

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Potential effects of climate changes on slope stability

Effets potentiels des changements climatiques sur la stabilité des pentes

Luísa Mazzini Baby, Adrian Torrico Siaccara & Marcos Massao Futai

Department of Structure and Geotechnical Engineering, Brazil, luisa.mazzinibaby@gmail.com

Renan Craveiro Bezerra

Civil Engineer, Brazil

ABSTRACT: The influence of climate changes in geotechnical systems subjected to soil-atmosphere interaction is complex to quantify but of great concern. Increasing temperature and precipitation can lead to soil suction increase, effective stress reduction and thus trigger slope instability. The study analyzed a specific slope within 100 years of timeframe. Data corroborated with the observation of increasing temperature and other parameters were estimated based on the available information and literature. The variation of the slope's Factor of Safety (FoS) was observed in the month of March in 1899 and 1990. Results indicate that the FoS in 1899 maintained 6% to 10% higher than the FoS in 1990 throughout the month. In 1990, the FoS reached values around 1.03, which is concerning when it comes to geotechnical stability. Overall, the results indicated an increase in the slope instability possibly related to climate changes.

RÉSUMÉ: L'influence des changements climatiques dans les systèmes géotechniques soumis à une interaction sol-atmosphère est complexe à quantifier mais très préoccupante. L'augmentation de la température et des précipitations peuvent entraîner une augmentation de la succion du sol et une réduction des contraintes effectives. Ces facteurs peuvent entraîner une instabilité des pentes. L'étude a analysé une pente spécifique dans un délai de 100 ans. Les données ont confirmé l'augmentation de la température. D'autres paramètres ont été estimés sur la base des informations disponibles et de la littérature. La variation du facteur de sécurité de la pente a été observée au mois de mars en 1899 et 1990. Les résultats indiquent que le FS en 1899 a maintenu de 6% à 10% plus élevé que le FS en 1990 tout au long du mois. En 1990, le FS atteignait des valeurs autour de 1.03, ce qui est inquiétant pour la stabilité géotechnique. Dans l'ensemble, les résultats indiquent une augmentation de l'instabilité des pentes peut-être liée aux changements climatiques.

KEYWORDS: Climate changes, factor of safety, slope stability.

1 INTRODUCTION

Climate changes have been widely discussed in the past decade especially regarding temperature and precipitation increase, the greenhouse effect and sea-level rise (Abteu and Melesse, 2013; Blank, 2018; Briceño et al., 2007; Dixon et al., 2006; Füßel et al., 2012; IPCC, 2018; Obeysekera et al., 2011; Vardon, 2015). When it comes to geotechnical structures subjected to soil-atmosphere interaction, such as earth slopes, the impact of climate changes can be severe. The increase of temperature, altogether with the increase of mean rainfall, drought periods and overall intense events can have significant effects on soil stress conditions triggering slope instability and possible landslide scenarios (Augusto Filho and Fernandes, 2019; Dehn et al., 2000; Gens, 2010; Vardon, 2015).

Soil-atmosphere interaction involves a series of complex climate variables, such as temperature, relative humidity, wind speed and precipitation. Evidence suggests an increase in global temperature around 1.0°C compared to pre-industrial levels, possibly reaching 1.5°C between 2030 and 2052 (IPCC, 2018). However, in relation to the other variables there are still uncertain projections due to lack of specific data (IPCC, 2018). Thus, understanding the influence of each climate change process in the stability of geotechnical structures, as well as the combined action, becomes challenging (Vardon, 2015).

In literature, there are numerous studies regarding rainfall-induced landslides. This geotechnical problem is common especially in tropic and subtropic regions, where residual soils are abundant and mostly in unsaturated conditions (Augusto Filho and Fernandes, 2019; Rahardjo et al., 2010, 2007; Zhai et al., 2016). Notably, regarding earth slopes, the soil-atmosphere interaction variables are directly related to the water table

fluctuation, resulting in suction variation and possible reduction in soil effective stress (Alonso et al., 2003; Dehn et al., 2000; Travis et al., 2010; Vaughan et al., 2002).

In this study, the effects of climate changes were evaluated by seepage and stability analysis of an earth slope. The main goal was to compare the variation of the Factor of Safety in 100 years of timeframe.

