

1 **Assessment of critical rainfall scenarios for slope stability analyses based on**
2 **historical rainfall records in Singapore**

3 Yongmin Kim¹, Harianto Rahardjo^{1*}, Margarit Mircea Nistor¹, Alfrendo Satyanaga¹, Eng-
4 Choon Leong¹, Aaron Wai Lun Sham²

5 ¹School of Civil and Environmental Engineering, Nanyang Technological University,
6 Singapore

7 ²Building and Construction Authority, Special Functions Group, Enforcement & Structural
8 Inspection Department, Singapore

9 * Corresponding author: chrahardjo@ntu.edu.sg

10 **Abstract**

11 Rainfall-induced slope failure occurs in many countries including Singapore where slopes are
12 mostly covered with residual soils. Although the significance and impact of rainfall infiltration
13 in inducing slope failures are widely investigated, there have been diverse conclusions
14 regarding the relative roles between soil and rainfall to slope failures under various
15 environmental conditions. In this study, parametric studies were carried out for seven rainfall
16 scenarios and two soils to explore the critical rainfall scenarios affecting the slope stability in
17 Singapore. Special attention was given to the analyses of intensity and duration of the rainfall
18 based on historical rainfall data during the period of 1982-2017 in Singapore. A transient
19 seepage analysis was conducted, and the computed pore-water pressures were used in stability
20 analyses to calculate the variation of factor of safety of the slope during rainfall. The results
21 indicated that the slope with low permeability soil is mainly affected by the 5-day rainfall
22 scenario, while the slope with high permeability soil is mainly affected by the maximum daily
23 rainfall scenario in Singapore. Three case studies clearly validated the findings of this study.

24 **Keywords:** Rainfall scenarios, Residual soil, Slope stability, Numerical analysis

25 **Introduction**

26 In recent decades, a rising global temperature has generated rapid climate changes. Previous
27 studies indicated that rainfall events have become more intense in a number of countries, i.e.,
28 Malaysia (Noor et al., 2018; Hassan et al., 2018), Indonesia (Avia, 2019; Lestari et al., 2019),
29 Taiwan (Tung et al., 2016; Janati et al., 2019), United States (Kunkel 2003), Canada (Francis
30 and Hengeveld 1998), Australia (Suppiah and Hennessy 1998), South Korea (Lee and Bae
31 2013), South Africa (Mason et al. 1999), United Kingdom (Osborn et al. 2000) and Norway
32 (Forland et al. 1998). It is common that a slope may fail during or soon after heavy rainfall.
33 Mechanism of rainfall-induced slope failures is governed by many factors, such as the geology
34 and topography of the area, soil types, soil properties, local climate (rainfall and evaporation),
35 and water flow patterns within the slope.

36 Unsaturated soil mechanics is of importance in analyzing rainfall-induced slope failures.
37 In Singapore, slope failures during rainfalls are commonly associated with residual soil slopes
38 that are often found with a significant depth of unsaturated zone above groundwater table. The
39 unsaturated zone is defined by the presence of the negative pore-water pressures or matric
40 suctions above the groundwater table (Fredlund et al. 2012; Wu et al. 2016)). The rainwater
41 infiltration results in the variations of pore-water pressure and water content with depth within
42 the unsaturated zone. An increase in water content causes a decrease in matric suction. As a
43 result, the soil shear strength decreases, and this may lead to failure of the slope (Fredlund and
44 Rahardjo 1993; Kim et al. 2017).

45 Rainfall has been identified as the main triggering factor for landslides in Singapore,
46 Thailand, Vietnam, and Indonesia (Rahardjo et al. 2014). Chatterjea (1989) studied 79 minor
47 landslide events in Singapore and concluded that the landslides were related to rainfall. Wang
48 and Towhata (2015) observed that an increasing number of landslides might be correlated with
49 the increasing intensity of precipitation in Japan. In Hong Kong, the density (the number of

50 occurrences per km²) of natural terrain landslides increased exponentially with normalized
51 rainfall intensity (Ho et al. 2015). Lin et al. (2014) indicated that the number of landslides in
52 Taiwan had increased sharply in the last two decades, which coincided with an increase in
53 precipitation. These abundant observations point clearly that rainfall is closely related to slope
54 instability.

55 Many studies have been carried out to investigate the complex relationship between
56 rainfall and slope stability (Rahardjo et al. 2001; Rahimi et al. 2011; Ahmadi-adli et al. 2017;
57 Rahardjo et al. 2018). The Geotechnical Engineering Office of Hong Kong has developed
58 rainfall-landslide correlations, a probability-based framework to predict a number of landslides
59 from precipitation, by plotting landslide frequency against normalized rolling 24-h rainfall for
60 different types of slopes (Ho et al. 2015). Normalized maximum rolling 24-hour rainfall
61 intensities are calculated by dividing the maximum rolling 24-hour rainfall by the mean annual
62 rainfall at the same location. This is a better indicator of the severity of rainfall compared with
63 the maximum rolling 24-hour rainfall due to the significantly uneven rainfall distribution in
64 Hong Kong (Ho et al. 2015). Moreover, Taiwan authorities have developed a rainfall threshold
65 for different counties on the island based on rainfall data from 1989 to 2009 (Lin et al. 2014).
66 The rainfall threshold is defined to be the amount of rainfall that corresponds to the probability
67 of landslide occurrence larger than 50%. Superimposing this map of the rainfall threshold with
68 a map of landslide occurrence showed a strong spatial correlation between landslide and
69 rainfall (Lin et al. 2014).

