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Effect of variations in rainfall intensity on slope stability in Singapore

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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

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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).

One way to derive meaningful correlations between two variables Y and X is the use of linear regression governed by Eqs. (1) and (2) based on Weisberg (2015) equation.

$$(Y|X = x) = \beta_o + \beta_1 x \quad - - - - - \tag{1}$$

$$(Y|X = x) = \beta_o + \beta_1 x \quad - - - - - \tag{2}$$

where $E(YX = x)$ and $Var(Y|X{=}x)$ are the expected value of Y and expected variance of Y respectively when X is equal to x. β_0 and β_1 are parameters to be obtained to describe the best-fitting linear equation, and σ is the standard deviation.

The method of least squares method is one way to obtain the equation of a best fit line from a scatter plot, by minimising the squared of the distance between the data points and the line of best fit according to Eq. (3) (Weisberg, 2015).

$$RSS(\beta_o, \beta_1) = \sum_{i=1}^{n} \left[y_i - \left(\beta_o + \beta_1 x_i \right) \right]^2 \quad - - - - - \tag{3}$$

where RSS is the residual sum of squares. Minimising the RSS function allows us to obtain the parameters β_0 and β_1 for expressing the equation of the best fit line.

In addition, to quantify the strength of the correlation, the coefficient of determination or R^2 value is determined by using Eq. (4) (Weisberg, 2015).

$$R^2 = \frac{SS_{reg}}{SYY} = 1 - \frac{RSS}{SYY} \quad - - - - - \tag{4}$$

where SS_{reg} is the sum of squares due to regression; SYY is the sum of squares of Y's; and RSS is residual sum of squares. A larger R^2 value would suggest that a better correlation exists between the two variables analysed.

Furthermore, the Mann-Kendall test, a non-parametric approach that is widely used to identify trends against time, is used to determine the statistical significance of data in this study due to its common use in rainfall trends study (Dindang et al., 2013; Longobardi & Villani, 2010).

In this test, the null hypothesis H_0 is tested against the alternative hypothesis H_1 where the data follow a monotonic trend against time. If $X_1, X_2, \ldots, X_3$ are data from a population where the random variables are independent and identically distributed, the Mann-Kendall test statistic (S) can be computed using Eqs. (5) and (6) below.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(X_j - X_i\right) \quad - - - - - \tag{5}$$

where

$$\operatorname{sgn}(\theta) = \begin{cases} +1 \text{ if } \theta > 0 \\ 0 \text{ if } \theta = 0 \\ -1 \text{ if } \theta < 0 \end{cases} \quad - - - - - \tag{6}$$

If the sample is large enough ($n \geq 8$), the S statistic is approximately normally distributed with zero mean and variance as given by Eq. (7).

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \quad - - - - - \tag{7}$$

Thus, the standardized Z statistic can be derived using Eq. (8) below.

$$Z = \begin{cases} \dfrac{S-1}{\sigma} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \dfrac{S+1}{\sigma} \text{ if } S < 0 \end{cases} \quad - - - - - \tag{8}$$

This Z value is than compared with a critical z value obtained from a standard two-tailed z-test at a chosen level of significance α.

4. Rainfall data

Comprehensive analyses on rainfall characteristics based on duration were performed on daily rainfall data from 1985 to 2009 as obtained from National Environment Agency (NEA) weather stations (Meteorological Services Singapore, 2016) in Seletar and Paya Lebar as shown in Fig. 1. These two locations were chosen because they coincide with areas that experienced high rainfalls in January 2007 as suggested by the historical rainfall data from NEA. Rainfall events with durations of 5, 10, 20, 30, 60, 120, 180, 240, 300, 360, 420, and 600 min were chosen for statistical analyses

