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Assessment of Local Factor of Safety Field for Variably Saturated Embankments due to Climate Change Using In-Situ Stress Finite Element Analysis

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ABSTRACT
Climate change is expected to continue over this century and beyond with important impact on currently stable soil embankments. Soil response to precipitation pattern variation, due to climate change is directly related to pore water pressure and stress state changes. To accurately assess the behavior of embankments under changing climate, a deformation assessment using coupled hydro-mechanical analysis, with an appropriate elasto-plastic constitutive law may be required. However, priority in current engineering assessments is to identify the factor of safety against local, shallow or global failures, whereas deformation assessments are of a minor concern. In this research, the effect of climate change on the stability of embankments was quantified by estimating a field of Local Factor of Safety (LFS) using a coupled in-situ stress finite element analysis and variably unsaturated flow analysis. In this method, the effect of moisture content variation on the effective stress was taken into account using suction stress state. For a case study, the effects of climate change on the stability of a typical highway embankment consisting of sandy or silty soils in cities of Toronto and Niagara Falls in Ontario was considered. The study results demonstrate that the proposed simplified assessment approach is capable of identifying global and local failure zones without the use of advanced elasto-plastic simulations.

RÉSUMÉ
Le changement climatique devrait se poursuivre au cours de ce siècle et au-delà, avec un impact important sur les remblais de sol actuellement stables. La réaction du sol à la variation du régime de précipitation en raison du changement climatique, est directement liée à la pression interstitielle de l'eau et aussi aux changements de l'état de contraintes. Afin de mieux évaluer le comportement des remblais sous le changement climatique, une évaluation de la déformation en utilisant une analyse hydro-mécanique couplée, avec une loi de comportement élasto-plastique approprié peut être nécessaire. Cependant, la priorité dans les évaluations techniques actuelles est d'identifier le facteur de sécurité lié aux ruptures locales, superficielles ou globales, alors que les évaluations de déformation sont une préoccupation mineure. Dans cette recherche, l'effet du changement climatique sur la stabilité des remblais a été quantifié en estimant un champ de facteur de sécurité local (LFS) en utilisant une analyse par éléments finis de contraintes couplées in situ et une analyse d'écoulement insaturée de manière variable. Dans cette méthode, l'effet de la variation de la teneur en humidité sur la contrainte effective a été pris en compte en utilisant l'état de contrainte d'aspiration. Pour une étude de cas, les effets des changements climatiques sur la stabilité d'un remblai routier typique composé de sols sableux ou silteux dans les villes de Toronto et de Niagara Falls en Ontario, en Ontario, ont été considérées. Les résultats de l'étude démontrent que l'approche d'évaluation simplifiée proposée est capable d'identifier les zones de ruptures globales et locales sans utiliser des simulations élasto-plastiques avancées.

1 INTRODUCTION

Climate change is a long-term shift in weather conditions primarily identified by changes in temperature. Changes to the climate system is unequivocal and Canada is one of the countries that is warming at a fast rate (IPCC 2013). Climate warming will result in changes of other important climate variables, such as precipitation, and potential evaporation. Climate change involves both changes in average conditions and changes in variability, including frequency and intensity of extreme weather events. Strauch et al (2015) have indicated that climate change may cause the less frequent, but more intense rainfalls. According to IPCC (2013), it is expected that that the frequency and intensity of the extreme precipitation events in North America will increase in the future. Pk (2017) investigated the changes of climate variable over the next 90 years in Toronto. This research indicates that the mean annual temperature could increase up to 6°C by the end of 21st century. This research also shows higher annual precipitation up to 18.5% with more intensified extreme events.

Soil embankments are important class of geotechnical infrastructure in transit and transportation networks. Due to permanent exposure to the environment, stability of embankments is highly dependent on climate variables. Precipitation and evaporation are the two important climate variables that control the water balance at the embankment surface. The pore pressure distribution in the embankment is dependent on the water balance at the embankment surface. Increase in pore water pressure can reduce the shear strength of the unsaturated soil materials and can adversely affect the stability of embankments.

Several researchers have proposed numerical models for investigation of climate change impacts on the stability of slopes (e.g. Collison et al. 2000; Rouainia et al. 2009; Robinson et al. 2017; Pk et al. 2018). The majority of slope stability assessment studies have been carried out using the widely used limit equilibrium method (LEM). However, the conventional limit equilibrium method is not generally capable of capturing local and shallow failures that are more likely to occur in slopes subjected to extreme precipitations (Bagheri et al., 2019).

This study is a part of an ongoing research on the effects of climate change on the stability of highway embankments across Ontario. The objective of current study is to investigate the effect of climate change on the stability of earth fill embankments by estimating the field of Local Factor of Safety (LFS). In order to accomplish this objective, a coupled hydro-mechanical model equipped with soil-atmosphere boundary condition using unsaturated flow formulation was developed. The effect of water content variation on in situ effective stress field is applied using the suction stress state concept within the unsaturated soil mechanics framework. In the employed method, in situ stress field is calculated based on an elastic finite element analysis.