70 Rainfall-induced slope failures may also occur due to antecedent rainfall. Antecedent
71 rainfall is the rain that falls in the days immediately preceding a landslide event (Rahardjo et
72 al. 2001; Cai and Ugai 2004; Rahardjo et al. 2012). Zêzere et al. (2005) studied the landslide
73 events in Portugal for the past 50 years and concluded that shallow slope failures were caused
74 by one to fifteen days of rainfalls, while deep-seated slope failures were mainly caused by one

75 to three months of prolonged rainfalls. Guzzetti et al. (2007) reviewed rainfall thresholds for
76 the initiation of landslides. They found that many researchers in different parts of the world
77 related slope failures to antecedent rainfall, but with different durations, from 1 day to 120 days.
78 U.S. Army Corps of Engineers (1997) investigated the effect of antecedent rainfall on historical
79 landslide events in the western part of Washington, including the Seattle area, United States.
80 They identified the 3-day rainfall event as a landslide initiating rainfall threshold. The
81 cumulative antecedent rainfall triggering landslides in this area of the USA is around 95 mm
82 for three days. Chen et al. (2005) studied the slope responses (i.e., pore-water pressure
83 distribution) to rainfall events through comprehensive instrumentation of slopes in Taiwan.
84 They concluded that 5-day antecedent rainfall affects the stability of slopes in Taiwan. Studies
85 on the threshold of rainfall-induced landslides have been conducted in other countries in Asia,
86 such as: Bhutan (Dikshit et al., 2019); Japan (Hong et al., 2005); Bangladesh (Khan et al., 2012);
87 South Korea (Kim et al., 2015).

88 For Singapore, Rahardjo et al. (2008) studied the effect of antecedent rainfall on slope
89 failure and observed that 5-day antecedent rainfall affected the stability of some slopes. Rahimi
90 et al. (2011) addressed the role of antecedent rainfall on slope stability and found that the
91 relationship between rainfall intensity and soil hydraulic properties played a decisive role in
92 determining the critical rainfall pattern that caused slope failures. However, these studies were
93 restricted to certain areas with limited data; therefore, the results could not represent the entire
94 region of Singapore.

95 Wei et al. (1991) in a case study of the Bukit Batok landslide in Singapore found that
96 the failure occurred after a period of heavy rainfall and there was no rainfall at the time of
97 failure. It appears therefore that experiences from different regions have resulted in different
98 conclusions as to the significance of antecedent rainfall for slope instability (Morgenstern,
99 1992). Such mixed conclusions are probably the consequence of attempts to correlate the

100 incidence of landslides to event rainfall patterns alone rather than evaluating how successive
101 rainfall events (antecedent rainfall) lead to the development of worst pore-water pressure
102 conditions in a slope that could affect slope stability. This study therefore attempts to evaluate
103 the relative role of antecedent rainfall over event-based rainfall in producing worst pore-water
104 pressure conditions in a slope that could affect slope stability.

105 Although Singapore has a moderately low-lying relief, rainfall induced slope failure is
106 the most common form of landslide in Singapore. It usually occurs during rainy season of the
107 year when rainfall is especially heavy. During the period of December 2006 to January 2007
108 Singapore has recorded one of the highest average prolonged rainfall over the last 80 years of
109 345mm for over 20 hours, of which the 20 hours of continuous rainfall of 765.9mm from 19 to
110 20 December 2006 was the highest recorded for the past 137 years. During this period eleven
111 landslides occurred in Singapore (Rahardjo et al., [2008](#)).

112 A study on the increasing trend of rainfall in Singapore was conducted by Kristo et al.
113 ([2017](#)). They indicated a possible shift to longer duration rainfall events up to 2100. Based on
114 the derived trends, projected rainfall intensities in 2050 and 2100 were used in the seepage and
115 slope stability analyses performed on a typical residual soil slope in Singapore. A significant
116 reduction in factor of safety was observed in the next 50 years, with only a marginal decrease
117 in factor of safety in the subsequent 50 years. This indicates a possible detrimental effect of
118 variations in rainfall patterns on slope stability in Singapore, especially in the next 50 years.

119 The literature review on the past studies related to rainfall threshold triggering
120 landslides in different countries highlights the importance of analyzing the rainfall threshold
121 that causes slope failures in Singapore in order to provide alert level prior to the occurrence of
122 slope failures. Consequently, warning systems based on the alert level of rainfall threshold will
123 prevent casualties and damages to the surrounding infrastructures.

124

125 The main objective of this study is to investigate the two critical rainfall scenarios
126 affecting stability of residual soil slopes in Singapore through analyses of historical rainfall
127 data and case studies. It is necessary to study the relationship between local rainfall events and
128 soil types since Singapore residual soils exhibit a wide range of coefficient of permeability.
129 Rainfall analysis was comprehensively carried out based on historical rainfall data of Singapore
130 for the period of 1982-2017. The numerical studies based on actual landslides confirmed that
131 the two critical rainfall scenarios, i.e., 5-Day rainfall and Daily maximum rainfall were the
132 important factors that caused the failure of slopes with low and high permeabilities,
133 respectively.

