# Effect of climate change on soil embankment stability

Leila Baninajarian & Ali Ghassemi
*Department of Civil Engineering, York University, Toronto, Ontario, Canada*
Tony Sangiuliano & Andrew DeSira
*Ministry of Transportation of Ontario, Toronto, Ontario, Canada*
Rashid Bashir
*Department of Civil Engineering, York University, Toronto, Ontario, Canada*

## ABSTRACT

Climate change is expected to increase the magnitude and frequency of extreme events as well as long-term changes in average climatic conditions. Highway embankments which are required to be operational over their long lifetime, are likely to experience instabilities as a result of these events. This paper presents a numerical investigation of the stability of embankments for historical and future storms in Ottawa. Hydrological assessments for two different soil types – sands and silts were carried out using unsaturated flow modeling. Soil-atmosphere modeling was used to evaluate the water balance at the ground surface of embankments to determine the pore water pressure distribution within the embankments. The results from the hydrological assessments were used in slope stability assessments using the limit equilibrium method. The results indicate that over the coming decades the likelihood of stability deterioration will increase substantially. The issue is more critical for embankments constructed with fine-grained materials.

## RÉSUMÉ

Le changement climatique devrait augmenter l'ampleur et la fréquence des événements extrêmes ainsi que les changements à long terme des conditions climatiques moyennes. Les remblais routiers qui doivent être opérationnels pendant leur longue durée de vie risquent de subir des instabilités à la suite de ces événements. Cet article présente une étude numérique de la stabilité des remblais lors des tempêtes historiques et futures à Ottawa. Les évaluations hydrologiques de deux types de sol différents - les sables et les limons ont été réalisées à l'aide d'une modélisation des débits non saturés. La modélisation sol-atmosphère a été utilisée pour évaluer le bilan hydrique à la surface des remblais afin de déterminer la distribution de la pression interstitielle dans les remblais. Les résultats des évaluations hydrologiques ont été utilisés dans les évaluations de la stabilité des pentes utilisant la méthode de l'équilibre limite. Les résultats indiquent que dans les décennies à venir, le risque de détérioration de la stabilité augmentera considérablement. La question est plus critique pour les remblais construits avec des matériaux à grain fin.

## 1 INTRODUCTION

Scientific evidence implies that climate change is occurring (IPCC 2013). The climate change is associated with considerable alteration of important climate variables such as precipitation, potential evaporation, and intensity and frequency of extreme weather events. These changes can affect geotechnical structures in different ways. For example, increase in intensity of extreme precipitation may intensify soil erosion, increase the mobility of contaminants or trigger hydro-mechanical failures in slopes.

At the Ministry of Transportation of Ontario (MTO), there is approximately 17,000 km of highways. Embankment fills comprised of different soils and rock make up a large portion of the highway. Infrastructure sustainability is a provincial highway management priority. Due to continuous exposure to the environment, the stability of embankments can be affected by climate variables. The most critical climate parameter that affects the stability of soil embankments is precipitation. Meteoric water causes water seepage through the embankment soil mass. As a result, the effective stress and shear strength of the soil that rely on water balance could be reduced. This adversely affects the stability of slopes. Therefore, any change in extreme precipitation events due to climate change has the potential to affect the stability of the embankments.

Numerical simulation of climate change impact on the stability of embankments requires a multi-disciplinary methodology. It should consider high-resolution prediction of future climate data. A hydrological model equipped with soil-atmosphere boundary condition is required for simulation of variably saturated flow and estimation of pore water pressures. Also, stability of the slopes should be assessed considering the effects of suction on soil shear strength of the soil.

This study is a part of an ongoing research project on the effects of climate change on the stability of highway embankments across Ontario. In this paper, the effect of climate change on the stability of highway embankments in and around the Ottawa area is investigated. For this purpose, a 30-year historical climate dataset (i.e. 1981-2010) and sixteen 90-year (i.e. 2011-2100) future climate datasets were compiled. Long-term variation of soil moisture conditions under different future climate scenarios was investigated using 1D transient unsaturated seepage finite-element (FE) simulations considering two different soil types with distinctively different hydraulic properties. Long-term variations of the spatial distribution of pore water pressure (PWP) within the embankments were obtained using 2D transient unsaturated seepage finite-element (FE) models with consideration from both precipitation and actual evaporation using the soil–atmosphere boundary. Assessment of slope stability overtime during extreme precipitation events was carried out by exporting PWP spatial distributions from the hydrological model into a 2D limit equilibrium slope stability model. The model could account for the contribution of matric suction on the soil strength parameters model at each time step. The soil-atmosphere boundary for the hydrological model was prepared using Chicago storm hyetographs based on historical and future intensity-duration-frequency (IDF) curves. In addition, a statistical model was employed to estimate the probability of occurrence of a predicted factor of safeties. The effects of changing climate were finally quantified by comparing the results for factor of safety (FOS) values and their probabilities of occurrence in the future with those obtained based on historical climate data.

## 2 BACKGROUND

Due to the development of advance climate, hydrological, and geotechnical models and availability of powerful computational resources, quantification of climate change impacts on the stability of slopes has become feasible.