The calculated LFS contour maps was compared to the yield zone obtained from elasto-plastic finite element analysis. Moreover, conventional limit equilibrium method and finite element limit equilibrium in which the stability condition is identified in terms of single factor of safety were considered.

For a case study, the effects of climate change on the stability of a typical highway embankment consisting of sandy or silty soils in cities of Niagara Falls and Toronto in Ontario were considered in this study. For this purpose, the evolution of LFS field over the time of 6-hr design storm was investigated. The initial moisture condition within the embankments were obtained based on statistical analysis on the results of seepage analyses. In these analyses, the embankments were subjected to long-term historical and future design climate for the locations under consideration.

2 CLIMATE AND CLIMATE CHANGE INFORMATION

Design climate for the assessment was constructed based on the compilation, classification, and analysis of historical and future climate data. Historical climate data (1981-2010) for the cities of Toronto and Niagara Falls was compiled from relevant weather stations for these locations maintained by Environment and Climate Change Canada. Climate classification was carried out according to the procedure by Thornthwaite and Hare (1955). Future climate data was obtained from Ontario Climate Change Projections (OCCP) published by the Laboratory of Mathematical Parallel System (LAMPS), York University. Future climate data is from four different global circulation models (GCM) and all four Representative Concentration pathways (RCP) (i.e., 2.6, 4.5, 6.0, and 8.5). After a detailed review, analysis and comparison of historical and future climate data, data from GCM HadGEM2-ES and RCP 2.6 for the period 2011-2030 was identified as the critical climate data and was used in further assessments. Figure 1. shows the climate classification for historical and selected future climates for the cities of Toronto and Niagara Falls. It can be observed that the larger changes are expected for City of Toronto in comparison to the city of Niagara Falls. These historical and future climate datasets were used in assessment of long-term moisture conditions in the embankment which served as the initial conditions for the embankment's stability assessment under extreme precipitation events.

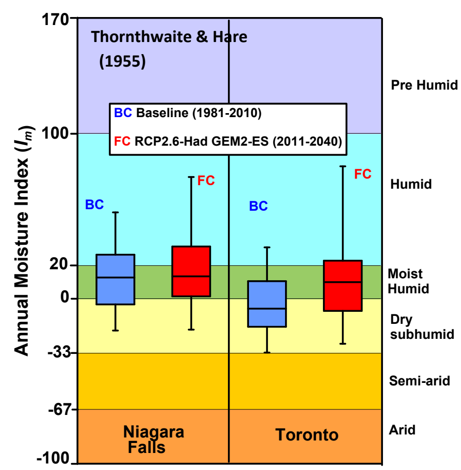

Figure 1. Climate classification for historical and future climates in cities of Niagara Fall and Toronto

Rainfall intensity-duration-frequency (IDF) curves present the probability of occurrence of extreme precipitation in a region and are a practical tool for many analysis and design applications. In order to quantify the effect of climate change on extreme precipitation events, IDF curves based on historical measured and future predicted climate data were analyzed. Historical IDF curves for the cities of Toronto and Niagara Falls were obtained from Environment and Climate Change Canada. Future IDF curves were obtained from the Ministry of Transportation, Ontario (MTO 2018), and Ontario Climate Change Data Portal (CCDP 2018). Both sources use different methodologies for the prediction of the future IDF curves.

Intensity duration frequency curves are available for different return periods (2, 5, 10, 25, 100 year) and durations (5, 10,15, 30 minutes, and 1, 2, 6, 12, 24 hours). Predictions from CCDP are available for both the fourth (AR4) and fifth Assessment Report (AR5) of the IPCC (IPCC 2007, IPCC 2013). After detailed analyses, predictions from CCDP for RCP 8.5 were selected. These predictions are from a regional climate model RegCM driven by boundary conditions from the general circulation model HadGEM2-ES. Figure 2 shows the percent change in intensity of 6-hr precipitation events for various returns periods. It can be observed that the changes for Niagara Falls are greater than for Toronto. In this study, extreme precipitation for 50-year and 100-year return periods were considered.

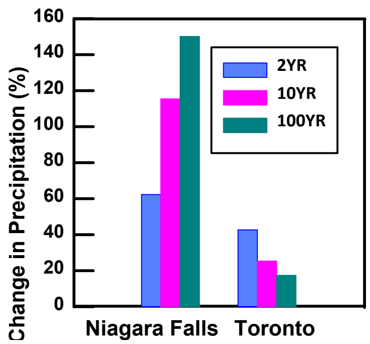

Figure 2. Change in intensity of 6-hr precipitation events for various returns periods

3 SLOPE STABILITY ASSESSMENT BASED ON FINITE ELEMENT ANALYSIS

The use of finite element method for slope stability analysis is becoming increasingly common. One of the main advantages of finite element is that stress and strain field can be calculated without simplifications that is normally used in conventional limit equilibrium method of slices. The finite element method has also been utilized to estimate the factor of safety as a widely used indicator for slope stability assessment. Some of the common approaches to determine factor of safety based on the finite element analysis are as follows:

- Strength Reduction Method: The FOS is defined as the factor by which the original shear strength parameters must be divided to bring the slope to the point of failure (Griffith and Lane 1999; Hammah et al. 2005). The advantages of this approach over conventional limiting equilibrium method is that no assumption is needed about the shape or location of the critical failure surface (Hammouri et al., 2008).
- Finite Element Limit Equilibrium Method: In this method, the critical slip surface corresponding to the minimum FOS is identified using limit equilibrium methods. In contrast to conventional LEM, the field of stresses is calculated by using finite element analysis (Fredlund and Scoular, 1999; Liu et al., 2020).
- Elastoplastic Finite Element Analysis: Local instabilities may not necessarily lead to global shear failures that can be identified by LEM. Local instabilities can be extracted from yield points in elastoplastic finite element analysis. In this method, slope stability is assessed by taking into consideration stress concentration without assumptions or identification of potential failure surfaces.

In this study, the effect of climate change on the stability of embankments was quantified by estimating a field of Local Factor of Safety (LFS) using a coupled finite element in-situ stress analysis and variably unsaturated flow analysis. A simple approach is employed to determine the field of local factor of safety based on elastic finite element analysis. The method can be used not only to identify the local instabilities, but also to determine the extension of zones with lower factor of safety within the slope.

4 STUDY OF SLOPE FAILURES USING LFS FIELD

Local factor of safety (LFS) is the ratio of Coulomb stress of the potential failure state under the Mohr-Coulomb criterion (τ^*) to the Coulomb stress at the current state of stress (τ) (Lu et al., 2012):

$$LFS = \frac{\tau *}{\tau} \qquad [1]$$

Figure 3 illustrates the definition of τ^* and τ for a given Mohr circle stress state on a shear stress-normal stress space. As can be seen on this figure, while the state of stress in a slope represented by the Mohr circle is below the Mohr-Coulomb failure envelope, the LFS is greater than unity. LFS can also be easily derived based on the mean and deviator effective stresses (p' and q') in two-dimensional space as follows (Lu et al., 2012):

$$LFS = \frac{2\,cos\emptyset'}{q'}\,(c' + p' \tan \emptyset') \qquad [2]$$

where c′ is the drained cohesion of the slope material, ϕ′ is the drained friction angle of the slope material. LFS can be calculated at each point using Equation 2. LFS contour map can then be obtained by joining the points with same LFS values indicating an accurate stability condition for a given slope. The zones with LFS greater than unity imply statically stable conditions. While, zones with LFS equal or less than unity, are at the limit state and local failure can be expected.

It should be noted that soil-atmosphere interaction affects the pore water pressure distribution through embankment fill over time. This leads to the evolution of the effective stress fields that consequently can be translated to the LFS field. The changes in effective stress field can be estimated by calculating the suction stress based on a single stress state variable framework proposed by Lu and Likos (2006). A brief review of this framework is presented in the following section.

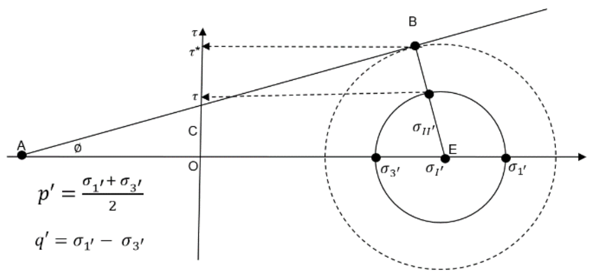

Figure 3. Illustration of definition of τ^* and τ for a given Mohr circle stress state (Adopted from Lu et al., 2012)

3 SINGLE STRESS STATE VARIABLE FRAMEWORK

Matric suction or negative pore pressure has the effect of increasing the shear strength of unsaturated soils. Therefore, considering the contribution of matric suction in the slope stability assessment is of great importance (Fredlund et al. 2012; Adem and Vanapalli 2014 ; Arairo et al. 2015). Two common frameworks to take into account the effect of matric suction on shear strength are two independent stress state variables (e.g. Coleman 1962; Bishop & Blight 1963; Fredlund and Morgenstern 1977; Fredlund et al. 1996, Vanapalli et al. 1996) and single stress state variable framework (e.g. Bishop 1954; Bishop 1959; Lambe 1960; Lu and Likos 2006). In first approach, unsaturated shear strength is a function of the two stress variables: net normal stress and matric suction. The most frequently used method based on two stress state variables is as follows (Vanapalli et al. 1996):

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w)[(Sr) \tan \phi'] \quad [3]$$

where $c`$ is effective cohesion, $u_a$ is pore-air pressure, $u_w$ is pore-water pressure, $\sigma - u_a$ is net normal stress on the failure plane, $u_a - u_w$ is matric suction, $\phi`$ is effective angle of internal friction for the saturated soil and Sr is the degree of effective saturation as described below:

$$Sr = \frac{\theta - \theta r}{\theta s - \theta r} \quad [4]$$

where θ is the volumetric water content, and θ_s and θ_r are saturated and residual volumetric water content, respectively.