134 **Methodology**

135 *Analysis of historical rainfall*

136 Comprehensive studies were carried out by the Scottish government on the effect of antecedent
137 rainfall on slope stability for the development of policy to include rainfall threshold and
138 duration for slope stability in Scotland. They observed that the cumulative and duration of
139 antecedent rainfall triggering slope failures in Australia, Italy, Singapore, Scotland, and
140 Norway were 280 mm for 3 days; 320 mm for 5 days; 600 mm for 6 days; 195 mm for 14 days
141 and 190 mm for 7 days, respectively. The analyses from Pennington et al. (2014) on
142 comprehensive historical landslide data from the British Geological Survey indicated that 300
143 mm antecedent rainfall for 7 days results in the majority of landslides in the United Kingdom.
144 A summary of antecedent rainfall on slope stability studies from different countries can be seen
145 in Table 1.

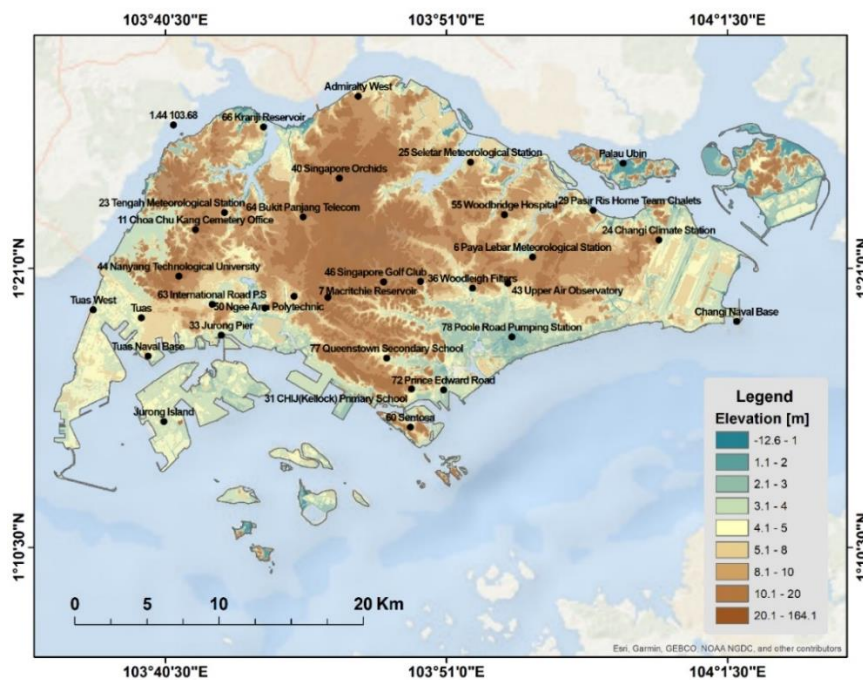
146 Figure 1 shows locations of the 37 meteorological stations which have hourly records
147 of historical rainfall data for the period of 1982-2017 in Singapore. The maximum daily rainfall
148 and the maximum 5-day antecedent rainfall from 1982 to 2017 were calculated and used as
149 rainfall loading in slope stability analyses. The maximum daily rainfall of 354 mm/day was

150 observed on 19 December 2006 from Woodbridge Hospital rainfall station. The maximum 5-
 151 day antecedent rainfall of 577 mm was observed from 17 to 21 December 2006. It should be
 152 noted that the term 5-day antecedent rainfall refers to the rainfall amount observed within five
 153 continuous days.

154 **Table 1** Summary of different durations of antecedent rainfall triggering slope failures in
 155 different countries

Country	Published by	Year	Days of antecedent rainfall (total amount)
Malaysia	Lee et al. (2014)	2014	3-day (150 mm)
Taiwan	Chen et al. (2005)	2005	5-day (390 mm)
Singapore	Transport and Work Scotland unit, Transport Scotland, Scottish Government	2008	5-day (320 mm)
China	Yang et al. (2020)	2020	7-day (300 mm)
Indonesia	Chikalamo et al. (2020)	2020	15-day (200 mm)

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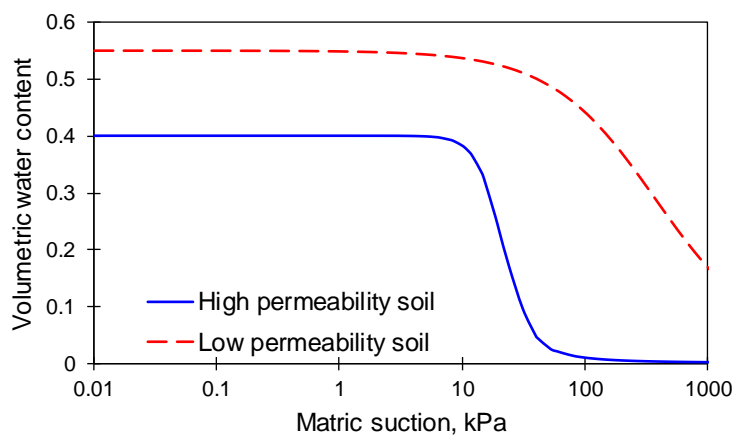