Collison et al. (2000) studied the potential impact of predicted climate change on landslides in southeast England. They developed a one-dimensional hydrology model, a digital terrain model, and an infinite slope model for the factor of safety analysis. Their results showed that climate change would not cause frequent large landslides, but small-scale instabilities could occur due to changes in groundwater elevation Rouainia et al. (2009) used combined hydrological and geotechnical models to predict the response of an embankment to different climate scenarios. They demonstrated that the future scenario of increased rainfall intensity of shorter duration coupled with an increase in average temperature would potentially lead to a reduction in the infiltration. The decreased infiltration would lead to high negative pore water pressures contributing positively to the stability of the embankment.

Robinson et al. (2017) assessed the impact of future extreme precipitation events on a homogeneous silty soil slope located in the Seattle region of Washington state in the United States. They used a fully coupled two-dimensional variably saturated flow and stress – strain finite element model. Their results indicated that the increase in rainfall intensity will result in increasing the pore water pressure that will adversely affect the stability of a slope. Pk et al. (2018) studied the effect of climate change on the stability of embankments using a hydro-geotechnical model. They claimed that the hydraulic properties of fill materials can influence the embankment`s response to climate change. The highly permeable sand embankment can quickly drain water without any significant effect on stability. On the other hand, embankments built with low permeability finer materials such as silt showed a lower factor of safety (FOS).

Overall, previous studies indicate that extreme precipitation events will increase in the future and will adversely affect the stability of the slopes. However, it should be noted that these findings are dependent on the various assumptions and simplifications that are made in the development of the numerical models. Assumption of simple initial conditions for pore pressure distribution (e.g. Robinson et al. 2017), selecting future climate data only based on hydrological aspects (e.g. Bo et al. 2008), and considering uniform rainfall intensity during extreme events (e.g. Rahardjo et al. 2010) are some examples of the assumptions and simplifications in such studies. Moreover, most of the previous studies focused on the effect of climate change on FOS values and the probability of the predicted stability condition has been less considered.

## 3 FUTURE EXTREME EVENTS

The Intergovernmental Panel on Climate Change (IPCC) has indicated that the precipitation patterns in the world will change as a result of changing the climate. For North America, it is expected that the frequency and intensity of the extreme precipitation events will increase (IPCC 2013).

Rainfall intensity-duration-frequency (IDF) curves express the probability of occurrence of extreme precipitation in a region, and are used as a key tool for hydrological design of infrastructures. In Ontario, IDF curves are used as one of the major criteria for designing infrastructures subjected to storms by regulatory organizations such as the Ministry of Transportation (MTO), Ministry of the Environment, Conservation and Parks, and Conservation Authorities (Coulibaly et al. 2016).

For assessment of climate change impact on future IDF curves, a baseline climate consisting of 30 years of historical climate data (i.e. 1981-2010) was considered as the datum in this research. Historical IDF curves for the province of Ontario can be obtained from Environment Canada. Future IDF curves for the province of Ontario are available from the Ministry of Transportation, Ontario (MTO 2018) and the Ontario Climate Change Data Portal (CCDP 2018). The IDF curves by MTO have been developed using time trend analysis with observations from 1960 to 2014. These IDF curves are the extrapolation of the historical data and assume that the rate of change will remain constant. The future IDF curves by CCDP are predicted using two different regional climate models namely PRECIS and RegCM. The IDF curves are available for emission scenarios A1B, RCP4.5, and RCP8.5 based on both fourth (AR4) and fifth Assessment Report (AR5) of the IPCC.

Both MTO and CCDP future IDF curves show a significant increase in future extreme precipitation during the last 30 years of this century (i.e. 2070-2100). Predicted IDF curves for this period were considered in the current study. The future IDF curves from CCDP and MTO for the city of Ottawa are shown in Figure 1. Review of this figure indicates that for all return periods, CCDP`s IDF curves predict higher intensities for longer durations compared to MTO. Among all IDF curves by CCDP, IDF curves for scenarios A1B-P90% (A1B scenario with 90 percentile) and RCP8.5-RegCM show higher predictions of the rainfall intensities. Since A1B-P90% is part of the older assessment report of IPCC, IDF curves from RegCM under RCP8.5 were taken as the critical scenario in this study.