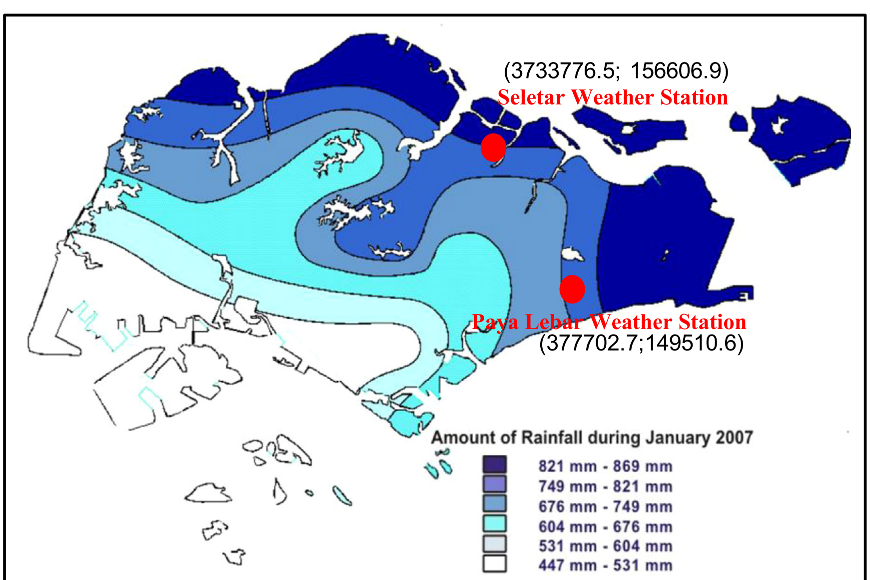

Fig. 1. Selected Automated Weather Stations for rainfall data collection and analysis superimposed with the simplified geological map of Singapore (NEA, 2007).

Table 1
Annual maximum amount of rainfall (in mm) by duration in Seletar weather station from 1985 to 2009.

Year	Rainfall duration (min)						
	5	10	30	60	120	240	360
1985	2	13.9	11.7	13.8	54.7	29.5	23.5
1986	1.1	13.4	30.3	54.5	21.2	65.1	61.7
1987	3	8	15.2	44.8	49	11.9	57.1
1988	7.7	7	17.7	42.7	22.4	21.4	–
1989	4	21	16.5	67.3	47.6	8.2	81
1990	4.8	21.3	44.6	54.9	48.8	6.6	37.3
1991	1.9	14	23.4	35.6	60.5	38.1	–
1992	3.3	7.7	36.3	35.5	58.3	34.9	44
1993	7.4	14.8	14	39.6	38.6	88.1	81
1994	2.6	8.5	54.8	40.2	107.4	65.5	–
1995	11.5	9.1	22.5	74	44.1	34.7	47.4
1996	5.3	24.2	29.4	50.7	85	32.3	–
1997	5.5	6.6	15.9	35.7	4.5	–	–
1998	7.9	11	26.6	34.1	33.2	60.2	–
1999	4.1	12.6	46.8	31.8	51.2	17.8	15.3
2000	7.3	6	22.5	70.3	55.8	26.8	–
2001	6.4	10.8	37.2	46.1	67.6	37	33.8
2002	6.7	8.9	20.1	42.5	59		45.4
2003	6	15.5	11.4	42.5	83.1	69.7	7.2
2004	5.3	11	24.4	34.5	88.4	42.1	–
2005	6.2	15.3	15	55.8	87.2	13.6	–
2006	9	8	16.4	40.2	39.4	135.1	57
2007	3.6	13.3	43.5	32	71	42.1	–
2008	3.2	12.3	50.2	32.4	95.8	27	15.4
2009	2.2	12.4	47.8	30.6	67.1	31.5	84.9

Table 2
Annual maximum amount of rainfall (in mm) by duration in Paya Lebar weather station from 1985 to 2009.