158
 159 **Fig. 1** Locations of the meteorological stations used for the rainfall distribution in Singapore
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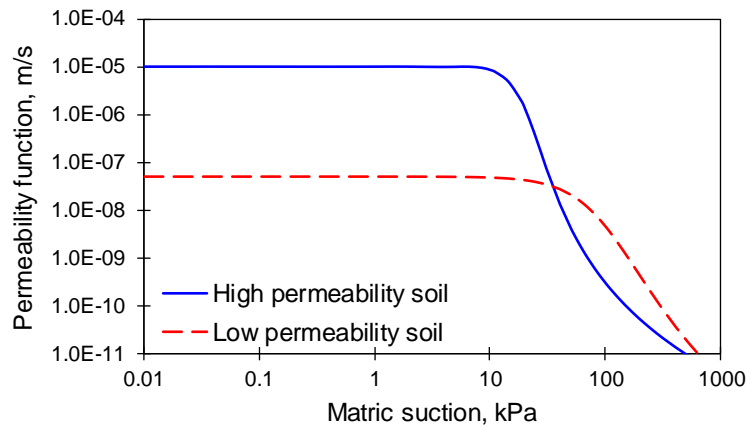
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162 **Parametric study**

163 Parametric studies were conducted to assess the stability of residual soil slopes in Singapore,
164 subjected to different rainfall loadings. Two different saturated coefficients of water
165 permeability were used in the analyses; $k_s = 5.0E-8$ m/s (referred to as low permeability soil
166 herein) and $k_s = 1.0E-5$ m/s (referred to as high permeability soil herein). Rahardjo et al. (2007)
167 did the parametric studies on the effect of slope height and rainfall intensity on stability of
168 residual soil slopes in Singapore. They concluded that the minimum factors of safety of slopes
169 higher than 6 m are almost the same under heavy rainfall higher than 240 mm/day regardless
170 the slope height. Typical slope geometry in Singapore with 6 m slope height and 45° slope
171 angle was used in the numerical analyses. Unsaturated soil properties of soil-water
172 characteristic curves (SWCCs) and permeability functions associated with low and high
173 permeability soils were used as input in the seepage analyses (Fig. 2). The transient seepage
174 analyses and slope stability analyses were conducted using SEEP/W and SLOPE/W,
175 respectively (Geo-Slope 2012).



176
177 (a) Soil-water characteristic curves



178
 179 (b) Permeability functions
 180 **Fig. 2** Unsaturated hydraulic properties of two soils for seepage analyses
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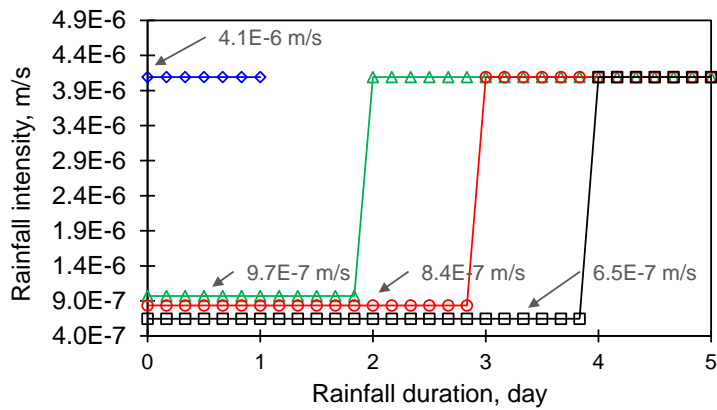
182 The parametric studies consist of seepage and stability analyses with seven scenarios
 183 of rainfall application (Table 2 and Figs. 3 and 4). In scenario 1, a maximum daily rainfall of
 184 354 mm/day (Max. Daily rainfall) based on historical rainfall data from 1982 to 2017 (Rahardjo
 185 et al., 2020) was applied for one day on the soil surface (see Fig. 3). In scenario 2, a maximum
 186 cumulative rainfall of 521 mm for three days (3-Day rainfall) based on historical rainfall data
 187 from 1982 to 2017 was applied in the analyses. The distribution of rainfall loading for scenario
 188 2 consisted of the application of 112 mm/day for two consecutive days (on the first two days)
 189 and the application of 354 mm/day on the last day (see Fig. 3). In scenario 3, a maximum
 190 cumulative rainfall of 570 mm for four days (4-Day rainfall) based on historical rainfall data
 191 from 1982 to 2017 was applied in the analyses. The distribution of rainfall loading for scenario
 192 3 comprised the application of 75 mm/day for three consecutive days (on the first three days)
 193 and the application of 354 mm/day on the last day (see Fig. 3). In scenario 4, a maximum
 194 cumulative rainfall of 577 mm for five days (5-Day rainfall) based on historical rainfall data
 195 from 1982 to 2017 was applied in the analyses. The distribution of rainfall loading for scenario
 196 4 was the application of 56 mm/day for four consecutive days (in the first four days) and the
 197 application of 354 mm/day on the last day (see Fig. 3). In scenario 5, uniform cumulative
 198 rainfall of 577 mm for five days (5-Day uniform rainfall) based on historical rainfall data from