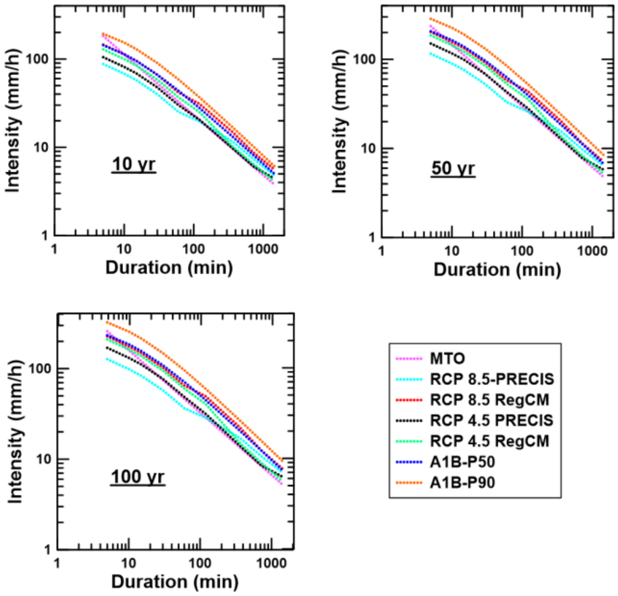


Figure 1. Comparison between different future IDF curves

# 4 METHOD OF ANALYSIS

## 4.1 Geometry and Material

The embankment profile considered in the current study represents a typical highway embankment in Ontario. Since the problem is symmetrical, only one-half of the domain as shown in Figure 2, was simulated. The height of embankment was considered to be 8 m. This is the maximum allowable height for an earth-fill embankment without a berm in Ontario (OPSD 202.010). Side slopes of the embankment are 2H:1V and a 3 m width unpaved shoulder were assumed at the top of the embankment. The distance between the slope toe and the right side of the model was set to more than three times the height of the slope to minimize the influence of the side boundary condition (Rahardjo et al., 2010). The water table was conservatively assumed to be at the natural ground surface, which is 4 m below the level of slope toe.

In this research, sand and silty materials, typically used in the construction of highway embankments in Ontario were considered. Hydraulic properties of these materials are shown in Figure 3. The van Genuchten (1980) function was used to describe the soil-water characteristic curves (SWCC). Unsaturated hydraulic conductivity functions (HCF) for these materials were determined from SWCC using the van Genuchten-Mualem approach (Mualem 1976, van Genuchten 1980). The relevant parameters for hydraulic functions were taken from Pk et al. (2018).

All embankment fill used in MTO projects is placed and compacted following OPSS 206 and OPSS 501. Thus, an effective friction angle (ϕ`) of 32° is usually assumed in the geotechnical design of MTO embankments. Although the value can be argued to be conservative for compacted sand, it was applied for stability analyses of both sand and silt embankments in this study.

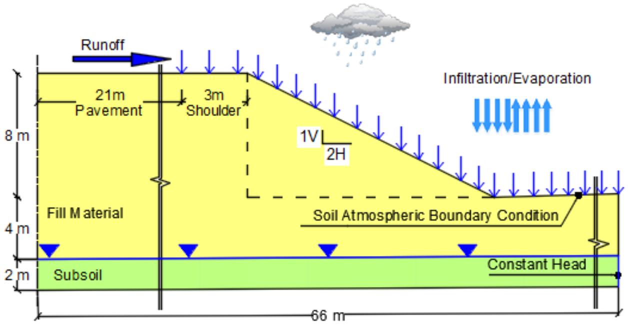
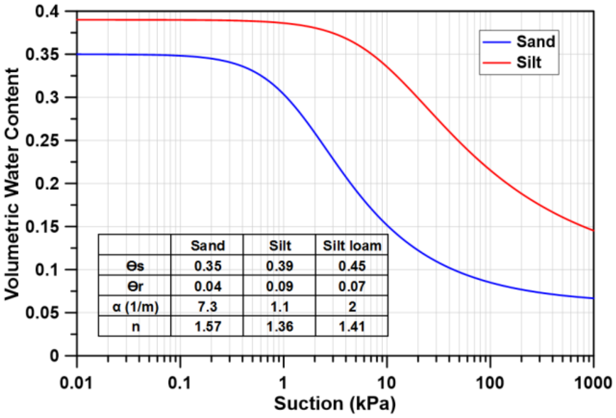


Figure 2. Design profile of the highway embankment



| | Sand | Silt | Silt loam |
|---|---|---|---|
| Θs | 0.35 | 0.39 | 0.45 |
| Θr | 0.04 | 0.09 | 0.07 |
| α (1/m) | 7.3 | 1.1 | 2 |
| n | 1.57 | 1.36 | 1.41 |

Figure 3. Unsaturated hydraulic properties of fill materials

## 4.2 1D Unsaturated Flow Modeling

HYDRUS 1D (Šimůnek et al. 2009) was used to analyze the long term variation of moisture in sand and silt materials for different climatic conditions. HYDRUS 1D is a one-dimensional transient variably saturated flow model, which solves a modified form of Richards equation (Richards 1931) using the finite element method. HYDRUS 1D supports a system-dependent boundary condition using an approach proposed by Neuman et al. (1974). This boundary condition can estimate actual evaporation and surface runoff using climatic records of precipitation and potential evaporation together with transient soil-moisture conditions.

Thirty years of historical climate data (i.e. 1981-2010) and sixteen climate datasets of 90 years of predicted future climate data (i.e. 2011-2100) for the city Ottawa were used as input to estimate the water balance in a 4 m high soil column. Future climate datasets are based on four different general circulation models (GCM) namely CCSM4, GFDL-ESM2M, Had GEM2, and Nor ESM1 and four representative concentration pathway (RCP) of 2.6, 4.5, 6.0, 8.5 (IPCC 2013). Hydrological simulations were carried out for the active period of each year. The active period refers to the thawed ground conditions when moisture can flow freely in and out of the ground surface. Use of active period approach greatly reduces the computation time and unnecessary complexities associated with ground freezing (Fredlund et al. 2012). Active period can be identified carrying out a detailed review of the daily temperature records to identify the freeze and thaw dates. Results of the numerical simulation were analyzed in terms of variation of saturation over time. This analysis indicates that the maximum estimated saturations during the historical period are 61.4% and 97.5% for sand and silt material, respectively. In order to compare the long-term effects of different future climate scenarios on two column types, the frequency of high saturation occurrence (number of events that saturation degree of the soil exceeds the maximum saturation degree experienced during the historical period) were considered. As shown in Figure 4, the future climate data based on Had GEM2 and RCP 8.5 gives the highest number of events among the analyzed climate predictions. This prediction was applied in the next stages of the study.