Year	Rainfall duration (min)						
	5	10	30	60	120	240	360
1985	4.8	12.1	12.7	28.8	52.9	24.8	24.5
1986	7	18	17.9	46.8	43	37.8	44.9
1987	4	12.5	37.5	41.3	36.3	35.7	35.9
1988	4.5	15.8	40.3	33.3	60.1	18.5	12.3
1989	8	4.5	25	59.4	53.4	20.3	71.3
1990	1	7.5	19.5	29.1	78.2	27.8	30.7
1991	5.3	6.1	17	35.6	48.3	40.6	–
1992	3.3	11.4	27.2	56.7	34.2	19.1	47.1
1993	1.6	8.9	13	35.2	46.1	30.3	70.5
1994	2.3	9.3	28.1	60.9	52	25.7	120.5
1995	5	10.2	26.2	33.8	47.8	37	9.2
1996	1.1	8.4	36.5	29.1	20.3	64.5	42.8
1997	2.3	13.2	48.5	56.7	15.4	14.7	62.5
1998	5	14.6	25	22.3	47.6	43.9	7.4
1999	4.6	11	24.6	71.5	68.7	81.2	–
2000	4	13.7	27.8	51.4	59.4	15	16.6
2001	4.3	11.5	43.2	33.7	31.7	54.4	–
2002	3.2	8.9	29.1	48.8	56.7	16.3	11.1
2003	7	15.4	36	34.8	32.8	63.6	11.9
2004	5	8.4	23.9	38	23.8	41.7	31.1
2005	2.3	7.8	19	41.3	30.5	18.7	21.8
2006	2.8	7	23	40.2	43.5	68.7	–
2007	3.2	17.8	22.7	32.1	65.7	31.6	52.3
2008	5	12.5	46	45	92	50.6	16
2009	1	13.2	45.7	44.2	49.9	45.8	13.5

with regards to its temporal variation over time. Possible trends were investigated using linear regressions to estimate how the rainfall with different durations and intensities will change in the future. The results are shown in Table 1 and Table 2, as well as Figs. 2(a)-2(d) for the graphical representations of selected durations in both Seletar and Paya Lebar weather stations.

5. Discussions

The data obtained from Seletar and Paya Lebar weather stations show high variability despite having classified the rainfall events according to its observed durations. This is evident from the low R^2 values as shown in Table 3 and Table 4 below. These low R^2 values are consistent with results from studies in neighbouring Malaysia by Dindang et al. (2013). Furthermore, none of the linear regression models is statistically significant at 10% level of significance (with a critical Z-value of 1.645) from the Mann-Kendall test, which are also consistent with findings by Dindang et al. (2013). Note that Mann-Kendall analyses could not be carried out for rainfall with duration 420 and 600 min from Seletar weather station due to small data sample ($n \leq 8$). Moreover, it is also observed that the data from Seletar weather station shows a larger R^2 values than the data from Paya Lebar weather station, indicating a better correlation of data from Seletar weather station.

Although none of the trends observed are statistically significant over the 25 years of historical rainfall data, it may be statistically significant if longer historical records of rainfall are to be analysed.

The linear equations describing the best fit curve for each station are tabulated in Table 5 and Table 6 below in the form of $y = ax + b$, where a and b are the parameters governing each curve. Using the equations given, the maximum rainfall amount in 2050 and 2100 for each duration in each weather station can be calculated.

In general, it can be observed that the average maximum rainfall intensity increases over the years in both Seletar and Paya Lebar weather stations. In Seletar weather station, the average maximum rainfall intensity is expected to increase to 50.9 mm/h in 2050 and to 69.4 mm/h in 2100. Similarly, in Paya Lebar weather station, the average maximum rainfall intensity is expected to increase to 47.1 mm/h in 2050 and increases further to 54.1 mm/h in 2100. It can also be observed that the rainfall intensity in Seletar weather station is higher than in Paya Lebar weather station in 2050 and 2100, suggesting that the current observed spatial distribution trend as shown in Fig. 1 above is unlikely to change in the future. Moreover, the data seem to illustrate that the rate of increase in rainfall intensity in Seletar weather station is greater than that in Paya Lebar weather station. Upon closer inspection, not all rainfall durations register an increase in maximum rainfall intensity. In Seletar weather station, rainfall with durations of 10, 20, 60, and 360 min show a constant trend in maximum rainfall intensity, while in Paya Lebar weather station, rainfall with durations of 5, 20, 180, 300 and 360 min also show a constant trend in maximum rainfall intensity. These results seem to suggest that there is a possible transition from a short duration rainfall to a longer rainfall duration in the future. A possible explanation would be the fact that warming atmospheric temperature will allow more water vapour to be stored in the atmosphere before falling back as precipitation, resulting in a longer duration and more intense rainfall.

A limitation that may undermine the reliability of the results is the unavailability of long duration rainfall data both in Seletar and Paya Lebar weather stations, especially rainfall events with a duration of 300 min and longer. There seemed to be few rainfall events with long durations in the past. However, this is expected to increase in the future.