2 MATERIALS AND METHODS

2.1 Slope characteristics

The slope in this study is composed of a residual soil (Franch, 2008) and its geometry is based on a slope located between the cities of São Carlos and Ribeirão Preto in São Paulo (Calle and Vilar, 2001). A typical section is shown in Figure 1.

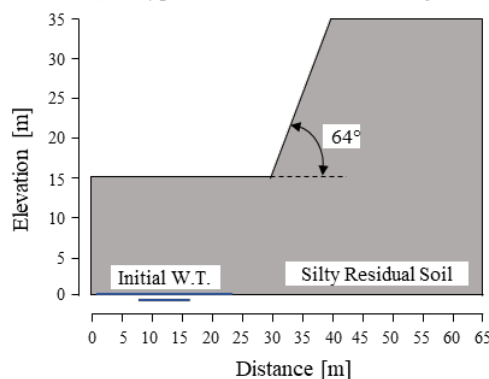


Figure 1. Typical section of the slope

The water table was considered 15,0m below the slope's foot based on *in situ* tests, thus the entire soil was in unsaturated condition. The geotechnical parameters of the residual soil are presented in Table 1. The van Genuchten (1980) model was used (Table 2) and both the Soil Water Retention Curve (SWRC) and the Hydraulic Conductivity function are presented in Figure 2.

Table 1. Soil properties

Soil parameter	Value
γ (kN/m ³)	17.8
c' (kPa)	5.0
ϕ' (°)	25
ϕ^b (°)	20

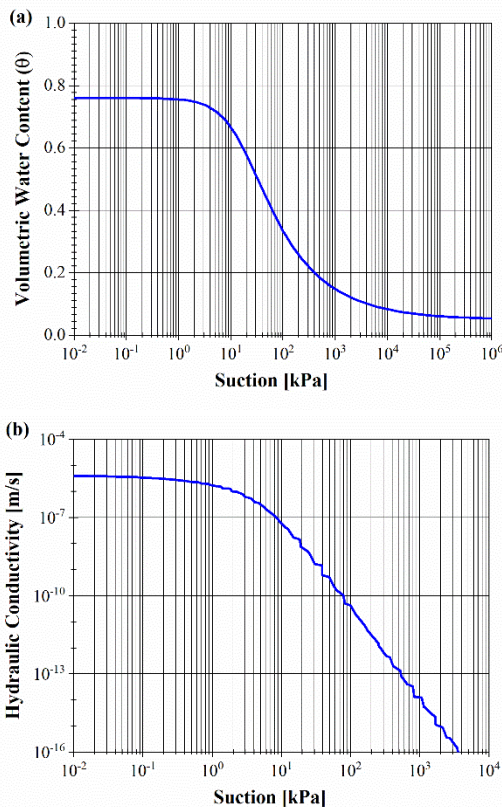


Figure 2. (a) SWRC curve (b) Hydraulic conductivity curve.

Table 2. van Genuchten (1980) model parameters

Parameter	Value
α	0.067
m	0.320
n	1.47
θ_s	0.76
θ_r	0.05

2.2 Numerical simulation

The software used in the analyses were SEEP/W and SLOPE/w from GeoStudio 2019 to evaluate both the unsaturated flux and the slope stability. To analyze the variation of the slope's Factor

of Safety (*FoS*) regarding the climate changes occurring in 100 years, two periods were selected for comparison: (a) from 1896 to 1899 and (b) from 1987 to 1990. The first three years of each period were analyzed only in SEEP/W to guarantee convergence of the unsaturated properties of the residual soil, so that the initial condition could be equivalent to reality. The *FoS* was analyzed in March 1899 and 1990 and compared to visualize any differences due to climate changes.

The specific periods mentioned above were chosen from a global analyses of precipitation data. Two decades were firstly chosen, being: (a) from 1890 to 1899 and (b) from 1990 to 1999. The decade precipitation pattern was observed and the years 1899 and 1990 were chosen from each period due to the representation of the respective decade.

Infiltration analyses on SEEP/W require precipitation, evapotranspiration, temperature, and relative humidity data. The meteorological station of Luz (LMS) located in the central region of São Paulo was chosen to provide the information concerning the precipitation profile, due to its longer period of rainfall measurement. Complementary data were collected from the Mirante de Santana meteorological station in view of the absence of registration regarding evapotranspiration, temperature, and relative humidity in LMS. However, the information from the Mirante de Santana station began around 1970, thus some adjustments and estimations were necessary for period (a) analysis.