Despite its popularity, two stress state variable approach is subjected to a major practical limitation: It cannot be utilized within the context of classical mechanics that consider effective stress as the single stress state variable governing the soil behavior (Lu et al. 2010). To overcome this limitation, Lu and Likos (2006) extended the pioneering work by Bishop (1954 and 1959), to define a new stress variable called suction stress (σ_s) within the context of Terzaghi's effective stress equation as following:

$$\sigma' = (\sigma - u_a) - \sigma^s \quad [5]$$

Lu et al. (2010) proposed a closed-form expression for suction stress for the full range of matric suction:

$$\sigma^s = -(u_a - u_w) \qquad u_a - u_w \leq 0 \quad [6]$$

$$\sigma^s = \frac{(u_a - u_w)}{(1 + [\alpha (u_a - u_w)]^n)^{(n-1)/n}} \qquad u_a - u_w \geq 0 \quad [7]$$

where α and n are the parameters used to define the soil water characteristic curve (SWCC) of a soil using van Genuchten's (1980) equation. Suction stress can also be expressed as a function of effective stress as following (Lu et al., 2010):

$$\sigma^s = -\frac{S_e}{\alpha}\left(S_e^{\frac{n}{1-n}} - 1\right)^{\frac{1}{n}} \qquad 0 \leq S_e \leq 1 \quad [8]$$

In this study, the single stress state approach by Lu et al. (2006, 2010) was used to capture the evolution of effective stress field in variably saturated embankments subjected to soil-atmosphere interaction. The effective stress field is the basis for developing LFS contours as explained in section 3. In addition, two stress state variable model by Vanapalli et al. (1996) was employed to estimate the shear strength of unsaturated soil through conventional limit equilibrium analyses.

4 NUMERICAL MODEL

4.1 Geometry and Material

The embankment profile considered in current study represents a typical highway embankment in Ontario. Since the problem is symmetrical, only one-half of the domain as shown in Figure 4, was simulated. The height of embankment was considered to be 8 m. This is the maximum allowable height of earth fill embankment without berms in Ontario (OPSD 202.010). Side slopes of embankment are 2 horizontal to 1 vertical (2H:1V) with a 3 m width unpaved shoulder at the top of embankment. The distance between the slope toe and the right side of the model was set to 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 at the natural ground surface that is 4 m below the level of slope toe.

In this paper, two different soils that cover the range of materials typically used in the construction of highway embankments in Ontario were selected for numerical simulations. The mathematical model suggested by van Genuchten (1980) was used to represent the soil water characteristic curve (SWCC) as shown in Figure 5 for two selected materials. The unsaturated hydraulic conductivity function (HCF) was determined from SWCC using the van Genuchten Mualem approach (Mualem 1976, van Genuchten 1980). The soil hydraulic parameters for the selected materials used in development of SWCCs are presented in Table 1.

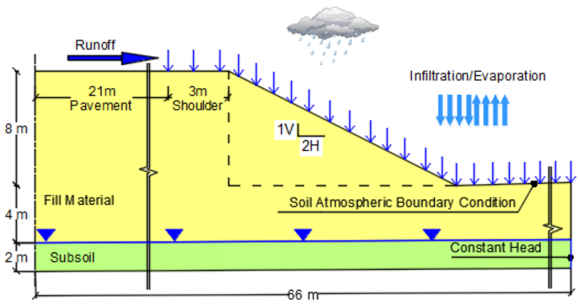

Figure 4. Design profile of the highway embankment

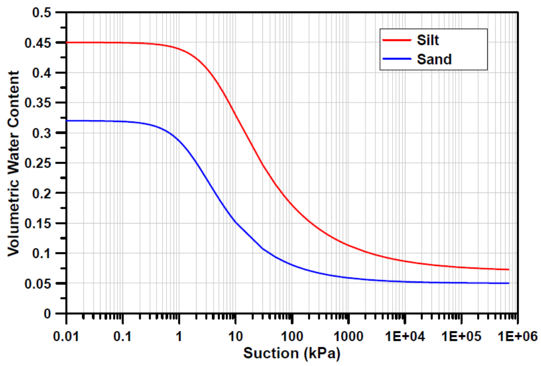

Figure 5. Soil water characteristics curves for selected material

Table 1. SWCC parameters used for sand and silt

	θ_s	θ_r	α (1/cm)	n
Sand	0.32	0.05	0.06	1.53
Silt	0.45	0.07	0.02	1.41

All embankment fill materials to be used in MTO projects are to be placed and compacted in accordance with the provincial standards, OPSS 206 and OPSS 501. An effective friction angle of 34° and 32° is assumed for compacted sand and silt materials, respectively. For finite element analyses, the value of Poisson's ratio that controls the development of horizontal stresses was assumed to be 0.3 and 0.35 for the sand and silt, respectively.