6. Seepage and slope stability analyses

Numerical analyses involving seepage and slope stability analyses were carried out to observe the variations of factor of safety due to the estimated changes in rainfall intensity for periods

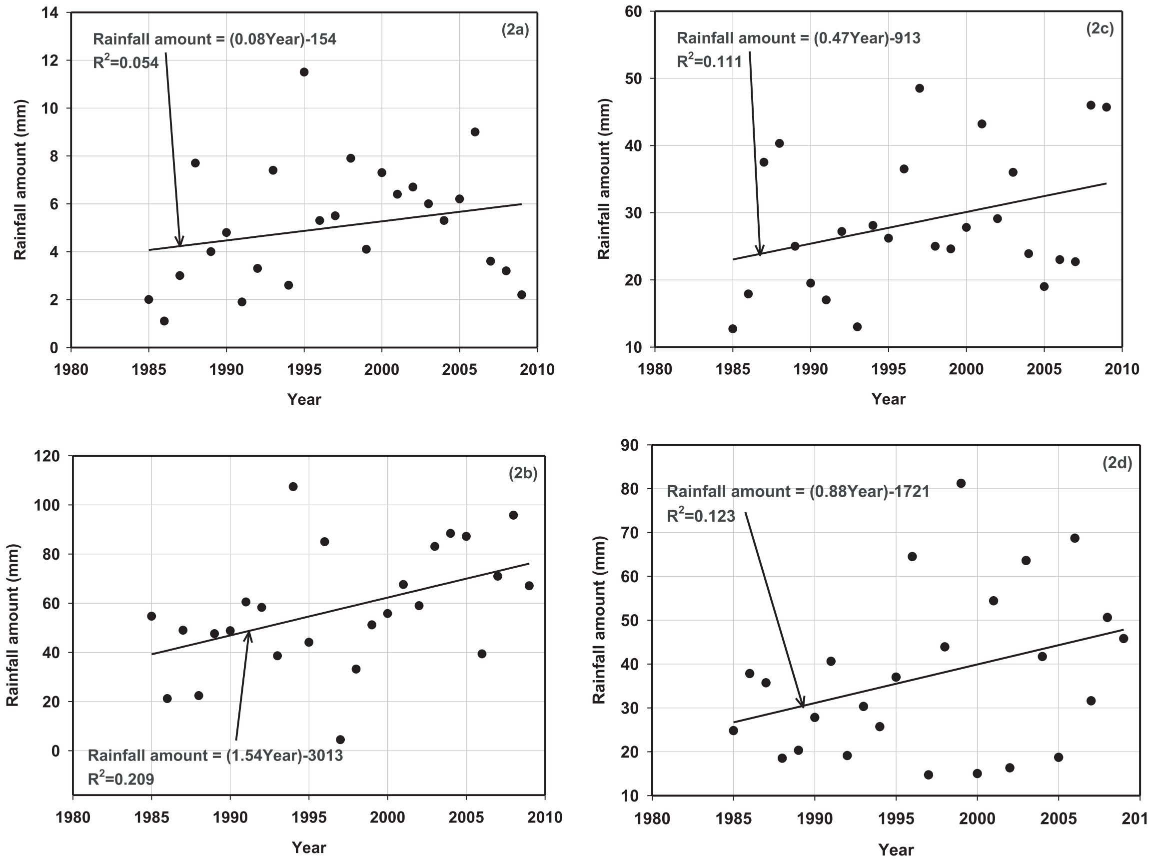

Fig. 2. Linear regression plots for different rainfall durations in Seletar and Paya Lebar weather stations. (a) Linear regression plot for 5-min rainfall events in Seletar weather station. (b) Linear regression plot for 120-min rainfall events in Seletar weather station. (c) Linear regression plot for 30-min rainfall events in Paya Lebar weather station. (d) Linear regression plot for 240-min rainfall events in Paya Lebar weather station.

Table 3
Summary of R^2 values from Seletar weather station in 1985–2009.

Duration (minutes)	R^2 for Linear Regression	Z-value from Mann-Kendall Test	Statistically Significant
5	0.0539	0	No
10	0.0255	0	No
20	0.0070	0	No
30	0.0762	0.0248	No
60	0.0597	0.1488	No
120	0.2091	0.0744	No
180	0.0501	0	No
240	0.0513	0.0282	No
300	0.2505	0	No
360	0.0061	0.0547	No
420	0.0203	–	No
600	0.8042	–	No
Average R^2	0.1345	0.03309	–

Table 4
Summary of R^2 values from Paya Lebar weather station in 1985–2009.

