Effect of climate change on the stability of earthen embankments

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ABSTRACT
The foundations of highways and railways are often constructed on top of soil embankments which are climate dependent. The Intergovernmental Panel on Climate Change (IPCC) has predicted a significant change in climate across the country over this century. It is therefore important to ensure the future safety of soil embankments. This research aims to quantify the probable effects of climate change on the stability of soil embankments in Ontario, Canada. The changes in climate were estimated by analyzing 30 years of historical and 90 years of predicted climate data. The required embankment design parameters were collected from literature. The stability of the embankments was analyzed for the current and future climates using numerical modeling techniques. The results of this research show that the climate change could reduce the factor of safety of embankments by as much as 10%, potentially triggering failures.

RÉSUMÉ
Les fondations des autoroutes et des voies ferrées sont souvent construites sur des remblais de sol qui dépendent du climat. Le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) a prédit un changement important du climat à travers le pays au cours de ce siècle. Il est donc important d'assurer la sécurité future des remblais de sol. Cette recherche vise à quantifier les effets probables du changement climatique sur la stabilité des remblais du sol en Ontario, au Canada. Les changements climatiques ont été estimés en analysant 30 années de données historiques et 90 années de prévisions climatiques. Les paramètres de conception du remblai requis ont été recueillis dans la littérature. La stabilité des remblais a été analysée pour les climats actuels et futurs en utilisant des techniques de modélisation numérique. Les résultats de cette recherche montrent que le changement climatique pourrait réduire le facteur de sécurité des remblais de 10%, ce qui pourrait entraîner des défaillances.

1 INTRODUCTION

The effect of climate change is slowly becoming apparent with more frequent natural disasters including extreme storms, floods, intense drought, etc. Such extreme events involving temporal characteristics have a detrimental effect on the transportation infrastructures (Frauenfelder et al. 2016). For example, intense heat and drought followed by sudden heavy rainfall and flooding influences the vulnerability of natural and man-made slopes. Several Ontario highways pass adjacent to slopes or have embankments that are founded on a slope (Bashir et al. 2017). Failure of these slopes can be dangerous, disruptive and expensive. Traditional design of slopes and embankments cannot account climate change effects. However, it is necessary to incorporate these effects to ensure safety and serviceability of highway infrastructure.

The potential impacts of climate change on slopes and embankments in Canada have been presented by several researchers (Bo et al. 2008; Cloutier et al. 2016). Bo et al. (2008) presented the effect of climate change on natural and engineered slopes in Canada, and identified climate change as a potential threat. Cloutier et al. (2016) studied the impact of climate change on landslide occurrences in Canada. The authors concluded that climate change might create additional challenges in Canada due to the variable geological, geomorphological, and climatological settings across the country. Therefore, it is important to quantify the impacts of climate change on slopes and embankments to ensure a safe and sustainable transportation network. However, there is no peer reviewed research available in the literature that has quantified the climate change impact on slopes and embankments for Canada.

Quantification of climate change effects on slopes and embankments involves climate modeling, processing of climate modeling data for using in geotechnical analysis, soil-atmosphere modeling, geotechnical analysis, and design or redesign of slopes based on climate inputs (Bashir et al. 2017; Pk 2017). This requires a multidisciplinary approach (including climatology, unsaturated zone hydrology, surface hydrology and geotechnical engineering), incorporating the effects of subsurface movement and surface water (from sudden events) on soil stability and strength.

Recent advancement in mathematical modeling and computational power of the modern computer has made it possible to quantify climate change impacts on geotechnical infrastructure. Researchers around the world have attempted to quantify the effects of climate change on slopes and embankments (Dehn and Buma 1999; Collison et al. 2000; Davies 2011; Melchiorre and Frattini 2012; Dijkstra et al. 2014; Robinson et al. 2017). Collison et al. (2000) quantified the probable climate change impacts on future landslide activities in south east England. Davies (2011) quantified the climate change effects on a railway embankment and a cutting as a part of his doctoral dissertation. In a recent study, Robinson et al. (2017) investigated the impact of future extreme precipitation events on landslides in an area near Seattle, Washington. The authors concluded that climate change might cause detrimental effects on the stability of slopes, and consideration of historical climate only in design could lead to underestimation of the potential risks.