The solution for this problem was adding or subtracting, depending on the parameter, a percentage of the specific value from period (b) to achieve the corresponding value for period (a). For example, temperature data from 1961 to 2019 were plotted by month to visualize and confirm the statement that temperature has been increasing in the past years due to climate changes. Thus, 1899's temperature was estimated as 95% of the 1990's temperature, a coherent approach as indicated by literature.

For the relative humidity, the same procedure was applied. First, yearly data from Mirante de Santana station were collected and plotted so that a tendency could be observed. It was then possible to infer a general decrease in relative humidity. Therefore, the relative humidity from 1899 was estimated by an increase of 10% from 1990's data.

For the evapotranspiration data the procedure had some modifications. The information about this parameter was limited only for 2007 to 2019 so it was difficult to observe any pattern. Literature indicates the existence of an "evapotranspiration paradox" (Han et al., 2018; Xu et al., 2018). Some authors indicate an increase with climate changes based on the increase in temperature (e.g. Abteu and Melesse, 2013; Tian et al., 2018), whereas others defend a decrease due to deforestation and land cover changes (Strengers et al., 2010; Tian et al., 2018; Xu et al., 2018). The authors adopted the latter hypothesis and considered a decrease in potential evapotranspiration throughout the years.

Thus, the data for 1990 was said to be the same as presented for 2010, since 20 years is not a valid period of time to represent any climate changes (Blank, 2018). To estimate 1899's evapotranspiration the authors considered an increase of 15% from 2010's data. The evapotranspiration of the years 1987, 1988 and 1989 were treated as the same as 2007, 2008 and 2009, respectively.

The same approach was considered for the three years before 1899. The percentages used to achieve 1899's data of temperature, relative humidity and evapotranspiration were used with the corresponding years to estimate the same information from 1896, 1897 and 1898. Table 3 summarizes the methodology applied in this study for each parameter necessary in SEEP/W.

Table 3. Base year and percentage applied for each period and parameter

Year	Evapotranspiration	Relative Humidity	Temperature
1987	2007	1987	1987
1988	2008	1988	1988
1989	2009	1989	1989
1990	2010	1990	1990
1896	+15% of 2007	+10% of 1987	-5% of 1987
1897	+15% of 2008	+10% of 1988	-5% of 1988
1898	+15% of 2009	+10% of 1989	-5% of 1989
1899	+15% of 2010	+10% of 1990	-5% of 1990

The FoS variation from March 1990 and 1899 was compared and it was possible to visualize the climate changes consequences on slope stability.

3 ANALYSIS AND RESULTS

The effect of the climate changes in 100 years on an earth slope were evaluated by a combination of seepage and stability analysis. Firstly, the accumulated precipitation from march of each year was compared to observe any differences that could be related to climate changes.

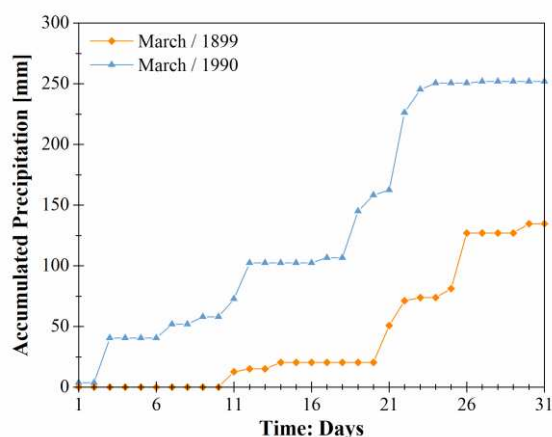


Figure 3. Accumulated precipitation in March in 1899 and 1990.

In Figure 3 it is possible to observe that the amount of precipitation in 1990 was considerably higher than the accumulated precipitation in 1899. By the end of the first two weeks, the accumulated precipitation in 1990 represented five times the amount of rainfall in 1899. By the end of the month, the difference reduced but continued significant, being the accumulated precipitation from 1899 half of 1990's. Overall, an average of 80mm of precipitation difference was observed.

The main goal of this study was to observe the FoS variation regarding climate changes and its consequences on the soil-atmosphere interaction and thus slope stability. As can be seen in Figure 4, the FoS variation in 1899 was maintained always above the FoS in 1990.