199 1982 to 2017 was applied in the analyses. The distribution of rainfall loading for scenario 5
 200 was the application of 115 mm/day for five days (see Fig. 4). In scenario 6, the uniform rainfall
 201 loading of 534 mm/day (maximum daily rainfall based on historical rainfall data from 1982 to
 202 2017) was applied for 10 days (Max. 10-Day uniform rainfall) on the soil surface (see Fig. 4).
 203 In scenario 7, the uniform rainfall loading of 56 mm/day (minimum daily rainfall based on
 204 historical rainfall data from 1982 to 2017) was applied for 10 days (Min. 10-Day uniform
 205 rainfall) on the soil surface (see Fig. 4). The selection of maximum daily and maximum 5-day
 206 rainfall were based on the occurrences of past landslides in Singapore. Some landslides
 207 occurred after 1 day of rainfall. Other landslides occurred after 5 days of rainfall (Rahardjo et
 208 al., 2007)

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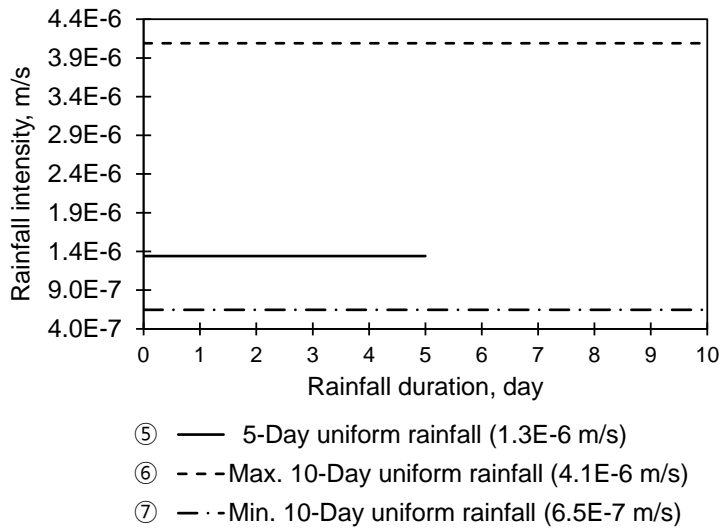
210 **Table 2** Different rainfall scenarios applied in parametric studies

Scenario No.	Rainfall pattern	Intensity (mm/day)	Intensity (m/s)
1	Max. Daily rainfall	1×354	$1 \times 4.1E-6$
2	3-Day rainfall	$2 \times 112 + 354$	$2 \times 9.7E-7 + 4.1E-6$
3	4-Day rainfall	$3 \times 75 + 354$	$3 \times 8.4E-7 + 4.1E-6$
4	5-Day rainfall	$4 \times 56 + 354$	$4 \times 6.5E-7 + 4.1E-6$
5	5-Day uniform rainfall	5×115	$5 \times 1.3E-6$
6	Max. 10-Day uniform rainfall	10×354	$10 \times 4.1E-6$
7	Min. 10-Day uniform rainfall	10×56	$10 \times 6.5E-7$



- ① —◇— Max. Daily rainfall
- ② —△— 3-Day rainfall
- ③ —○— 4-Day rainfall
- ④ —□— 5-Day rainfall

211
212 **Fig. 3** Rainfall applications in scenarios 1 to 4
213



- ⑤ — 5-Day uniform rainfall (1.3E-6 m/s)
- ⑥ - - -Max. 10-Day uniform rainfall (4.1E-6 m/s)
- ⑦ - · -Min. 10-Day uniform rainfall (6.5E-7 m/s)

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215 **Fig. 4** Rainfall applications in scenarios 5 to 7
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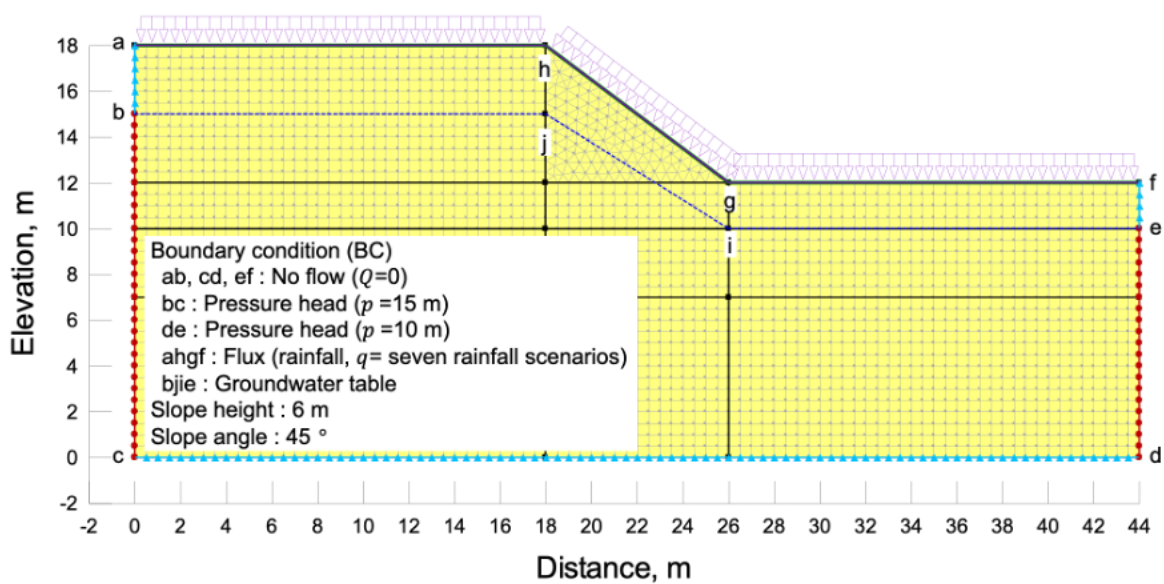
217 ***Seepage and slope stability analysis***