In this research, the impact of climate change was quantified for a typical highway embankment with different construction fill materials located in southern Ontario, Canada. The probable changes in future climate were estimated by analyzing 30 years of historical and 90 years of predicted climate data. The design climate events were constructed based on the findings of climate data analysis. The design climate contained daily precipitation of varying temporal resolutions to address the effects of regular as well as extreme events. The embankment design parameters were selected based on relevant previous studies and Ontario Provincial Standards Specification (OPSS) for roads and public works. The effect of probable changes in future climate was primarily quantified by estimating changes in porewater pressures (PWPs) within the embankment using numerical modeling. The predicted PWPs were used to estimate probable effect on the stability of embankment using a limit equilibrium method. The impacts of climate change were then quantified by comparing the results for the historical climate with those for the predicted future climate.

2 ANALYSIS OF HISTORICAL AND PREDICTED FUTURE CLIMATES

Climate change impact assessment studies require a baseline climate (BC) as a datum for comparison with future climate. In addition, BC helps to understand and characterize local climate for a specific site. In this research, the BC consisted of a record of 30 years of climate data (1981-2010) for the city of Toronto, Ontario, Canada. The collected climate variables were daily precipitation along with the maximum, mean, and minimum temperature. The required climate data was obtained from the Environment Canada weather station at Pearson International Airport in Toronto (WMO ID: 71624) (Environment Canada 2011). The collected climate data was analyzed and a plot of major findings is presented in Figure 1.

The daily precipitation data is plotted in Figure 1a. The 30 years of baseline precipitation (*P*) shows an average annual value of 786 mm. Figure 1a shows that the highest amount of precipitation in a day was 71.6 mm, and daily precipitation events of 40 mm or greater occurred 28 times over the 30-year period. Therefore, it can be concluded that 40 mm or higher precipitation events occur approximately once per year. This was selected as an extreme precipitation event for Toronto.

The daily mean temperature is shown in Figure 1b. The mean temperature for the baseline period shows average positive and negative values of 12.8 and -5.9°C, respectively. It can be observed in Figure 1b that during the winter period the temperature remains negative continuously for several months. The historical highest and lowest mean temperature of 31.5 and -24.7°C were recorded in 2006 and 1993, respectively.

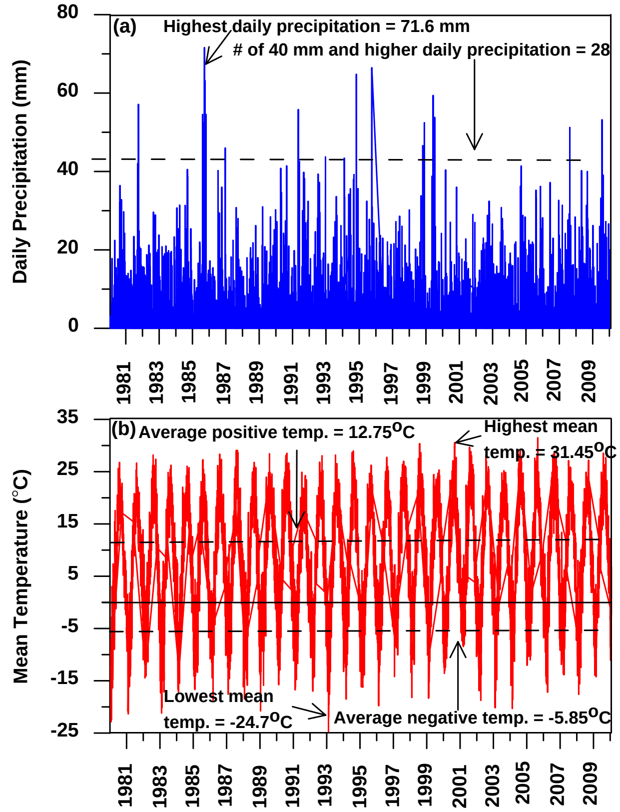

Figure 1. Major climate variables for baseline climate at Pearson International Airport in Toronto

Predicted future climate data was collected from the Laboratory of Mathematical Parallel Systems (LAMPS) housed at York University, Toronto, Canada. Among 33 general circulation models (GCMs), the three best performing models for Ontario were CCSM4, GFDL-ESM2M, and NorESM1-M (Deng et al. 2017). These models were selected for this research. The future climate dataset contained all four Representative Concentration Pathways (RCPs) and 90 years (2011-2100) time period. This time period was divided into three periods of 30 years. Each of these periods represent one GCM and one RCP, defined as Climate Ensemble (CE). Therefore, a total of 3 GCMs, 4 RCPs, and 3 periods of 30 years (total 90 years) form 36 climate ensembles for future climate.