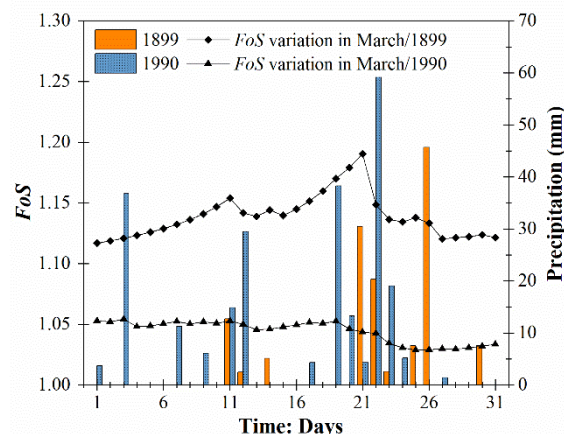


Figure 4. FoS variation in 1899 and 1990.

The precipitation in 1899 is mostly concentrated in the last 10 days, in which there is a slight decrease in slope stability, but still not reaching values below 1990's. Overall, the FoS from 1899 was 6% to 10% higher in comparison to 1990. On March 20th the Factor of Safety from 1899 reached the highest value, being 14% higher than 1990's.

Additionally, it is important to observe the increase in number of extreme rainfall events, from two events in 1899 to four events in 1990. Overall, FoS reduction occurred after heavy rainfalls, being the variation higher in 1899, possibly due to the slope suction state originated from the previous years. Regarding 1990, it can be observed that the FoS was maintained around 1.05, reaching the lowest value of 1.03. These values are concerning regarding slope stability and are not in agreement with the geotechnical engineering common practice.

4 CONCLUSIONS

In this study, a slope was analyzed in 100 years of timeframe. The main goal was to observe any influence of the climate changes in the variation of the FoS .

The results pointed out a significant increase in precipitation, possibly due to climate changes. The accumulated precipitation in 1990 was maintained higher than 1899 throughout the entire month, reaching a 120mm difference by the end of the period considered. Furthermore, the number of intense rainfall events in 1990 was twice the number in 1899.

In addition, the analyses regarding slope's Factor of Safety indicated that the slope stability reduced in 100 years of timeframe. The FoS in 1899 was 6% to 10% higher and the FoS in 1990 reached 1.03 after rainfall periods, which is a concerning but coherent result since the precipitation increase is alarming.

There is no doubt that quantifying the climate changes influence in slope stability is complex and challenging. However, it is important to highlight the existence and the significance of the correlation, especially regarding precipitation rise and geotechnical systems safety.

5 ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian National Council for Scientific and Technological Development (CNPq) for the financial support (1610466 / 2019-3).

6 REFERENCES

- Abtew W, Melesse A. Evaporation and evapotranspiration: Measurements and estimations. *Evaporation Evapotranspiration Meas Estim* 2013;9789400747:1–206. <https://doi.org/10.1007/978-94-007-4737-1>.

