for Projecting Future Changes in Rainfall in the Onkaparinga Catchment. Science of the Total Environment, 530-531, 171-182.

Trzaska, S. and Schnarr, E. 2014. A Review of Downscaling Method for Climate Change Projections. U.S. Agency for International Development.

Varallyay, G. 2010. The Impact of Climate Change on Soils and on Their Water Management. Agronomy Research.

Yeh, H.F., Chang, P.H., Chen, J.F., and Lee, C.H. 2006. Instability of Unsaturated Soil Slopes Due to Infiltration. International Symposium on Geohazards Mitigation. Taiwan.