4.2 Initial Condition

It is a common practice to assume hydrostatic pore pressure distribution as the initial condition for the numerical simulation of a slope subjected to rainfall (e.g. Robinson et al. 2017; Pk et al. 2018). However, the hydrostatic conditions are a special and rare case in reality at the field scale when thermodynamic equilibrium is reached (Lu and Godt, 2013).
In this research, the saturation degrees corresponding to 50^{th} and 90^{th} percentiles for sand and silt embankments (IP50% and IP90%) were considered for selection of initial condition in the slope stability analyses under extreme rainfalls. The daily saturation degree data within the embankments were obtained based on soil-atmosphere modeling in which the embankments were subjected to long-term historical and future design climate for the under investigated locations.

4.3 Design Storm

In this study, the Chicago method was applied for providing intensity distribution over time for historical and future extreme precipitation events (design storms). First proposed by Keifer and Chu (1957), this method has been widely incorporated in Canadian practice (e.g. MTO, 1997). 6-hr rainfalls based on 50 and 100 year return periods were considered for development of historical and future design storms.

4.4 Hydro-Mechanical Models

In this study, HYDRUS 2D (Šimůnek et al. 2006) was used for analyzing the variation of water balance distribution through the embankment subjected to historical and future long-term and design storm climate datasets. HYDRUS 2D is a finite element software that numerically solves the Richards' equation for analysis of water flow in variably saturated soil. The software utilizes a system-dependent boundary condition that controls the maximum amount of water that can either evaporate or enter the boundary. In seepage analyses, 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 to be 4 m below the level of slope toe using a constant head boundary (Figure 4). The runoff from the pavement was assumed to be distributed over the earth fill embankment.

To compute the field of LFS, Slope Cube module (Lu et al. 2016) of the HYDRUS 2D software package was used. This supplemental module computes the soil stresses under gravity by using a two-dimensional finite element code for plane stress linear elasticity analysis. The pore pressure distribution obtained from HYDRUS 2D seepage analysis is introduced to Slope Cube to calculate effective stresses and the field of local factor of safety.

Elastoplastic finite element analyses were carried out using SIGMA/W which is a stress-strain finite element module of the widely used commercial software package GeoStudio (Geo-Slope International Ltd. 2016). Mohr-Coulomb yield criterion was used in this study. The Mohr-Coulomb parameters have the same values as used in limit equilibrium analysis.

Finite element limit equilibrium analyses were carried out by coupling the SIGMA/W and limit equilibrium software SLOPE/W. Both software are modules of GeoStudio and can be coupled very easily. For this type of analysis, the stress distribution calculated by SIGMA/W is used in SLOPE/W to determine safety factors along slip surfaces. Morgenstern-Price method (Morgenstern and Price 1965) that considers both the static force and moment equilibrium was used in limit equilibrium analyses.

In conventional limit equilibrium analysis, the strength due to suction in unsaturated soil was estimated using Equation 3 based on two stress state variable framework. However, the extended Terzaghi's effective stress equation using suction stress concept (Equation 5) was utilized in finite element limit equilibrium approach.

All finite element in situ stress analysis were carried out with the left and right boundaries free to move in the vertical direction; while the bottom boundary is fixed in both vertical and horizontal directions. In limit equilinbrium analyses, the minumum slip mass depth were set to a small value to allow capturing surfacial failures which is more likely to occur in slopes subjected to precipitaion.

5 RESULTS AND DISSCUSSION

5.1 Global Factor of Safety vs Local Factor of Safety

The stability of sand and silt embankments were assessed at the end of 100-year future design storm for Niagara Fall using different slope stability analysis approaches. Figure 6 and Figure 7 indicate the critical slip surface and the minimum global factor of safety using conventional and finite element limit equilibrium methods for sand and silt embankment, respectively. In conventional LEM, the forces acting on each slice is determined such that all slices are in force equilibrium and have the same factor of safety (Krahn et al., 2003). The generated stress distribution along a slip surface is not necessarily realistic, as the limit equilibrium method does not incorporate constitutive stress-strain relationship when computing factor of safety (Geo-Slope International Ltd. 2016). In finite element LEM, the stress distribution within the ground can be computed under applied loads such as gravity. In this study, the in-situ stress field was calculated using SIGMA/W and exported to SLOPE/W to find the critical slip surface and global factor of safety. Based on the obtained results, deeper critical slip surface and larger value for factor of safety were noted for embankment slopes under applied design storms. Moreover, the calculated global factor of safety does not show any potential local instability.