Two major climate variables: daily precipitation and mean temperature were selected to estimate the probable changes over 90 years into the future. In addition, the changes in the number of extreme precipitation events were also investigated as extreme precipitation is a significant threat to the stability of slopes and embankments. The temporal change in annual precipitation, increase in daily mean temperature, and change in annual occurrence of extreme precipitation events were calculated for all 36 CEs. The results are plotted in Figures 2a, 2b, and 2c, respectively. Figure 2a shows that most of the climate ensembles predict an increase in annual precipitation. The increase in precipitation shows a raising trend from the lower to higher

RCPs (i.e. RCP2.6 to RCP8.5) between 2020 and 2080. A total of eight climate ensembles show negative (decreasing) trend [within 0 to -3%]. However, the magnitude of these negative changes is relatively small (Figure 2a). Therefore, it is reasonable to believe that there will be an increasing trend in cumulative precipitation in the future. In general, the projected increase in annual precipitation would be within 0 to 5% in the next decade, 0 to 8% over the next three decades, and 0 to 19% over the next six decades.

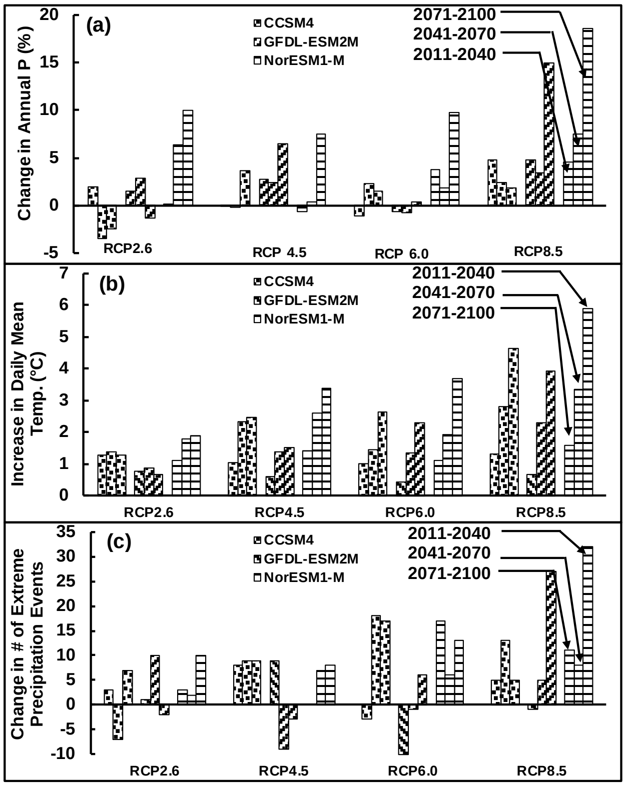

Figure 2. Expected changes in major climate variables

The daily mean temperature shows a consistent increasing trend. The results of the analysis for the 36 CEs are plotted in Figure 2b. The changes in mean temperature were calculated by subtracting the average value of BC from the FC. It can be observed that all three GCMs show a consistent increasing trend with the RCPs and time. RCP2.6 shows the lowest change while the highest change is observed in the RCP8.5. The temporal variation shows a gradual increasing trend from 2020 to 2080. The observed range of variation is within 0.5 to 5.9°C. Therefore, it can be concluded that the future temperature in Toronto would increase gradually with time.

Events involving 40 mm or higher precipitation were estimated for each of the 36 future CEs. The results are reported as a change from the baseline value involving 28 events over a 30 years of period. A plot of the results is shown in Figure 2c. An increasing trend in number of extreme precipitation events can be observed in this figure. Even though a few future CEs (8 out of 36) have a decreasing trend, the average decrease in extreme precipitation events is around 4. Therefore, it can be concluded that the future climate is likely to experience more frequent extreme precipitation events. Among 36 future CEs, 28 show an increasing trend with an average number of extreme events at 10. However, the highest increase in extreme precipitation events is 32 for the last CE, which would suggest an increase of 114%.

Based on the analysis of historical and future climates, it can be concluded that the climate might be warmer with higher precipitation accumulation and more extreme events in the future. These changes in climate may have detrimental effects on the stability of currently stable slopes and embankments which needs to be quantified.