Duration (mins)	R^2 for Linear Regression	Z-value from Mann-Kendall Test	Statistically Significant
5	0.0258	0.0248	No
10	0.0029	0	No
20	0.0476	0.0248	No
30	0.1113	0	No
60	0.0004	0.0248	No
120	0.0019	0.0248	No
180	0.0226	0.0248	No
240	0.1229	0.0248	No
300	0.0290	0	No
360	0.0114	0	No
Average R^2	0.0376	0.0149	–

between 2010 and 2100. Transient seepage analyses were conducted using the finite element software Seep/W (Geoslope International Ltd, 2007a) and slope stability analyses were conducted using Slope/W (Geoslope International Ltd, 2007b). The rainfall reading from Seletar weather station was used in the analyses since this station was located in the area with the highest rainfall intensity in Singapore. Rainfall intensity of 8 mm/h (year of 2003), 31 mm/h (year of 2050) and 57 mm/h (year of 2100) were applied in three sets of seepage and slope stability analyses for 10 h.

A typical slope profile for residual soil slope in Singapore was used in the analyses. The slope geometry, boundary conditions and location of groundwater table, obtained from Rahardjo, Satyanaga, Leong, and Ng (2010) for the numerical analyses are presented in Fig. 3. The slope has a height of 15 m with a slope angle of 27°. Boundary conditions were applied to the slope model for the transient seepage analyses. Non-ponding boundary condition was applied in order to prevent excessive accumulation of rainfall on the slope surface. The flux boundary, q, equal to the desired rainfall intensity and duration was applied to the surface of the slope. The nodal flux, Q, equal to zero was applied along the sides above the water table line and along the bottom of the slope in order to simulate no flow zone. The sides below the water table were defined as head boundaries equal to the specific position of the groundwater level (total head, h). The finite element model down to 5 m below the slope surface had a mesh size of approximately 0.5 m, smaller than the mesh size in other parts of the slope, in order to obtain accurate results within the infiltration

Table 5
Summary of linear fitting equations for data from Seletar weather station and expected rainfall intensity for the period of 2050 and 2100.

Duration (minutes)	y = ax + b: a	b	Expected rainfall in 2050 (mm)	Rainfall Intensity in 2050 (mm/h)	Expected rainfall in 2100 (mm)	Rainfall Intensity in 2100 (mm/h)
5	0.0798	−154.33	9.3	111.1	13.3	159.0
10	0.0000	13.00	13.0	78.0	13.0	78.0
20	0.0000	19.00	19.0	57.0	19.0	57.0
30	0.5067	−984.10	54.6	109.3	80.0	159.9
60	0.0000	40.00	40.0	40.0	40.0	40.0
120	1.5378	−3013.30	139.2	69.6	216.1	108.0
180	0.8267	−1596.30	98.4	32.8	139.8	46.6
240	0.8751	−1706.50	87.5	21.9	131.2	32.8
300	2.9409	−5818.90	209.9	42.0	357.0	71.4
360	0.0000	48.00	48.0	8.0	48.0	8.0
420	0.6167	−1187.40	76.8	11.0	107.7	15.4
600	5.1565	−10264.00	306.8	30.7	564.7	56.5
Average	1.0450	−2050.40	91.9	50.9	144.1	69.4

Table 6
Summary of linear fitting equations for data from Paya Lebar weather station and expected rainfall intensity for the period of 2050 and 2100.

Duration (minutes)	y = ax + b: a	b	Expected rainfall in 2050 (mm)	Rainfall Intensity in 2050 (mm/h)	Expected rainfall in 2100 (mm)	Rainfall Intensity in 2100 (mm/h)
5	0.0000	4.20	4.2	50.4	4.2	50.4
10	0.0261	−40.89	12.6	75.7	13.9	83.5
20	0.0000	40.00	40.0	120.0	40.0	120.0
30	0.4715	−912.89	53.7	107.4	77.3	154.5
60	0.0326	−23.13	43.7	43.7	45.3	45.3
120	0.1052	−162.53	53.1	26.6	58.4	29.2
180	0.0000	38.00	38.0	12.7	38.0	12.7
240	0.8802	−1720.50	83.9	21.0	127.9	32.0
300	0.0000	40.00	40.0	8.0	40.0	8.0
360	0.0000	35.00	35.0	5.8	35.0	5.8
Average	0.1516	−270.27	40.4	47.1	48.0	54.1

zone. In this study, the seepage and stability analyses were performed for 20 h and they were divided into 40 time steps or 40 time increment. Each time step was equivalent to 0.5 h.