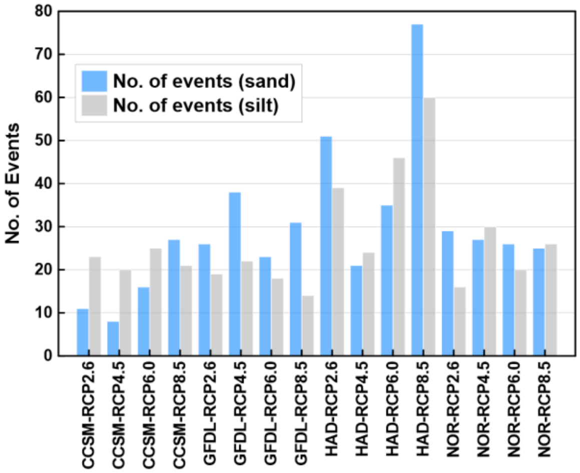


Figure 4. Frequency of high saturation occurrence

### 4.3 2D Unsaturated Flow Modeling

HYDRUS 2D (Šimŭnek et al. 2006) was used for analyzing the variation of water balance distribution through the embankment. The 2D finite-element model consists of 13802 triangular elements. The finer mesh was generated near the unpaved surfaces to provide an appropriate resolution within the infiltration zone.

Thirty years historical climate data and 90 years future climate data based on the selected scenario were applied as the soil-atmospheric boundary. The pavement at the top of the embankment was modeled as a no-flow boundary. A no-flow boundary was also assigned to the left side and bottom of the domain. At the right-hand boundary, the groundwater table was applied using a constant head boundary. Hydrostatic condition above the water table was used as the initial condition of the hydrological model.

Based on the obtained results, the PWP distribution corresponding to the highest saturation in the slope area (encompassed by dashed lines in Figure 2) during the historical period was determined and applied as the initial condition for the hydro-geotechnical model.

### 4.4 Hydro-Geotechnical Model

Limit equilibrium method (LEM) is the most widely used analytical technique for slope stability assessment. Application of this method for unsaturated soil conditions requires consideration of the contribution of matric suction on the soil strength parameters. Matric suction depends on the degree of soil saturation, which changes continuously because of soil-atmosphere interactions. Therefore, assessment of slope stability during extreme events requires a hydro-geotechnical model in which spatial distribution of pore water pressure from the hydrological model is consecutively introduced into the geotechnical model.

For the geotechnical model, the widely used limit equilibrium software SLOPE/W was employed. A hydrological model was developed in seepage software SEEP/W. Both softwares are modules of a software suite called GeoStudio (Geo-slope International Ltd. 2016) and can be easily coupled. This coupling ensures the continuous calculation of factor of safety by SLOPE/W for each time step for which pore pressure distribution is made available from the seepage assessment in SEEP/W. The Morgenstern-Price method (Morgenstern and Price 1965) was used in the limit equilibrium analyses. It considers both the static force and moment equilibrium. The strength due to suction in unsaturated soil was estimated using Vanapalli et al. (1996) model:

$$\tau = c` + (\sigma - u_a) \tan \phi` + [(\theta - \theta_r)/(\theta_s - \theta_r)]\, \psi \tan\phi` \quad [1]$$

where c` is effective cohesion (kPa) and $\phi$`is effective angle of internal friction. $\sigma - u_a$ and $\psi$ are the net normal stress and the soil suction (kPa), respectively.

The coupled hydro-geotechnical model was used to investigate the embankment stability under historical and future design storms. The factor of safety (FOS) against global failure was considered as the main indicator of slope stability condition in this research. It should be noted that in order not to consider shallow slip surfaces, a minimum sliding mass depth of 1.0 meter was set in the analyses.

### 4.5 Design Storm

Ideally, actual storms should be used in a hydrologic analysis. However, actual storm records are not usually available for every location. In addition, such an approach is not applicable when the effects of future climate are under study. There are several methods for generating design storm hyetographs in the literature based on the IDF curves. In this study, the method proposed by Keifer and Chu (1957), known as the Chicago design storm was applied. This method has been widely incorporated in Canadian practice (Marsalek and Watt 1984). The method also has been suggested by MTO to be applied for assessment of the storm impacts to the drainage systems (MTO 1997).

Based on numerical modeling results, Pk et al. (2018) indicated that any effect of rainfall duration on embankment stability depends on the hydraulic properties of the fill materials. Herein, a range of duration (1, 6, and 24 hours) for three return periods (10, 50, and 100 years) was considered as input rainfalls for slope stability analyses. Figure 5 shows the Chicago design storms developed based on historical and future IDF curve for 100-years return period and 1-hour duration.