218 Numerical models and boundary conditions used in the parametric studies are presented in Fig.
219 5. A typical groundwater table at a depth of 3 m and 2 m below the crest and the toe of the
220 slope, respectively was adopted in the analysis. The side boundaries are at a distance of 18 m
221 from the crest and the toe (3 times the height of the slope) to avoid any influence of the
222 boundary conditions on the seepage process within the slope. The boundary conditions adopted
223 were as follows: zero total flux was applied to the bottom boundary and the side boundaries

224 above the groundwater table; pressure head was applied to the side boundaries below the
 225 groundwater table; and unit flux boundary according to the rainfall intensity with potential
 226 seepage face review was applied to slope surface to simulate rainfall infiltration with no
 227 ponding.

228 The pore-water pressure distributions from SEEP/W were used as input for the slope
 229 stability analyses in SLOPE/W. The objective of this study is to show the effect of rainfall on
 230 slope stability. The main property affecting the rate of rainwater infiltration is the permeability
 231 of soils. Hence, one set of soil shear strength with two different permeabilities was used in the
 232 numerical analysis. The soil properties used in the slope stability analyses are unit weight ($\gamma_t =$
 233 19.6 kN/m^3); effective cohesion ($c' = 6 \text{ kPa}$); effective friction angle ($\phi' = 26^\circ$) and
 234 unsaturated ϕ^b angle ($= 13^\circ$), which were within the typical range of residual soil properties
 235 in Singapore, as studied by Rahardjo et al. (2012). Bishop's simplified method of slices for
 236 circular slip surfaces was used in the calculation of factor of safety. It is assumed that no tension
 237 crack is allowed, and the recovery of matric suction after the end of rainfall due to evaporation
 238 and evapotranspiration is not considered in the analyses.

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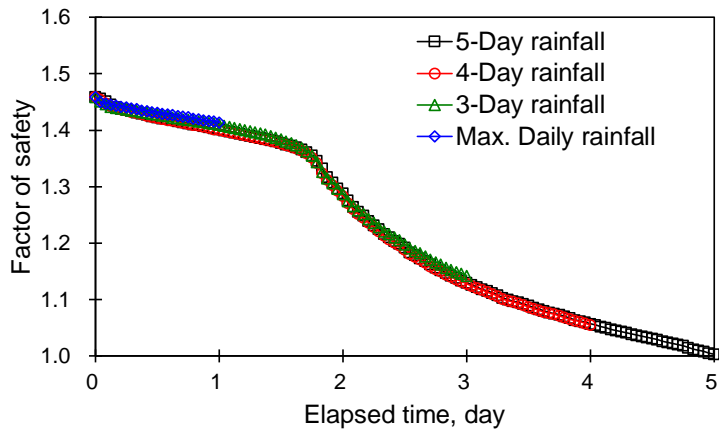
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Fig. 5 Numerical model and boundary conditions used in parametric studies

243 **Discussions on results of parametric studies**

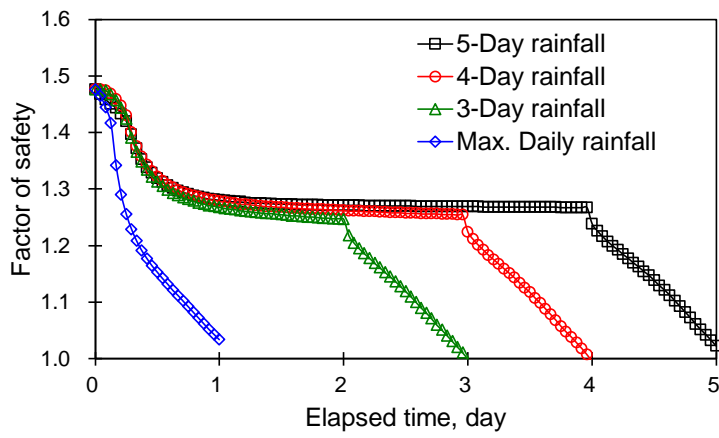
244 The variations of factor of safety (FS) obtained from slope stability analyses are presented in
245 Figs. 6 to 8. Figure 6a shows that FS of the slope with low permeability soil decreased and
246 reached a critical FS of 1 only at the end of 5-Day rainfall (scenario 4). This might be attributed
247 to the relatively lower permeability of the soil as compared to the rainfall intensities in
248 scenarios 1 to 4. Hence, the same amount of rainwater infiltrated into the soil layer resulting in
249 the same rate of decreasing in factor of safety in scenarios 1 to 4. Figure 6b shows that FS of
250 the slope with high permeability soil decreased significantly from the initial FS of 1.48 to the
251 critical FS of 1 at the end of Max. Daily rainfall (scenario 1). This happened since the rainwater
252 easily percolated down to the soil layer due to the high permeability of the soil. A similar trend
253 was observed in the changes in FS for scenarios 2 to 4 regardless of days of antecedent rainfall.
254 The significant decrease in FS for the slope with high permeability soil under 3-Day, 4-Day,
255 and 5-Day rainfall scenarios occurred on the last day of rainfall. This might be attributed to the
256 high rainfall intensity on the last day for scenarios 2 to 4 that lead to a significant drop of matric
257 suction in the slope.