3 DESIGN CLIMATE CONSTRUCTION

To investigate the impact of climate change effectively, it is important to select the appropriate design climate. The selected design climate should be able to predict the lowest potential factor of safety in the slope stability assessments. The factor of safety is a function of pore pressure distribution which is directly affected by the climate. A wetter climate can create a pore pressure distribution which results in a lower FOS. Therefore, the design climate should contain the wettest possible condition.

Annual Moisture index, I_m (Thornthwaite and Hare 1955) is widely used for estimation of water availability or scarcity at the ground surface for a particular site (Fredlund et al. 2012; Bashir et al. 2015). It has also been frequently used in climate change studies (McCabe and Wolock 1992; Whitfield and Cannon 2000; Grundstein 2008; Leao 2014). The I_m can be estimated as follows:

$$I_m = 100\left(\frac{P}{PE} - 1\right) \quad [1]$$

where *P and PE are* annual cumulative precipitation and potential evaporation respectively. An I_m value of zero indicates neutral or zero water balance at the ground surface. A positive I_m value means a surplus of net water and is indicative of a wetter climate whereas a negative I_m value indicates a scarcity of water indicating drier climates.

In this research, the annual *P* was estimated from the daily precipitation data. The daily *PE* was estimated from the daily mean, maximum, and minimum temperature using a modified Thornthwaite (1948) method proposed by Pereira and Pruitt (2004). The annual *PE* was then calculated by adding estimated monthly *PE*. The I_m values were estimated for all the 36 future climate ensembles, and the CE with the highest positive I_m value was selected as the design climate, defined as future climate 1 (FC1). In addition, the last CE for the FC was also selected as a design climate because it showed the highest increase in precipitation and number of extreme events (Figures 2a and 2c). This design climate was defined as design climate 2 (DC2). Although the I_m values of this ensemble are not high due to higher evaporative demand, it is expected that the higher amount of precipitation will affect the embankment stability. The CE for the BC was also selected as a design climate to compare the results of future CEs. Therefore, a total of three CEs were selected as design climates.

The climate data used in this research was available in daily resolution. However, the actual duration of the precipitation can vary from a few minutes to hours. To address the effect of temporal resolution of precipitation, the daily precipitation was distributed over 12, 2, and 1-hour periods. Review of Intensity Duration and Frequency (IDF) curves revealed that distribution of daily precipitation data over 12, 2, and 1 hour period represents regular and extreme events of 10-25 and 50-100 year return periods, respectively (Bashir et al. 2017; Pk 2017). This procedure of higher resolution design climate construction has been applied in other studies (SRK Consulting Inc. 2010) with satisfactory performance.

4 EMBANKMENT DESIGN PARAMETERS AND NUMERICAL MODEL DEVELOPMENT

A design profile of a highway embankment was created based on previous related studies and OPSS. The design embankment profile with Finite Element Mesh (FEM) and assigned boundary conditions is shown in Figure 3. The crest of the embankment is 7 m high and 25 m wide including 22 m of pavement and 3 m of unpaved shoulder. Following OPSS of highway embankment design, an embankment slope of 2H:1V was selected.

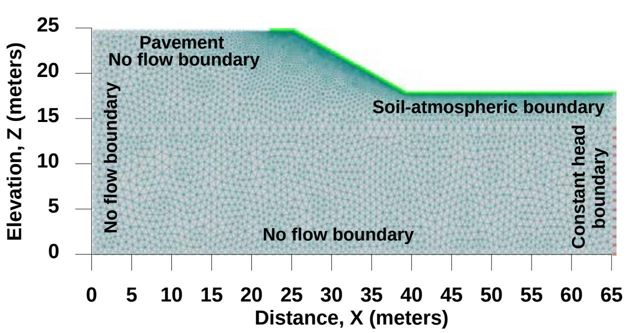

Figure 3. Design embankment profile with FEM mesh and boundary conditions

The subsoil and fill material properties were collected from the previous relevant studies by the Ministry of Transportation, Ontario (MTO) (Bashir et al. 2017). A review of the fill materials indicated that the highway embankments in Ontario usually contain two different types of fill materials which can be classified as sandy loam and silt loam according to the United State Department of Agriculture (USDA) textural classification system. In this research, these two fill materials were selected and named as sand and silt, respectively. The review of the subsoil materials indicated the presence of medium to low permeable till (Bashir et al. 2017). The strength properties of the tills were also similar. It was determined that the groundwater table showed fluctuation and has the potential to reach ground level.