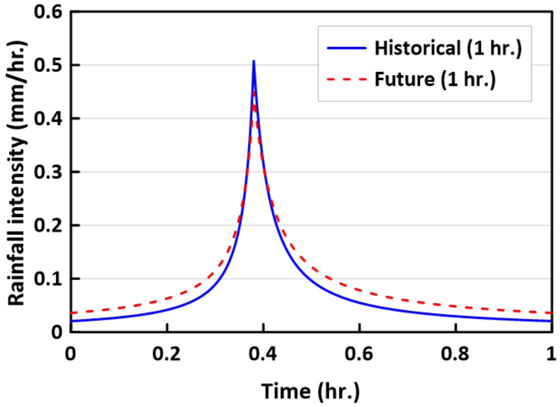


Figure 5. Chicago design storm for 1-hour, 100-year storm

## 5 RESULT AND DISCUSSION

### 5.1 FOS Variation during Extreme Events

The effects of climate change on the stability of slopes under extreme events was evaluated by tracking the variation of FOS under historical and future storms. Figure 6 presents the variation of FOS overtime under 1-hour and 6-hour storms considering 10, 50 and 100-year return periods for the sand embankment. For all cases, initial FOS is the same due to the same initial condition based on the wettest condition from the historical time period. During the 1-hour storm, FOS remains almost unchanged over the first 10 minutes for all return periods. Then, it decreased gradually until around 30 minutes. After this point, FOS decreased at a higher rate, especially for higher intensity future events. The decrease in FOS even up to end of rainfall duration is mainly because the slope does not have enough time to totally drain the entered water. Over 6-hour rainfall, FOS remains constant for approximately 2 hours, then it begins to decrease at a high rate due to the increase of the rainfall intensity. However, in contrast to 1-hour rainfall, the sand fill has sufficient time to drain that results in FOS go up again. A similar trend was obtained for 24-hour rainfall simulation.

Figure 7a shows the PWP distribution in sand embankment for a 100-year return period storm with three different durations at the time of critical FOS. The value of FOS and critical slip surface for three rainfall duration are also shown. The figure illustrates that the minimum FOS achieved for 24-hour rainfall in comparison to other examined duration (1-hour and 6-hour). In this figure, it can be observed that the critical slip surface contains several local saturated zones. In these areas, the soil suction component of the shear strength diminishes that leads to a lower value of FOS.

It is worth mentioning that even for critical cases the obtained FOS for sand embankment is still greater than the allowable value of FOS for earth embankment slopes that is normally used for design purposes in MTO projects (FOS=1.3). It is because the embankments are mostly designed under dry conditions that conservatively ignore the positive effect of suction on slope stability.

Results in figure 8 indicate that for 6-hour storms, the temporal distribution of FOS for the historical and future climate is very similar. This might seem counterintuitive as the future climate events have high intensities and should have resulted in higher pore water pressure generation and lower FOS. However, due to low conductivity and higher retention properties of silt material, an increase in the intensity of the event results in an increased generation of runoff with similar quantities entering the embankment. This can also be observed in 24-hour precipitation events when FOS for all future events is similar.

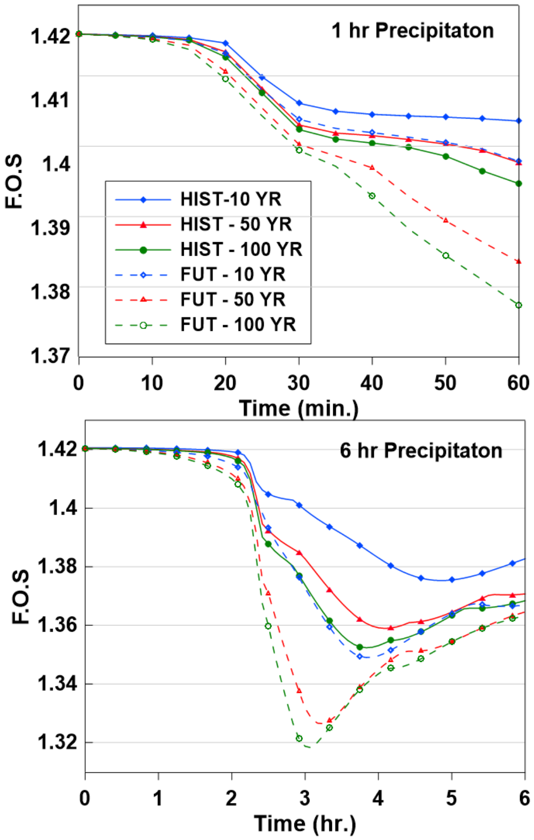
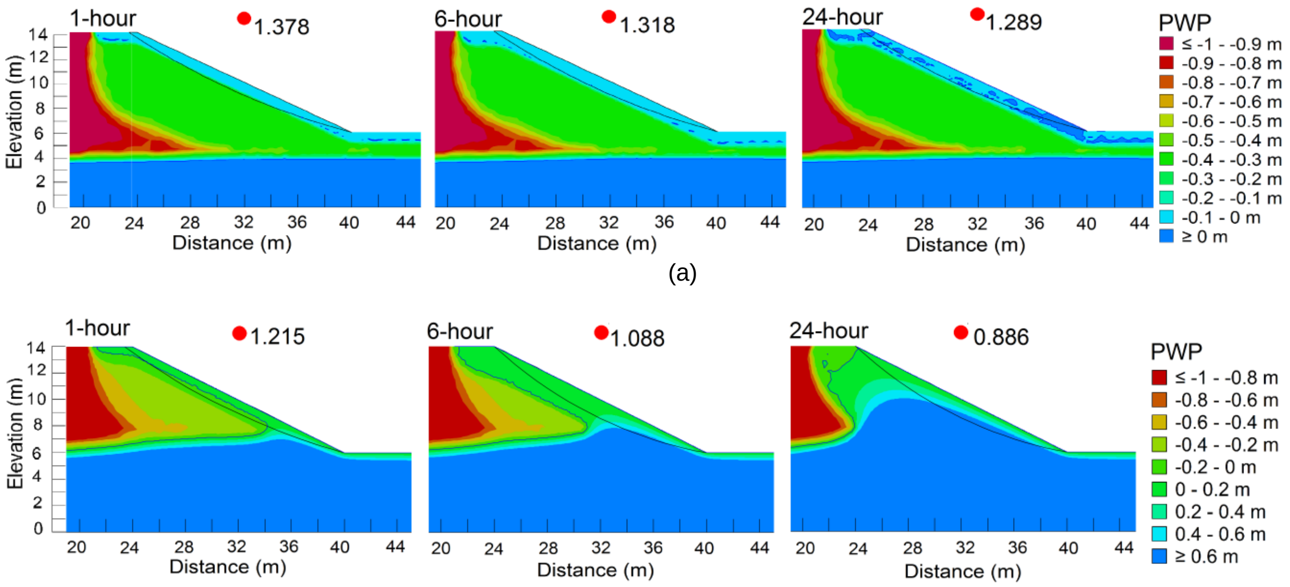


