International Soil and Water Conservation Research ∎ (∎∎∎∎) ∎∎∎–∎∎∎

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

International Soil and Water Conservation Research

journal homepage: www.elsevier.com/locate/iswcr

Original Research Article

Effect of variations in rainfall intensity on slope stability in Singapore

Christofer Kristo [a], Harianto Rahardjo [b,*], Alfrendo Satyanaga [b]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Hall of Residence 9, Block 46, #04-867, Singapore 639811, Singapore
[b] School of Civil and Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 6 January 2017
Received in revised form
30 June 2017
Accepted 13 July 2017

Keywords:
Climate change
Rainfall
Seepage
Slope stability

ABSTRACT

Numerous scientific evidence has given credence to the true existence and deleterious impacts of climate change. One aspect of climate change is the variations in rainfall patterns, which affect the flux boundary condition across ground surface. A possible disastrous consequence of this change is the occurrence of rainfall-induced slope failures. This paper aims to investigate the variations in rainfall patterns in Singapore and its effect on slope stability. Singapore's historical rainfall data from Seletar and Paya Lebar weather stations for the period of 1985–2009 were obtained and analysed by duration using linear regression. A general increasing trend was observed in both weather stations, with a possible shift to longer duration rainfall events, despite being statistically insignificant according to the Mann-Kendall test. Using the derived trends, projected rainfall intensities in 2050 and 2100 were used in the seepage and slope stability analyses performed on a typical residual soil slope in Singapore. A significant reduction in factor of safety was observed in the next 50 years, with only a marginal decrease in factor of safety in the subsequent 50 years. This indicates a possible detrimental effect of variations in rainfall patterns on slope stability in Singapore, especially in the next 50 years. The statistical analyses on rainfall data from Seletar and Paya Lebar weather stations for the period of 1985–2009 indicated that rainfall intensity tend to increase over the years, with a possible shift to longer duration rainfall events in the future. The stability analyses showed a significant decrease in factor of safety from 2003 to 2050 due to increase in rainfall intensity, suggesting that a climate change might have existed beyond 2009 with possibly detrimental effects to slope stability.

1. Introduction

Climate change has been a major concern for people globally as it affects their livelihood and living environments to a considerable extent. A consensus has developed among governments, industries and academics that global warming exists. Due to its urgency and wide-ranging effects, many research works have been conducted to study climate change and the ways to mitigate its impacts. Temperatures are predicted to rise and rainfall are projected to be more intense and less frequent (Strauch et al., 2017). Changes in rainfall patterns, in particular, will influence the flux boundary condition across ground surface. The changes in groundwater hydrology could reduce the effective stress and the shear strength of soil that may result in rainfall-induced slope failures (Chen, Lee, & Law, 2004). This could be catastrophic and may claim many lives. One way to prevent these undesirable rainfall-induced slope failures is to understand the variation in rainfall intensity which can be used to estimate rainfall patterns in the future. Limited studies have been carried out on the effect of climate change with respect to the variation in rainfall intensity on slope stability in Singapore. Therefore, the objective of this study is to investigate the seasonal variations in rainfall intensity in Singapore and their effects on the stability of residual soil slope in Singapore. The scope of the project involves statistical analyses of the changes in rainfall patterns and rainfall amounts in Singapore. In addition, seepage and slope stability analyses were carried out to observe the variations of factor of safety due to changes in rainfall intensity.

2. Literature review

2.1. Climate change

The majority of climate scientists and researchers have come to a consensus that there exists a climate change that is caused by

* Corresponding author.
E-mail addresses: ckristo001@e.ntu.edu.sg (C. Kristo), chrahardjo@ntu.edu.sg (H. Rahardjo), alfrendo@ntu.edu.sg (A. Satyanaga).
URL: http://www.ntu.edu.sg/cee/staff/infrastructure/academic/chrahardjo.asp (H. Rahardjo).

http://dx.doi.org/10.1016/j.iswcr.2017.07.001
2095-6339/

humans or anthropological actions. Over 97% of climatologists who are actively conducting research works on climate change agreed that human activity contributes a significant factor in altering global mean temperatures (Doran & Zimmerman, 2009). The Intergovernmental Panel on Climate Change (IPCC) was established to coordinate and lead the battle against climate change through discussion and research. The IPCC has projected that the global average surface temperature would be 4 °C higher than the 1986–2005 average, following the worst case scenario RCP8.5, which predicted the annual anthropogenic CO_2 emissions to be more than 100 $GtCO_2$/yr (Pachauri et al., 2014).

A study by Strauch et al. (2017) showed that climate change resulted in the changes in rainfall patterns which may cause less frequent, but more intense duration of rainfall. Based on a study in Hawaii, he suggested that a decrease in mean annual rainfall is correlated with the increase in rainfall intensity and increased number of dry days with no rainfall. Monsoon seasons in South East Asia are predicted to be delayed by 15 days in the future, and precipitation is likely to be 70% lower than normal levels (Loo, Billa, & Singh, 2015). However, the topography (such as mountainous or islands) of some areas could increase the rainfall intensity, making the weather more extreme, with possibly intense flooding and intense drought at different areas and different periods of time.