To simulate hydrological and geotechnical numerical models, the hydraulic and strength properties of soils are required. The required soil properties were collected from a previous MTO study (Bashir et al. 2017). The hydraulic properties used van Genuchten (VG) (1980) parameters in the development of the soil water characteristic curve (SWCC). The unsaturated hydraulic conductivity functions were estimated using the Mualem (1976) model. Plots of the SWCCs and hydraulic conductivity functions are shown in Figures 4 and 5, respectively. The sandy fill material has the highest drainage properties, while the silt has the lowest. Properties of subsoil silt loam fall somewhere in the middle.

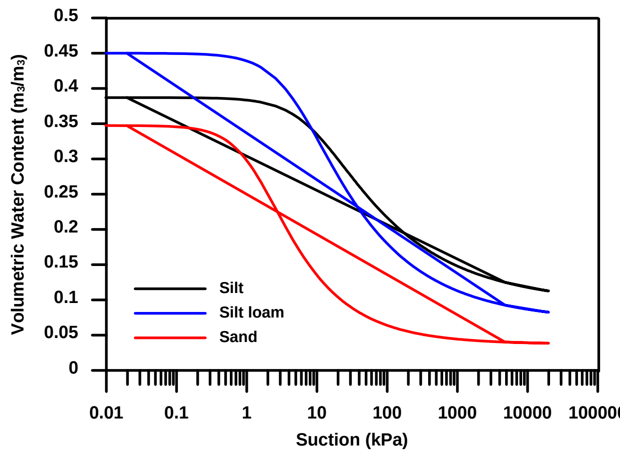

Figure 4. Soil water characteristic curves (model: van Genuchten 1980) (after Bashir et al. 2017)

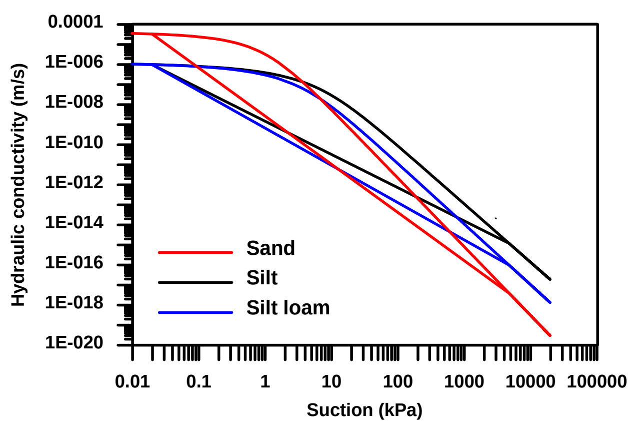

Figure 5. Hydraulic conductivity functions (model: Mualem 1976) (after Bashir et al. 2017)

The strength properties of the subsoil and embankment fill were chosen based on values used in the previous study conducted by Bashir et al. (2017). It was found that the subsoil has a friction angle ranging from 24° to 36°. In this research, an average friction angle of 32° was selected for the subsoil silt loam. The strength properties of the fill are quite similar, varying from 30° to 34°. As such, an average friction angle of 32° was selected. It was found that both the fill and the subsoil were modelled with zero effective cohesion. The unit weight, effective cohesion, and effective friction angle of the soil are summarized in Table 1.

Table 1. Selected effective strength properties of the fill and subsoil materials (after Bashir et al. 2017)

Soil	Unit Weight ɣ (kN/m^3)	Effective Cohesion c′ (kPa)	Effective Friction Angle ϕ′ (deg.)
Sand	19	0	32
Silt	21	0	32
Silt loam	21	0	32

4.1 Hydrological Model

A hydrological model takes climate data as input and calculates the temporal variation of the PWPs within the embankment. In this research, a commercial 2D finite element (FE) hydrological modeling software, HYDRUS-2D was used. It was found that HYDRUS-2D takes a reasonable amount of time to simulate 30 years of climate data and is capable of simulating transient PWPs effectively (Pk, 2017). The design profile of the embankment along with the FE mesh and applied boundary conditions of the HYDRUS-2D model are shown in Figure 3. The pavement at the crest 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 embankment. At the right hand boundary, the groundwater table was assumed to be 4 m below ground level of the embankment and the section above water table was assumed to be a no flow boundary.