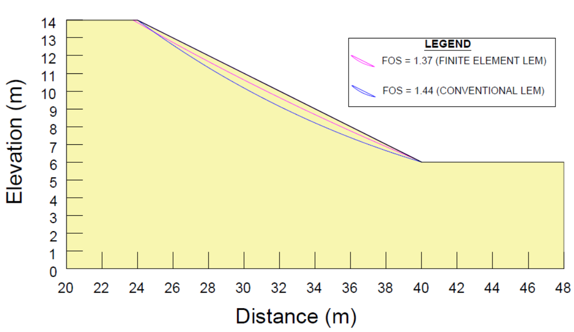

Figure 6. Conventional vs Finite Element LEM- Sand Embankment

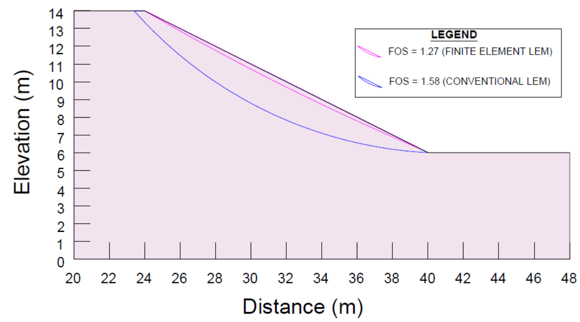

Figure 7. Conventional vs Finite Element LEM- Silt Embankment

In limit equilibrium analyses, global factor of safety (FOS) represents the stability condition of the entire slope. The limit equilibrium approach cannot be effective for identification of local instabilities which is a typical failure mechanism in slopes subjected to extreme precipitation events. Local instability can be captured using finite element analysis with elastoplastic constitutive models. A set of adjacent yield points defined in stress-strain analysis can be utilized to characterize the local instabilities. Figure 8 and Figure 9 illustrate the results of elastoplastic finite element analysis for the sand and silt embankments at the end of 100-year future design storm. Alternatively, the local factor of safety field can be developed to determine the contour of local factor of safety based on elastic in situ stress finite element analysis.

In LFS method, a local factor of safety is calculated for every point in the domain. Thus, a map of LFS contours that trace lines of equal LFS values can be established. The method can be used to estimate the local instabilities by mapping the contour of LFS=1.0. Figure 8 and Figure 9 also show the contour of LFS=1.0 for sand and slit embankment, respectively. These contours are in good agreement with the characterized yield points zone obtained from elastoplastic finite element analysis. The results confirm that shallow surficial failures under the considered climate condition that are not identified by LEM based analysis can be captured by assessment of local factor of safety.

It is noteworthy to mention that LFS method can be used to develop contour map for any desired LFS value. As an example, the contour map of LFS=1.3 are also shown in Figure 8 and Figure 9 for sand and silt embankments, respectively.

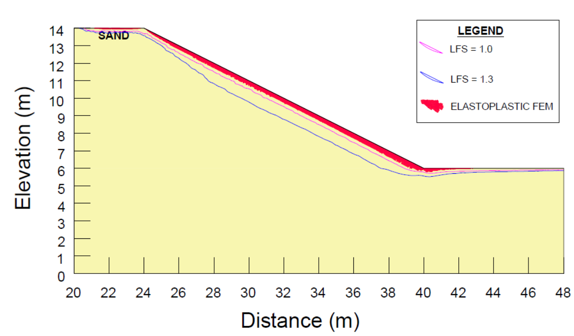

Figure 8. LFS field vs Yield points- Sand Embankment

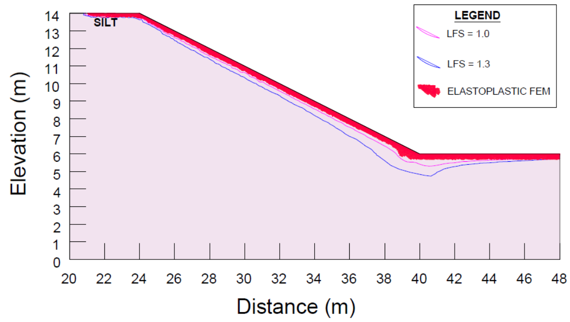

Figure 9. LFS field vs Yield points- Silt Embankment

5.2 Evolution of LFS field due to Extreme Events

Although LFS contour maps can present a general display of slope stability conditions, a quantitative LFS indicator is required particularly when the variation of LFS over time is of interest. Bagheri et al. (2019) defined a slope stability indicator based on the area of LFS contour measured in the numerical model cross section. For example, the value of $A_{LFS<1}$ is the area of zone in which LFS is less than unity. Obviously, this value represents the mass of local failure zone in a two-dimensional domain. This indicator was employed in this study.

Figures 10 to 13 and Figures 14 to 17 present the variation of $A_{LFS<1}$ over time in Niagara Falls and Toronto, respectively. For each city, sand and silt embankments were assessed under a 6-hr precipitation duration.

50-year and 100-year return period design storms were introduced to HYDRUS model for both cities using historical and future climate data. All embankments were assessed for initial conditions corresponding to IP50% and IP90%, as described in Section 4.2. A summary of the findings is presented as follows.

As the assumed historical and future initial conditions were identical, both historical and future $A_{LFS<1}$ evolution have commenced from the same initial failure mass area.

It is noted that in sand embankments, variations of $A_{LFS<1}$ is developed approximately after one and half hour after the introduction of precipitation event. This is in contrast to silt embankments where evolution of $A_{LFS<1}$ started immediately after the commencement of rainfall. The above noted differences are related to different soil hydraulic properties as well as the dissimilar initial saturated degree of sand and silt. In general, the silt embankments were at higher initial saturation degree in comparison to sand embankments.