Simplified slope profiles with a homogeneous soil layer (one layer) for residual soil slope from Old Alluvium were used in the numerical analyses. Typical SWCC (Fig. 4) and permeability function (Fig. 5) for residual soil slope from Old Alluvium (Rahardjo, Satyanaga, Leong, & Ng, 2012) were used in the seepage analyses. The pore-water pressures were calculated in Seep/W for every time step at each node of the finite element mesh. The pore-water pressure output of the seepage analyses was incorporated into slope stability analyses. The typical saturated and unsaturated shear strengths for the residual soil slope from Old Alluvium were used in the slope stability analyses using Bishop's simplified method. The effective cohesion (c′) = 8 kPa, the effective friction angle (ϕ') = 35° and the angle indicating the rate of change in shear strength relative to matric suction (ϕ^b) = 20°. The pore-water pressure distribution was selected for each time increment and the corresponding factor of safety was calculated.

The variations of factor of safety for different rainfall intensities in 2003, 2050 and 2100 are shown in Fig. 6 above. It can be observed that at t = 10 h (when the rain stopped), there is a

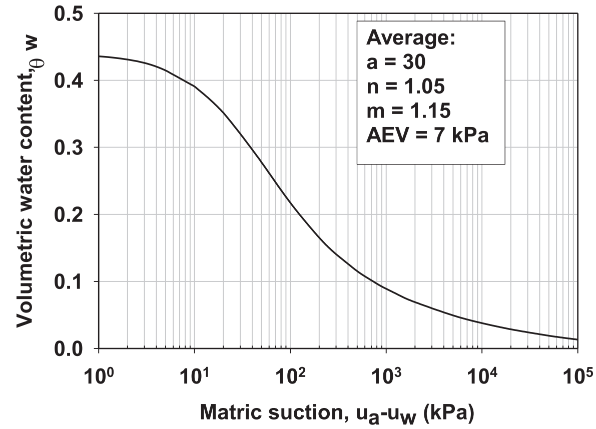

Fig. 4. Typical SWCC for residual soil slope from Old Alluvium used in seepage analyses.

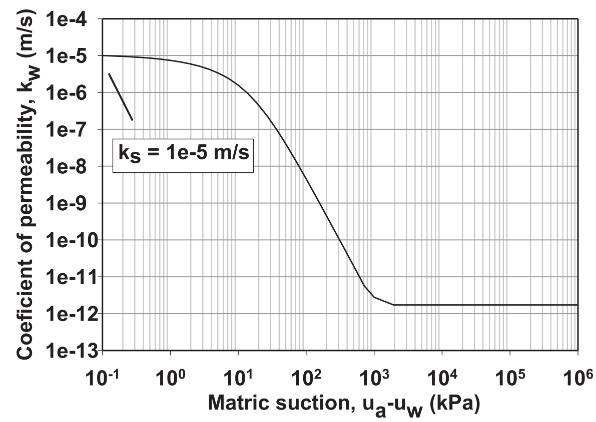

Fig. 5. Typical permeability function for residual soil slope from Old Alluvium used in seepage analyses.