A soil-atmospheric boundary comprised of daily precipitation and potential evaporation records was applied at the soil-atmospheric interface. The runoff from the pavement was collected and distributed over the earthen embankment. The initial condition of the hydrological model was generated by running an initial model using 30 years of historical climate for the city of Toronto starting with a static groundwater table 4 m below surface. The hydrological models simulated the three selected climate ensembles and each of the embankments (sand & silt).

4.2 Slope Stability Model

The slope stability model uses the PWPs calculated in the hydrological model as input and calculates the embankment stability using effective shear strength parameters. Slope stability analyses were performed using a frequently used commercially available software, SLOPE/W. The PWPs calculated in the hydrological models were transferred using a similar grid technique. The embankment profile shown in Figure 3 was used for the slope stability model. The fill and subsoil materials were modelled using the Mohr-Coulomb model. The effective shear strength parameters used to develop the Mohr-Coulomb models are presented in Table 1. The strength due to suction in the unsaturated soil was estimated using the Vanapalli et al. (1996) model. The calculated saturated and unsaturated shear strengths were used to calculate the embankment stability using the Morgenstern-Price method. This method considers both the static force and moment equilibrium and is widely used in slope stability analysis (Fredlund and Krahn, 1977).

5 RESULTS AND DISCUSSIONS

The impact of climate change was assessed by estimating the change in PWPs and factor of safety (FOS) for embankments. The results are presented for the sand and silt embankments in two separate sections. Three CEs and three temporal resolutions of precipitation form a total of 9 scenarios for each embankment. The analyses cover 30 years of time period, but it is difficult to present results for every single day. As such, the wettest day in 30 years was identified when the embankments were representative of the highest positive PWPs and resulted in the lowest FOS.

5.1 Results for the Sand Embankment

The PWPs were estimated for the wettest day in 30 years for three separate vertical sections. The sections are in the sloped portion of the embankment with their exact location shown in Figure 6a. The PWPs in the embankment on the wettest day at three separate sections are also shown in Figure 6b, 6c and 6d, respectively.

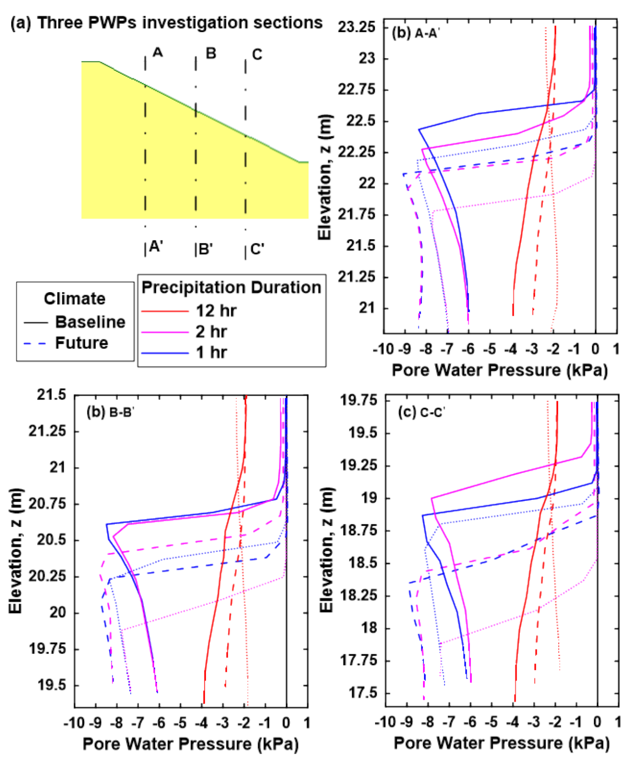

Figure 6. (a) Location of the three vertical sections, (b), (c), and (d) PWPs distributions for three CEs, and three temporal resolutions of precipitation at the top, middle, and bottom sections of the sand embankment

The PWPs in the embankment showed little variation beyond a depth of 2 m, and therefore the focus of Figure 6 is the top 2 m of the sand embankment. The overall PWPs profiles presented in Figure 6 are similar for all three sections of the embankment. However, the profiles change when comparing the temporal resolutions at each vertical section. For example, in Figure 6b, the PWPs profile for the 12-hour precipitation case shows that the PWPs for the BC, FC1 and FC2 are between -2 kPa and -4 kPa. In comparison, the 2-hour and 1-hour profiles show lower depth of influence, but higher difference in PWPs ranging from 0 kPa to -9 kPa. Similar results are found in the vertical sections B-B' and C-C' (Figures 6c and 6d, respectively). There are also differences in the PWPs profiles when comparing BC to the FCs. It can be observed in Figure 6 that both future CEs show an increase in PWPs and depth of influence when compared with the BC. This increase in PWPs from the BC to the FCs has the potential to affect the future stability of the sand embankment.