It should be noted that the majority of $A_{LFS<1}$ increase occurs within 1.5 to 4 hours of precipitation event for sand embankments. In contrast, silt embankment shows immediate and consistent increases in development of larger failed zone.

It is also noted that more intense changes in area of failure mass occur under IP50% initial condition as the changes in the embankments saturation degrees are more significant for dryer initial condition.

More importantly, all results are indicative of more extensive instabilities in future. This is in line with the climate change predictions that show more intense weather events in the future.

Comparison between results of Figure 10 to 13 and Figures 14 to 17 also indicate that embankments in the city of Toronto are more prone to develop larger zones of instabilities in the future. This consistent with the climate classification for historical and future climates for the cities of Toronto and Niagara Falls as presented in Figure 1.

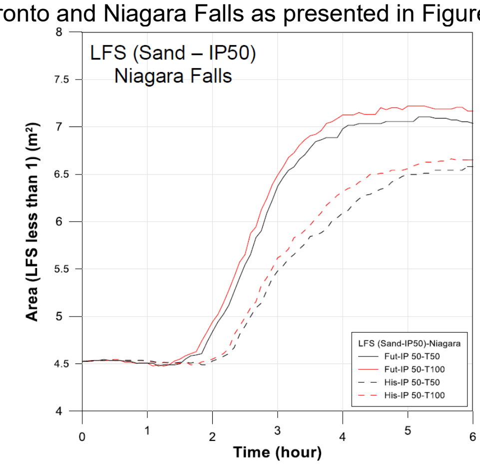

Figure 10. Niagara Falls – Sand - $A_{LFS<1}$ vs Precipitation Time - (IP 50%)

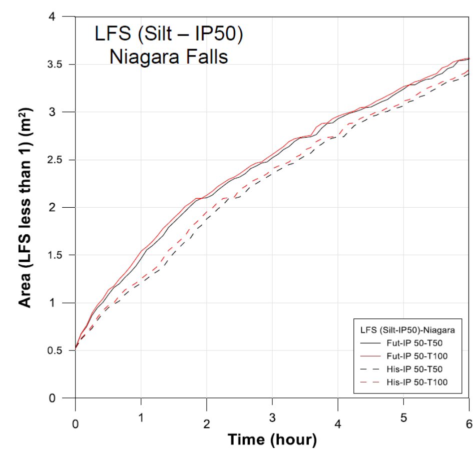

Figure 11. Niagara Falls – Silt - $A_{LFS<1}$ vs Precipitation Time - (IP 50%)

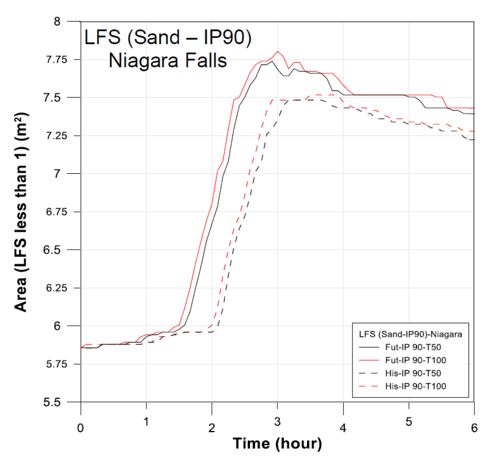

Figure 12. Niagara Falls – Sand - $A_{LFS<1}$ vs Precipitation Time - (IP 90%)

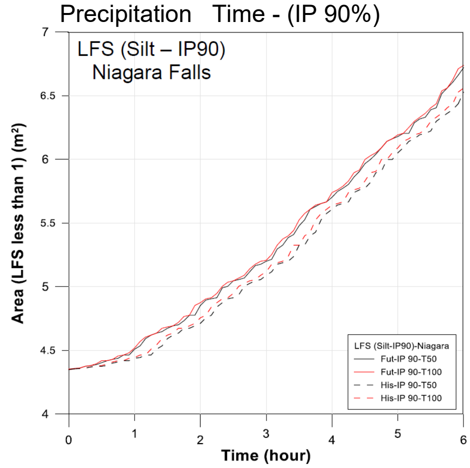

Figure 13. Niagara Falls – Silt - $A_{LFS<1}$ vs Precipitation Time - (IP 90%)

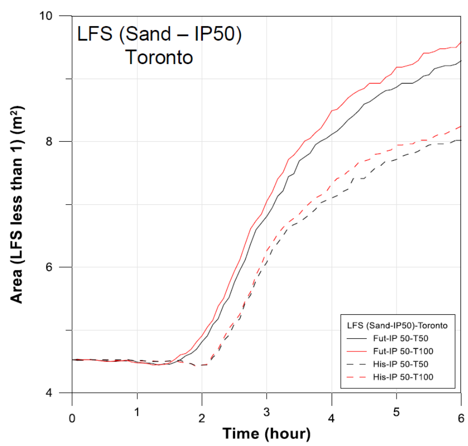

Figure 14. Toronto – Sand - $A_{LFS<1}$ vs Precipitation Time - (IP 50%)