In Singapore, the National Climate Change Secretariat (NCCS) of the Prime Minister Office led the climate research in Singapore. It was projected that Singapore's average temperature will be 2.7–4.2 °C higher than the present average temperature, while further studies are still ongoing to investigate how precipitation patterns will change in Singapore (NCCS, 2012). This project aims to fill in the missing data in this gap.

2.2. Rainfall-induced slope failure

Slope failures are common phenomena around the world where large masses of soil move downslope by gravity. It occurs when the shear stress on the slope exceeds the shear strength of the slope. Changes in rainfall patterns could alter the flux boundary conditions such as infiltration and evapotranspiration, affecting the water pressure in soil. As rainfall infiltrates through the soil pores, the water content of soil will increase and the groundwater table would be raised. This will lead to an increase in pore-water pressure and a subsequent decrease in effective stress, which reduces the shear strength of the soil to sustain loadings. When the shear strength mobilised along a critical slip surface is no longer adequate to support the shear stress, the soil mass will slip and the slope fails (Chen et al., 2004).

Many studies have been conducted to investigate this complex relationship between slope stability and changes in rainfall patterns around the world. For instance, in the region of Umbria, Italy, it was found that during the warm-dry season, the occurrence of slope failures is relatively unchanged, while during the cold-wet season, landslide events increased considerably when there is an increased in rainfall amount and rainfall intensity (Ciabatta et al., 2016). Furthermore, in Taiwan, where 75% of its area is mountainous, it is predicted that the average temperature would increase by 2–3 °C by 2100 as compared to the temperature in 2000, and seasonal mean precipitation would increase by 2–26% (Meei-Ling, Sheng-Chi, & Yu-Ching, 2014). As a result, the government has identified central Taiwan to be a landslide-prone area and have taken measures to address the problem.

Due to the complex inter-dependent relationship between water and soil with respect to stability, many studies have attempted to understand this essential relationship, which would allow for more reliable predictions of potential slope hazards. Junqueria Junior et al. (2017), for instance, has investigated the time-stability of soil water content (SWC) in a tropical native forest in Brazil, in response to variations in precipitation, and proposed a method for strategic monitoring locations for SWC to obtain a representative sample for the particular site. Moreover, soil thickness and rock fragment cover have also been identified by Fu et al. (2011) as key contributing factors to the soil's hydrological and erosional behaviours, in which thinner soils were found to exhibit higher infiltration capacity and lower erosion rates across various rainfall events.

In Singapore, many studies have been performed on the effects of rainfall on local slope stability. In December 2006 and January 2007, which coincide with above average monthly rainfall historically, eleven landslides occurred in Singapore (Rahardjo et al., 2011). Rahimi, Rahardjo, and Leong (2011) have shown that antecedent rainfall affects the stability of low-conductivity (LC) slopes more than high-conductivity (HC) slopes. It was found that different rainfall patterns affect different types of slopes. HC slopes tend to reach its minimum factor of safety (FS) under delayed rainfall pattern, where the intensity increases with time reaching a maximum near the end of the rainfall event. In contrast, LC slopes achieved a minimum FS under advanced rainfall pattern, where the intensity is high at the beginning of the rainfall event and decreases with time.

2.3. Statistical analyses

Due to the complex interactions in the atmosphere and the high variability of natural rainfall events, it is difficult to accurately predict rainfall characteristics in the future. Many researchers have developed several methods for performing statistical analyses to improve the reliability of rainfall characteristics prediction in the future. Lana, Burgueno, Martinez, and Serra (2009) found that monthly rainfall amounts in Catalonia, Spain could be successfully described using Gamma and Poisson gamma distribution. In Catalonia, Spain, for example, monthly rainfall amounts are found to be successfully described using gamma and Poisson gamma distributions. On the other hand, Catalnoia's annual rainfall amounts fit the Gamma and Log-normal distributions. Moreover, daily precipitation maxima is better analysed using Gumbel I distribution, while annual number of rainy days could be modelled using the exponential and Weibull distributions (Lana et al., 2009).

Another statistical method, Statistical Downscaling (SD) is useful in modelling future rainfall events. Onyutha, Tabari, Rutkowska, Nyeko-Ogiramoi, and Willems (2016) investigated the future rainfall characteristics near Lake Victoria in East Africa, using 3SD methods: change factor (Delta), simplified (simQP), and advanced (wetQP) quantile-perturbation-based approaches. The model predicted that the rainfall amounts in the wet and dry seasons will become wetter and drier in 2050s and 2090s. It was also found that the difference in the results obtained from the three approaches is not statistically significant, indicating consistency of the models. However, each model has its own advantages and disadvantages, with Delta method being unsuitable to predict rainfall extremes, while wetQP method performs better in predicting both rainfall extremes and rainfall amounts in seasonal and annual periods.

3. Applicable theory

Statistical analysis could be generally understood as a method to analyse sets of data using statistical or probabilistic approach to derive meaningful insights. Regression analysis is a method under the broad umbrella of statistical analysis, whose goal is to "summarize observed data as simply, usefully, and elegantly as possible" (Weisberg, 2005).