The critical FOS for the wettest day was estimated for all the three temporal resolutions and CEs. The results are plotted in Figure 7. The x-axis of Figure 7 represents the temporal resolution of precipitation and the y-axis represents the FOS for the sand embankment. In Figure 7, the critical FOS of the sand embankment gradually increases when temporal resolution decreases from 1 to 12 hours. This is true for all the CEs. A comparison of the FOS between the baseline and future climates shows that both future CEs result in lower FOS for all three different precipitation resolutions. The greatest reduction is observed for the temporal resolution of 2 hours which shows a decrease of approximately 10% in the FOS. The low retention and high drainage characteristics of the sand material discourage generation of excess PWPs. Therefore, the FOS values between the baseline and future climates are similar following the PWP distribution trend.

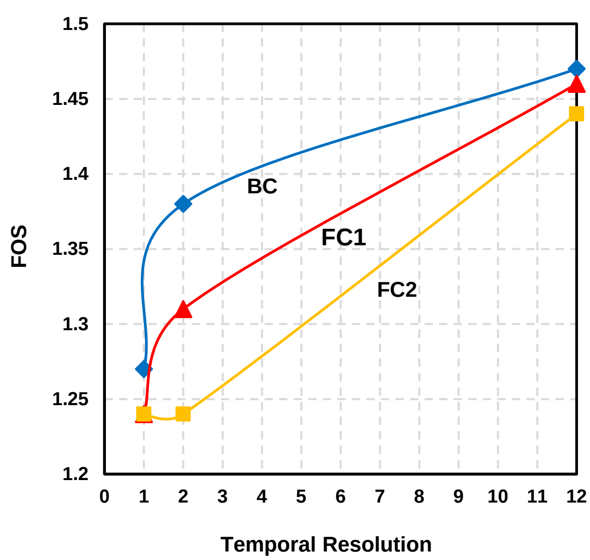

Figure 7. Variation of FOS of the sand embankment with temporal resolution of precipitation

5.2 Results for the Silt Embankment

The PWP and FOS for the silt embankment was estimated and plotted in the same manner as for the sand embankment. The PWPs at three cross sections in the silt embankment are plotted in Figure 8. The comparison between the baseline and future climate ensembles show that FC2 generates the highest PWPs followed by FC1 and BC. An exception was observed in the depth of saturation for the 12-hour resolution of FC1. These observations are consistent for all the three sections. However, The PWPs show variations when comparing them between different vertical sections. This is most significant for the precipitation of 12-hour resolution for FC2 (red dotted line). In profile A-A' (Figure 8b) the PWPs are approximately zero. Moving to profile B-B' (Figure 8c) and C-C' (Figure 8d) the PWPs gradually increase. This clearly emphasizes that the PWPs at the toe of the silt embankment are positive and are near positive at the crest of the slope. These excess PWPs have significant implications on the embankment stability.

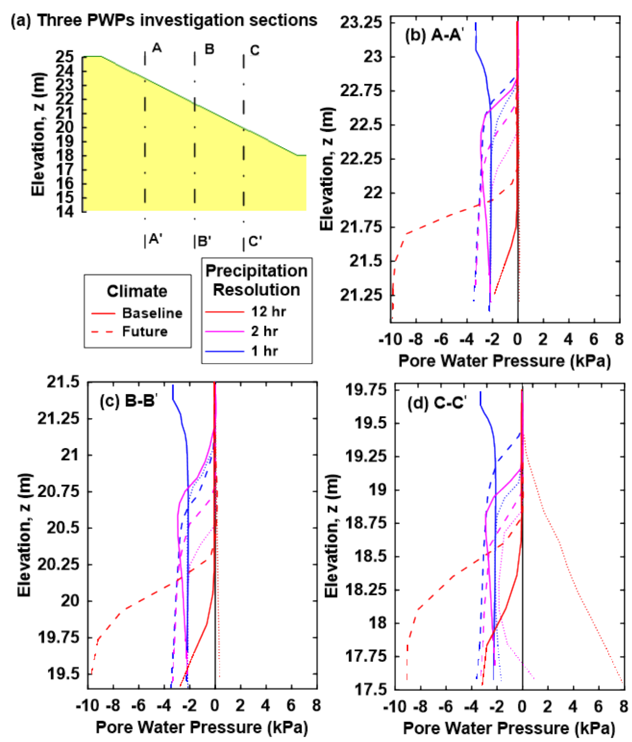

Figure 8 (a) Location of the three vertical sections, (b), (c), and (d) PWPs distributions for the three climate ensembles and three temporal resolutions of precipitation at the A-A′, B-B′, and C-C′ sections respectively