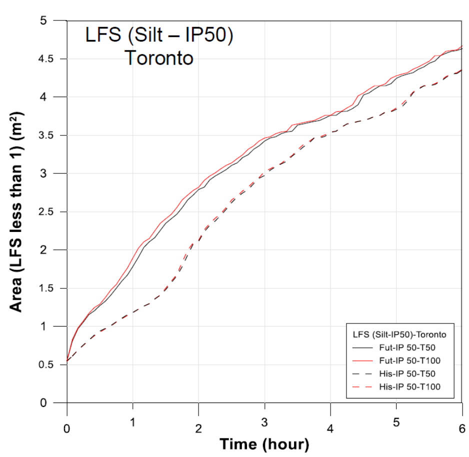

Figure 15. Toronto – Silt - $A_{LFS<1}$ vs Precipitation Time - (IP 50%)

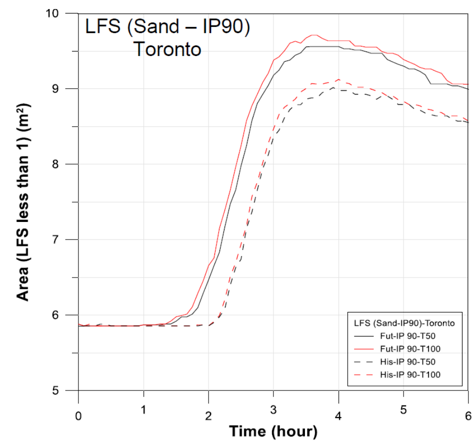

Figure 16. Toronto – Sand - $A_{LFS<1}$ vs Precipitation Time - (IP 90%)

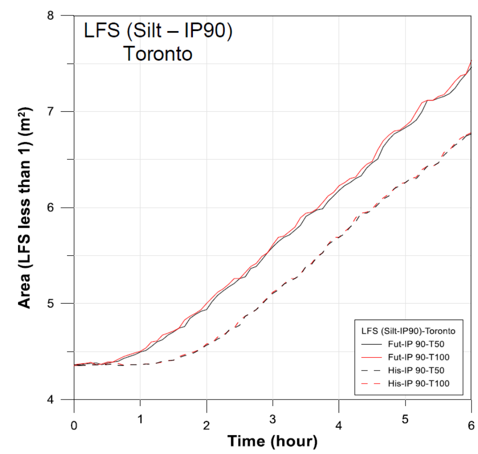

Figure 17. Toronto – Silt - $A_{LFS<1}$ vs Precipitation Time - (IP 90%)

6 CONCLUDING REMARKS

In this study, the effect of climate change on the stability of typical sand and silt embankments in cities of Toronto and Niagara Falls in Ontario was investigated by estimating the field of local factor of safety. A variably saturated seepage model equipped with soil-atmosphere boundary condition was employed to calculate the soil moisture distribution within the embankment. The effect of water content variation on in-situ effective stress field is applied using the suction stress state concept within the unsaturated soil mechanics framework.

In the method employed, in-situ stress field is calculated based on an elastic finite element analysis. The model was verified by comparing the contour of LFS<1 with yield points obtained from elastoplastic finite element analysis for a sample case. The case was also analyzed using both conventional and finite element limit equilibrium methods. The results indicated that the LFS method is capable of identifying the local surficial failures that are not obtained from the LE methods.

The area of zone in which LFS is less than unity ($A_{LFS<1}$) was considered as the indicator of the potential failure mass. The variation of $A_{LFS<1}$ over time were investigated for silt and sand embankments subjected to historical and future 6-hr design storms. In general, the results indicate that LFS method based on the concept of suction strength and single stress state variable framework is a viable approach to assess the stability of slopes under changing climate. Based on the conducted numerical simulations, the following conclusions can be drawn:

- The failed mass area in all cases increases over the course of the rainfall; however, the time of initiation and the rate of increase are different for the materials with different soil hydraulic properties. Silt embankments will see an appreciable decrease in stability at the onset of the event. However, sand embankments will see a decrease at later times. This was found to be consistent with the difference in initial conditions of the embankments.
- Two initial moisture conditions were considered in the numerical simulations. Higher increase in the mass of potential failure zone was obtained for the most probable initial condition (IP 50%). However, the ultimate total failure mass is higher for initial condition corresponding to IP 90%, particularly for silt embankment. For all the cases considered, more extensive shallow failures are expected in future. Moreover, silt embankments appear to be more prone to instabilities in the changing climate.
- The compilation and classification of the historical climate data suggests that median climate for the city of Toronto is dry subhumid, while for Niagara Falls is moist humid. Review of the future climate data suggests that wetter conditions can be expected for both the cities in the future. Moreover, intensity of the extreme precipitation events is expected to increase for both cities. The numerical simulation results in terms of failure mass area indicate that earth embankments in Toronto are more prone to shallow instabilities induced by future extreme precipitation events.

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