258 Figure 7 shows that FS of the slope with low permeability soil decreased and reached
259 a critical FS of 1 at the end of application of 5-Day uniform rainfall (scenario 5). This happened
260 due to the lower permeability of the soil causing a slow rate of rainwater infiltration into a
261 greater depth. The rainwater had reached the critical slip surface which was associated with
262 critical FS before the rainwater could flow out from the soil layer. The figure also shows that
263 FS of the slope with high permeability soil decreased and reached only to FS of 1.2 at the end
264 of application of 5-Day uniform rainfall (scenario 5). This was attributed to the relatively lower
265 rainfall intensity as compared to the permeability of the soil.



266

267 (b) Low permeability soil

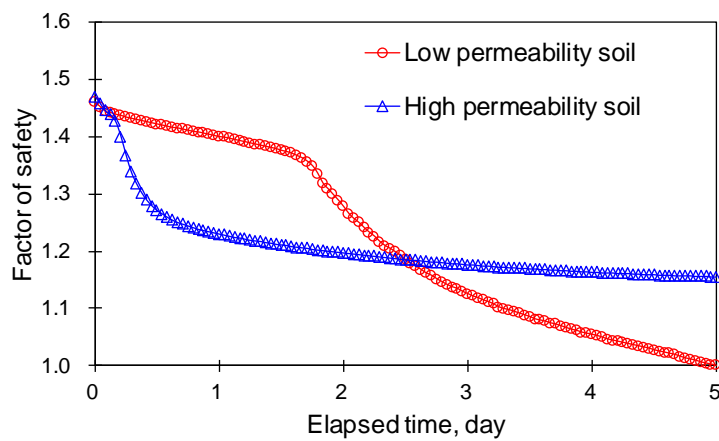


268

269 (b) High permeability soil

270 **Fig. 6** Variations in factor of safety for scenarios 1 to 4

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272

273 **Fig. 7** Variations in factor of safety for scenario 5 for low and high permeability soils

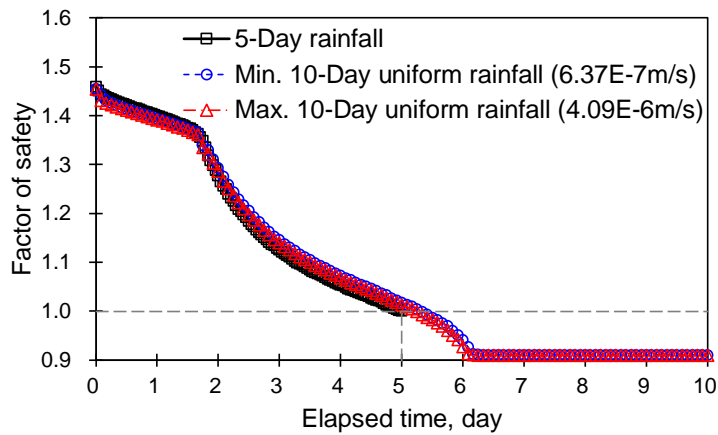
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275 The results from stability analyses of the slope with low permeability soil under both
276 Max. and Min. 10-Day uniform rainfall scenarios (scenarios 6 and 7), as shown in Fig. 8a
277 demonstrate that trends of the changes in FS were the same as those under Max. Daily rainfall,
278 3-, 4-, and 5-Day rainfalls, as shown in Fig. 6a. This might be attributed to the lower
279 permeability of soil as compared to the rainfall intensities in scenarios 6 and 7. Hence, the same
280 amount of rainwater infiltrated into the soil layer, resulting in the same decreasing rate in FS
281 for scenarios 6 and 7. In addition, the FS started to remain constant after 6 days application of
282 rainfall. This was attributed to the fully saturated condition of the slope due to the rising of the
283 groundwater table into the ground surface. The boundary condition on the ground surface was
284 set as flux with no ponding condition. Hence, no mounding of water occurred, although the
285 groundwater table rose up to the ground surface. As a result, the FS remained constant upon
286 reaching the fully saturated condition. Figure 8b shows that FS of the slope with high
287 permeability soil under Max. 10-Day uniform rainfall decreased significantly from the initial
288 FS of 1.48 to the critical FS of 1 after 1 day of rainfall. This happened due to the significant
289 amount of rainfall that was applied on the slope surface (353.6 mm/days), resulting in a large
290 amount of rainwater infiltration reaching critical slip surface associated with the critical FS of
291 1 within 1 day.

292 Overall, the results from the stability analyses shown in Figs. 6 to 8 indicated that the
293 slope with low permeability soil reached critical FS of 1 due to 5-Day rainfall scenario, while
294 the slope with high permeability soil reached critical FS of 1 under Max. Daily rainfall scenario.