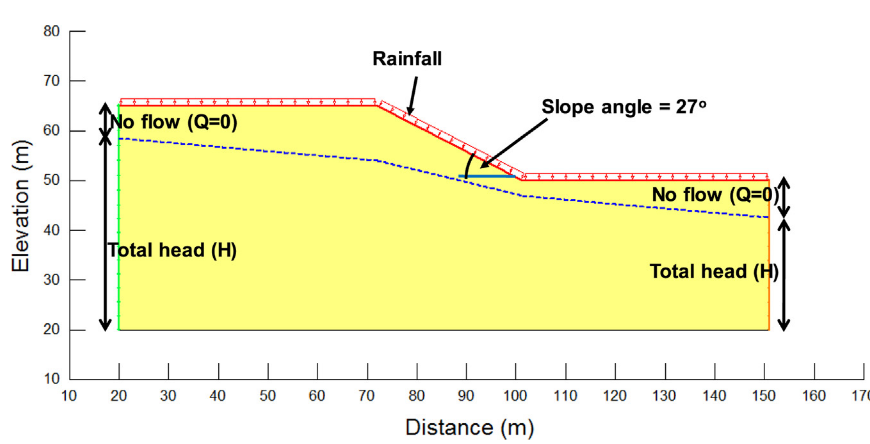

Fig. 3. Slope model for seepage and slope stability analyses parametric studies (slope height = 15 m and slope angle = 27°).

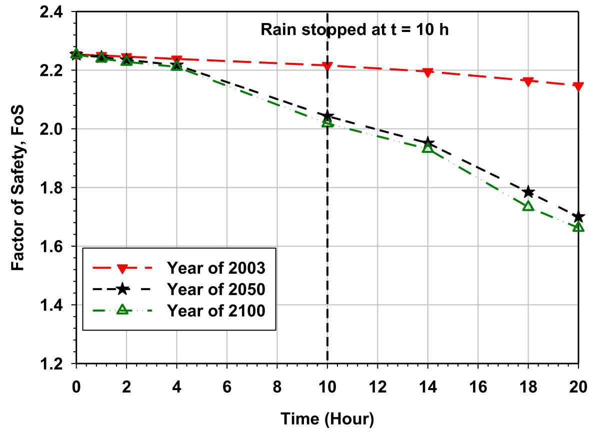

Fig. 6. Variations of factor of safety during and after rainfall for years of 2003, 2050 and 2100.

significant difference between the factor of safety in 2003 and 2050 of about 0.2. At rainfall intensity of 8 mm/h (in 2003), the factor of safety decreased marginally from 2.22 initially to 2.20 at $t = 10$ h, whereas at rainfall intensity of 31 mm/h (in 2050), the factor of safety dropped significantly to about 2.02 at $t = 10$ h. This result gives an indication of the existence of climate change beyond 2009, as indicated by the significant drop in factor of safety in 2050 as compared with the one in 2003.

Moreover, the factor of safety at $t = 10$ h for rainfall intensities 2100 is 2.01, which differs from the factor of safety in 2050 by a negligible 0.01 point. This suggests that there is a maximum amount of rainfall that can infiltrate into the soil to destabilise the slope, above which, additional water will flow by surface runoff, resulting in only marginal effects on the stability of the slope. Hence, the increase in rainfall intensity in the next 50 years will be more critical to slope stability than the increase in rainfall intensity in the subsequent 50 years. However, flooding due to surface runoff could be a major problem during this period of 2050–2100 if sufficient drainage provision is not available. Furthermore, it is also worth noting that the factor of safety still decreases after the rain has stopped at different rates and will most likely have differing rates of recovery as well. In general, Fig. 6 shows that the climate change may result in the increase in rainfall intensity. Hence, the stability of the slope in Singapore will be affected since the factor of safety may decrease in the future. The slope may be more prone to failure in the future and preventive measures are required to protect slopes from rainfall-induced slope failures. This study is important to maintain the sustainability of Singapore and to avoid casualties due to slope failures in the future.

7. Conclusions and recommendations for future work

Daily rainfall data from Seletar and Paya Lebar weather stations for the period of 1985–2009 were collected and analysed for temporal trends using statistical methods of linear regression and Mann-Kendall Test. It was found that generally rainfall intensity for most durations tend to increase over the years, with a possible shift to longer duration rainfall events in the future, although they are found to be statistically insignificant through the Mann-Kendall Test in the period of 1985–2009.

However, seepage and slope 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. In the subsequent 50 years, however, the increase in rainfall intensity only reduces the factor of safety further by a marginal amount, since the destabilising effect of water is limited by the infiltration rate.

Future research could attempt to derive more reliable and meaningful correlations of rainfall with time and space to better predict rainfall patterns in the future. Furthermore, the effect on seepage and slope stability in different soil types could also be investigated. Moreover, a further extension would be to superimpose the spatial rainfall distribution map with the geology and topography map of Singapore to identify areas prone to rainfall-induced slope failures by creating a slope-failure hazard map.

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