The FOS and temporal resolution plots for the silt embankment show the opposite trend when compared to the sand embankment (Figure 9). In Figure 9, the FOS of the silt embankment gradually decreases with a decrease in temporal resolution from 1 hour to 12 hours. The FOS calculated for the low intensity precipitation of 12-hour resolution (Figure 9) was 1.28 for the BC, while the FOS for 2, and 1-hour resolutions increased to 1.29 and 1.48, respectively. Similar observations can be made for the two FC ensembles. This shows that an increase in precipitation intensity decreases the FOS in a silt embankment, rather than increasing it. However, this observation is consistent with the water balance assessment where increase in precipition intensity results in larger quantities of runoff and less infiltration (Bashir et al. 2017). Comparison of FOS results between the future and baseline climate ensembles illustrates that FC2 has the lowest FOS followed by FC1 and BC. The lowest observed FOS values for the 12-hour resolution of precipitation are 1.28, 1.24, and 1.15 for the BC, FC1, and FC2, respectively which gives an estimated 10% decrease in FOS from the BC to the FC. Similar observations can be made for the 2 and 1-hour resolutions.

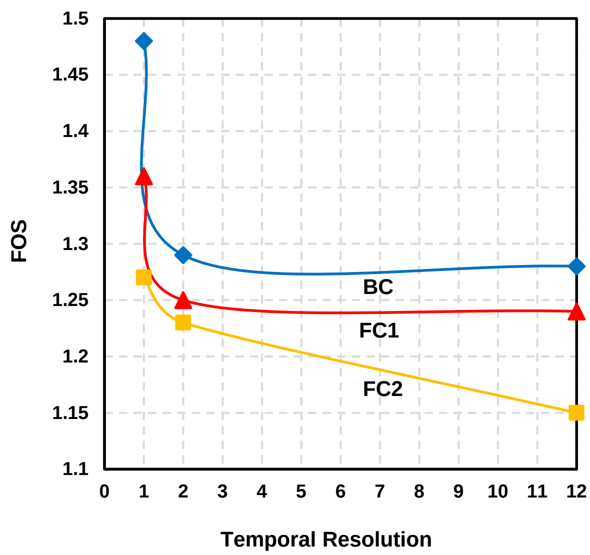

Figure 9. Variation of FOS of the silt embankment with temporal resolution of precipitation

6 CONCLUDING REMARKS

This research quantified the probable impacts of climate change on a typical highway embankment with two different construction fill materials for southern Ontario, Canada. The extent of climate change was estimated by analyzing the major climate variables for 30 years of historical and 90 years of future time periods. The embankment design climate was selected based on the climate change analysis results. The embankment design parameters were selected based on previous related studies and OPSS. The climate change impact was quantified using a numerical modeling exercise. The variation of PWPs within the embankment were estimated using a 2D transient FE model. The estimated PWPs were then used in the slope stability model to quantify the embankment stability.

The analysis of major climate variables showed that the predicted climate in southern Ontario might be warmer and wetter. In addition, a significant increase in extreme precipitation events is expected in the future. It was also found that the number of extreme precipitation events could more than double from the historical average.

The findings of this research illustrate that climate change could affect the stability of both sand and silt embankments. An estimated 10% decrease in FOS was observed for both embankments which could trigger a failure. The results for different temporal resolution of precipitation illustrate that the hydraulic properties of fill materials influence the response to climate change. The high permeable sand embankment can quickly drain water without any significant effect on stability and therefore shows minimal susceptibility to intense precipitation events. On the other hand, prolonged precipitation events of lower resolutions generate higher positive PWPs and conversely lower FOS for the silt embankment. This finding emphasizes the importance of considering realistic resolution of precipitation data and accurate determination of hydraulic properties in embankment design.

7 ACKNOWLEDGEMENT

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