Figure 6. Variation of FOS in sand embankment over time

Figure 7b illustrates the PWP distribution through silt embankment for a future 100 years return period storm with different durations at the time of critical FOS. The Figure shows that the critical slip mass becomes fully saturated even under 1-hour precipitation. However, the minimum FOS is lower for greater rainfall duration due to the extension of positive PWP zones within the slope that leads to decrease the effective stresses. The numerical results indicate that all considered future rainfalls with different return periods have the potential of triggering global slope failure (FOS<1.0) that is not predicted under historical extreme precipitation (see Figure 8). This highlights the necessity of considering the impact of climate change on slope stability of earth embankments especially those constructed with fine-grained soil material.



(a)

(b)

Figure 7. Spatial distribution of pressure head in (a) sand embankment, and (b) silt embankment

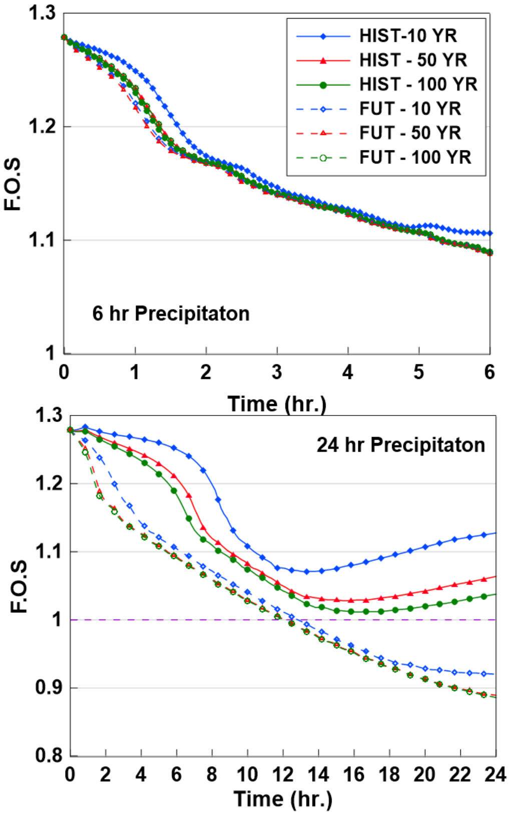


Figure 8. Variation of FOS in silt embankment over time

## 5.2 Probability of Future Events

As mentioned in the previous section, the initial PWP distribution through the embankment fill was established based on the maximum saturation degree of a soil column under 30-year historical climate data (1981-2010). The variation of saturation degree over time was obtained from the one-dimensional transient unsaturated flow model as described in Section 4.2. The results of the same model under future climate data indicate that maximum historical saturation degree would be exceeded a number of times in the future (see Figure 4). To explain the results in term of probability, the Poisson distribution model was employed.

Poisson distribution is the most common model that has been employed to demonstrate the temporal occurrence of random natural events such as earthquakes (e.g. Kramer 1996) and extreme storm rainfalls (e.g. Smith and Karr 1990). The model is established on the basis that the events follow a Poisson process where the average time between events is known, but the exact timing of events is random. Another assumption of this model is that the arrival of an event is independent of the event before; namely, the waiting time between events is memoryless. Based on Poisson probability model, the probability of occurrence of at least one event with a return period of *T* during the time span of interest (*t*) is given by:

$$P[N \geq 1] = 1 - e^{-\frac{t}{T}} \qquad [2]$$

Herein, Equation 2 was applied to estimate the probability of exceedance of average saturation from the maximum historical saturation in the future. On the other hand, the probability of occurrence of each IDF curve for a given return period can also be determined using Equation 2. For return periods of 10, 50 and 100 years, which were considered in this study, the probabilities of IDF curves are 95.0%, 45.1%, and 25.9%, respectively. Based on multiplication rule in the probability theory, the probability of two independent events happening at the same time can be estimated by multiplying the two probabilities. This rule was adopted to estimate the probability of minimum FOS in this study.