- Alonso EE, Gens A, Delahaye CH. Influence of rainfall on the deformation and stability of a slope in overconsolidated clays: A case study. *Hydrogeol J* 2003;11:174–92. <https://doi.org/10.1007/s10040-002-0245-1>.
- Augusto Filho O, Fernandes MA. Landslide analysis of unsaturated soil slopes based on rainfall and matric suction data. *Bull Eng Geol Environ* 2019;78:4167–85. <https://doi.org/10.1007/s10064-018-1392-5>.
- Blank RM. A Changing Climate: Problem Definition. *Clim. Infrastruct.*, Reston, VA: American Society of Civil Engineers; 2018, p. 11–49. <https://doi.org/10.1061/9780784415191.ch02>.
- Briceño S, Basabe P, Bonnard C. Landslides and Climate change: A world perspective, but a complex question. In: McInnes R, Jakeways J, Fairbank H, Mathie E, editors. *Proc. Int. Conf. Landslides Clim. Chang.*, Ventor, Isle of Wight, United Kingdom: Taylor & Francis; 2007, p. 3–6.
- Calle JAC, Vilar OM. Análise de Ruptura de Talude em Solo não Saturado. 4th Brazilian Symp. Unsaturated Soils, 2001, p. 451–70.
- Dehn M, Bürger G, Buma J, Gasparetto P. Impact of climate change on slope stability using expanded downscaling. *Eng Geol* 2000;55:193–204. [https://doi.org/10.1016/S0013-7952\(99\)00123-4](https://doi.org/10.1016/S0013-7952(99)00123-4).
- Dixon N, Dijkstra T, Forster A, Connell R. Climate change impact forecasting for slopes (CLIFFS) in the built environment. *Eng Geol Tomorrow's Cities Proceedings*, 10th Int Assoc Eng Geol Congr Geol Soc London 2006:1–8.
- Franch FAJP. Influência do tipo de revestimento superficial no fluxo não saturado e sua influência na estabilidade de taludes. Escola Politécnica da Universidade de São Paulo, 2008.
- Füssel H-M, Jol A, Kurnik B, Hemming D. Climate change, impacts and vulnerability in Europe 2012: an indicator-based report. 2012. <https://doi.org/10.2800/66071>.
- Gens A. Soil–environment interactions in geotechnical engineering. *Geotechnique* 2010;60:3–74. <https://doi.org/10.1680/geot.9.P.109>.
- van Genuchten MT. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils1. *Soil Sci Soc Am J* 1980;44:892–8. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>.
- Han J, Wang J, Zhao Y, Wang Q, Zhang B, Li H, et al. Spatio-temporal variation of potential evapotranspiration and climatic drivers in the Jing-Jin-Ji region, North China. *Agric For Meteorol* 2018;256–257:75–83. <https://doi.org/10.1016/j.agrformet.2018.03.002>.
- IPCC. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change., 2018.
- Obeysekera J, Park J, Irizarry-Ortiz M, Trimble P, Barnes J, VanArman J, et al. PAST AND PROJECTED TRENDS IN CLIMATE AND SEA LEVEL FOR SOUTH FLORIDA. 2011.
- Rahardjo H, Nio AS, Leong EC, Song NY. Effects of groundwater table position and soil properties on stability of slope during rainfall. *J Geotech Geoenvironmental Eng* 2010;136:1555–64. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000385](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000385).
- Rahardjo H, Ong TH, Rezaur RB, Leong EC. Factors Controlling Instability of Homogeneous Soil Slopes under Rainfall. *J Geotech Geoenvironmental Eng* 2007;133:1532–43. [https://doi.org/10.1061/\(asce\)1090-0241\(2007\)133:12\(1532\)](https://doi.org/10.1061/(asce)1090-0241(2007)133:12(1532)).
- Strengers BJ, Müller C, Schaeffer M, Haarsma RJ, Severijns C, Gerten D, et al. Assessing 20th century climate-vegetation feedbacks of land-use change and natural vegetation dynamics in a fully coupled vegetation-climate model. *Int J Climatol* 2010;30:2055–65. <https://doi.org/10.1002/joc.2132>.
- Tian L, Jin J, Wu P, Niu GY. Assessment of the effects of climate change on evapotranspiration with an improved elasticity method in a Nonhumid Area. *Sustain* 2018;10. <https://doi.org/10.3390/su10124589>.
- Travis QB, Houston SL, Marinho FAM, Schmeeckle M. Unsaturated infinite slope stability considering surface flux conditions. *J Geotech Geoenvironmental Eng* 2010;136:963–74. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000301](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000301).
- Vardon PJ. Climatic influence on geotechnical infrastructure: A review. *Environ Geotech* 2015;2:166–74. <https://doi.org/10.1680/envgeo.13.00055>.
- Vaughan PR, Kovacevic N, Ridley AM. The influence of climate and climate change on the stability of embankment dam slopes. In: Tedd P, editor. *Reserv. a Chang. World*, Trinity College, Dublin: Thomas Telford Publishing; 2002, p. 353–66. <https://doi.org/10.1680/riacw.31395.0028>.
- Xu S, Yu Z, Yang C, Ji X, Zhang K. Trends in evapotranspiration and their responses to climate change and vegetation greening over the upper reaches of the Yellow River Basin. *Agric For Meteorol* 2018;263:118–29. <https://doi.org/10.1016/j.agrformet.2018.08.010>.
- Zhai Q, Rahardjo H, Satyanaga A. Variability in unsaturated hydraulic properties of residual soil in Singapore. *Eng Geol* 2016;209:21–9. <https://doi.org/10.1016/j.enggeo.2016.04.034>.