Figure 9 and 10 illustrate the minimum values of FOS during 1, 6, and 24-hours rainfall events for sand and silt embankments, respectively. These graphs present the results obtained for two different return periods (10 and 100 years). It can be observed that an increase in rainfall duration results in lower values of FOS. It can also be observed that the critical storm for all cases that were considered is 24 hours rainfall of with 100-year return period. Although the minimum obtained FOS for sand embankment is still close to the allowable FOS (1.3), the FOS for silt embankments is less than allowable value for all rainfall durations. For silt embankment, the numerical model yields less than 1.0 for future 24 hours storms.

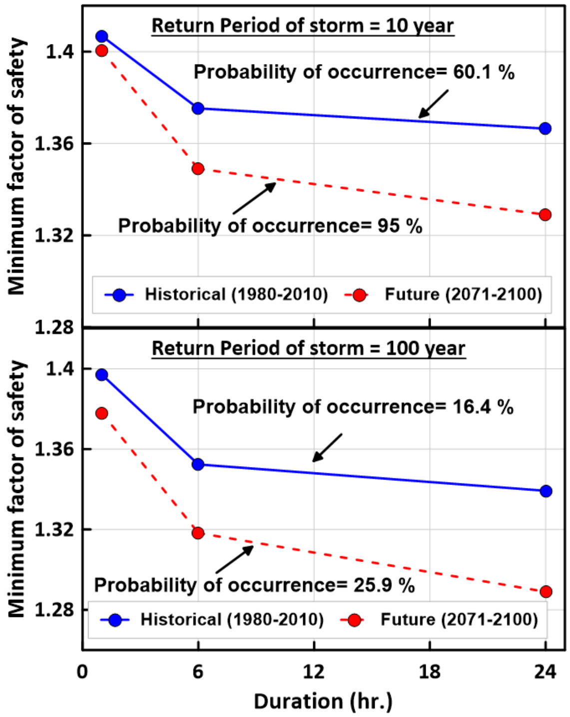


Figure 9. Probability of minimum FOS for sand embankment

The estimated probability of low-value FOS is also depicted in Figures 9 and 10. The comparison between the results for historical and future climate indicates that not only the future climate will generally result in lower FOS but also the probability of lower FOS will become higher for future climate changes. For instance, the minimum FOS in sand embankment under 1-hour historical and future 10 years storm is almost the same (~1.4), but the probability of the future event is about 35% greater than the probability of its occurrence in the historical time period (Figure 9). According to Figure 10, the minimum FOS value for silt embankment under future 24 hours, 10 years return period rainfall is less than 1.0 with 95% probability of occurrence. This implies a high likelihood of global failure of silt embankment under future extreme events.

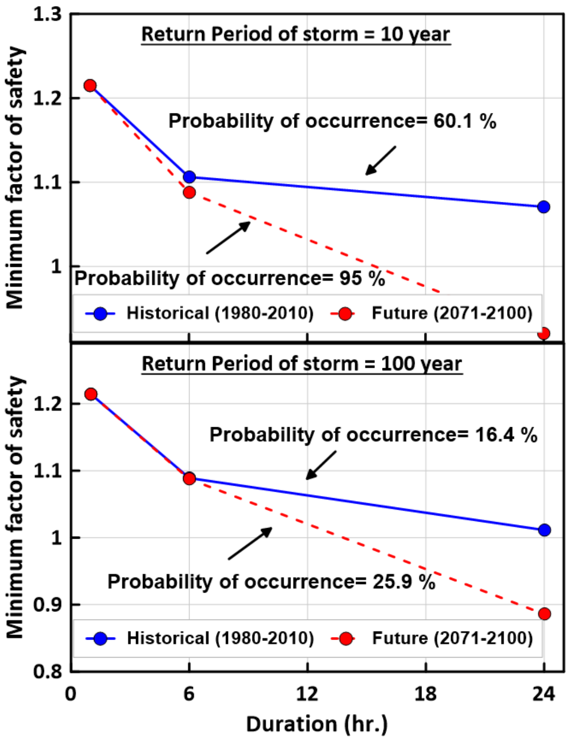


Figure 10. Probability of minimum FOS for silt embankment

## 6 CONCLUSION

In this study, the effect of climate change on the stability of a typical highway embankment in Ottawa, ON was investigated. While the long-term variation of soil moisture conditions was considered for changing the climate, the main focus of this research was on quantifying the effects of future extreme precipitation events on the stability of embankments. A one-dimensional variably saturated finite element flow model equipped with soil-atmosphere boundary was used for the assessment of long-term variation of soil moisture conditions under changing climates. This assessment was carried out for 30-year historical climate data and sixteen 90-year future climate datasets. The future climate datasets were based on four different GCMs and RCPs. The assessment was carried out for two different soil materials with typical hydraulic properties of coarse and fine soils. A 2D transient unsaturated flow finite element model was used to capture the spatial distribution of pore water pressure within the embankment for the critical set of future climate data.

Assessment of slope stability overtime during extreme events was carried out using a one-way coupled hydro-geotechnical model. In the hydrological model, Chicago synthetic storm hyetographs based on historical and future intensity-duration-frequency curves were applied for the soil-atmosphere boundary. The geotechnical model employs a limit equilibrium method with consideration of the contribution of matric suction on the soil strength parameters. Furthermore, the probability of predicted FOS values was estimated using a statistical method employing Poisson distribution.

Overall, the results of numerical modeling confirm the adverse impact of climate change on the stability of slopes. Not only lower values of factor of safety were predicted for next coming decades, but also the likelihood of high-risk events was found to be increased substantially.

Numerical results indicate that the effect of climate change is also dependent on the hydraulic properties of the embankment materials. For embankments constructed with coarser materials, the FOS will reduce under future extreme precipitation events but will remain above the threshold value of 1.3. However, for embankments built with fine materials such as silt, similar climatic changes have the potential to trigger global slope failures. Therefore, the climate change impact should be considered as a high priority issue in the design of future and assessment of existing embankments especially those constructed with fine-grained materials.

## 7 REFERENCES

Bo, M.W., Fabius, M. and Fabius, K. 2008. Impact of Global Warming on Stability of Natural Slopes, *Proceedings of the 4th Canadian Conference on Geohazards*, Quebec, QC, Canada. 594–601.

CCDP. 2018. Ontario Climate Change Data Portal. Available from http://www.ontarioccdp.ca

Collison, A., Wade, S., Griffiths, J. and Dehn, M. 2000. Modelling the Impact of Predicted Climate Change on Landslide Frequency and Magnitude in SE England, *Engineering Geology*, 55(3): 205–218.

Coulibaly, P., Henderson, J. and Fausto, E. 2016. Addendum – IDF Statistics, Curves and Equations: 244.

Fredlund, D.G., Rahardjo, H. and Fredlund, M.D. 2012. *Unsaturated Soil Mechanics in Engineering Practice*, Wiley, Hoboken, NJ, USA.

Geo-slope International Ltd. 2016. Stability Modeling with SLOPE/W: An Engineering Methodology (Computer Program), GEOSLOPE/W International Ltd. Calgary, Alberta, Canada.

IPCC 2013. Summary of IPCC. 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keifer, C.J. and Chu, H.H. 1957. Synthetic Storm Pattern for Drainage Design, *Journal of the Hydraulics Division*, 83(4): 1–25.

Kramer, S.L. 1996. *Geotechnical Earthquake Engineering*, Prentice Hall, Upper Saddle River, N.J.

Marsalek, J. and Watt, W.E. 1984. Design storms for Urban Drainage Design, *Canadian Journal of Civil Engineering*, 11(3): 574–584.

Morgenstern, N.R. and Price, V.E. (1965). The Analysis of the Stability of General Slip Surface, *Geotechnique* 15(1), 79-93.

MTO. 1997. Drainage Management Manual, Ronin House Publishing, under contract from Ministry of Transportation of Ontario, Ottawa, Ontario, Canada.

MTO. 2018. IDF Curve Look-up, Ministry of Transportation, ON, Canada.

Mualem, Y. 1976. A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media, *Water Resources Research*, 12(3): 513–522.

Neuman, S.P., Feddes, R.A. and Bresler, E. 1974. Finite Element Simulation of Flow in Saturated - Unsaturated Soils Considering Water Uptake by Plants.

OPS. 2010. Ontario Provincial Standards for Roads and Public Works, OPSS 501: Construction Specification for Compacting. Ontario, Canada.

OPS. 2014 OPSS.PROV 206: Construction Specification for Grading, ON, Canada.

OPS. 2016. OPSD.202.1010: Slope Flattening Using Surplus Excavated Material On Earth Or Rock Embankmentl, ON, Canada.

Pk, S., Bashir, R. and Beddoe, R. 2018. Effect of Climate Change on Earthen Embankments in Southern Ontario, *Canada, Environmental Geotechnics*, 1–70.

Rahardjo, H., Nio, A.S., Leong, E.C. and Song, N.Y. 2010. Effects of Groundwater Table Position and Soil Properties on Stability of Slope during Rainfall, *Journal of Geotechnical and Geoenvironmental Engineering*, 136(11): 1555–1564.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums, *Physics*, 1(5): 318–333.

Robinson, J.D., Vahedifard, F. and AghaKouchak, A. 2017. Rainfall-triggered Slope Instabilities under a Changing Climate: Comparative Study using Historical and Projected Precipitation Extremes, *Canadian Geotechnical Journal*, 54(1): 117–127.

Rouainia, M., Davies, O., O'Brien, T. and Glendinning, S. 2009. Numerical Modelling of Climate Effects on Slope Stability, *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 162(2): 81–89.

Šimůnek, J., Šejna, M., Saito, H., Sakai, M. and van Genuchten, M.T. 2009. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, University of California, Riverside, California.

Šimůnek, J. van Genuchten, M.T. and Šejna, M. 2006. The HYDRUS software package for simulating two-and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Technical manual, 1: 241.

Smith, J.A. and Karr, A.F. 1990. A Statistical Model of Extreme Storm Rainfall, *Journal of Geophysical Research: Atmospheres*, 95(D3): 2083–2092.

van Genuchten, M.T., 1980. A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *Soil Science Society of America journal*, 44(5): 892-898.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. and Clifton, A.W. 1996. Model for the Prediction of Shear Strength with Respect to Soil Suction, *Canadian Geotechnical Journa*l, 33(3): 379–392.