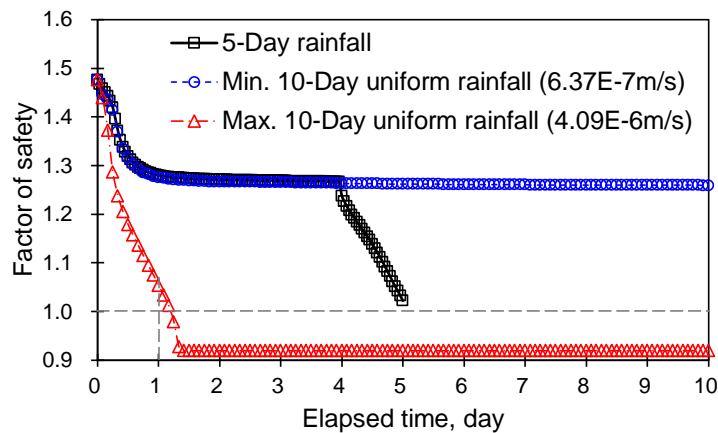
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296



297

298 (b) Low permeability soil



299

300 (b) High permeability soil

301 **Fig. 8** Variations in factor of safety for scenarios 4, 6 and 7

302

303 **Case study**

304 Three cases of slope failures based on historical records were analyzed in this section. The

305 locations of the three slope failures are indicated in Fig. 9.

306 **Case 1: slope at Yio Chu Kang Road**

307 A slope failed near Yio Chu Kang Road on 21 December 2006. The height and angle of the

308 slope near Yio Chu Kang Road are 5.5 m and 32°, respectively, which were obtained from the

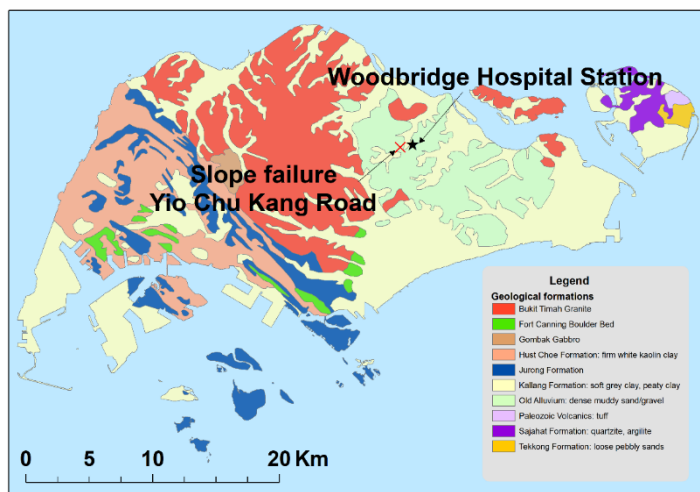
309 digital elevation model (DEM) map. The groundwater table was located at 3 m below the crest

310 of the slope and 2 m below the toe of the slope. The rainfall data were obtained from the closest

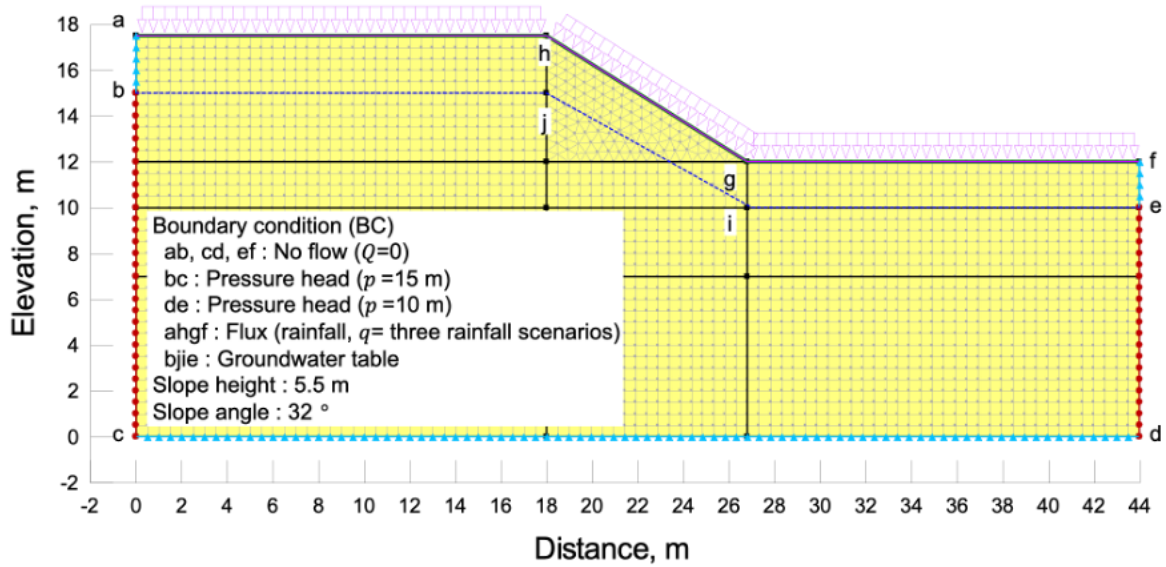
311 rainfall station at Woodbridge Hospital Station (Fig. 9). The cumulative 1-day of rainfall on

312 the day when the slope failed was 7.1 mm. This indicated that antecedent rainfall is the more
 313 likely cause of failure. In this case, the numerical analyses were carried out to consider 5-Day
 314 rainfall (scenario 4). The 5-days cumulative rainfall prior to slope failure near Yio Chu Kang
 315 Road was 577.1 mm which was the maximum 5-Day antecedent rainfall for the period of 1982-
 316 2017.

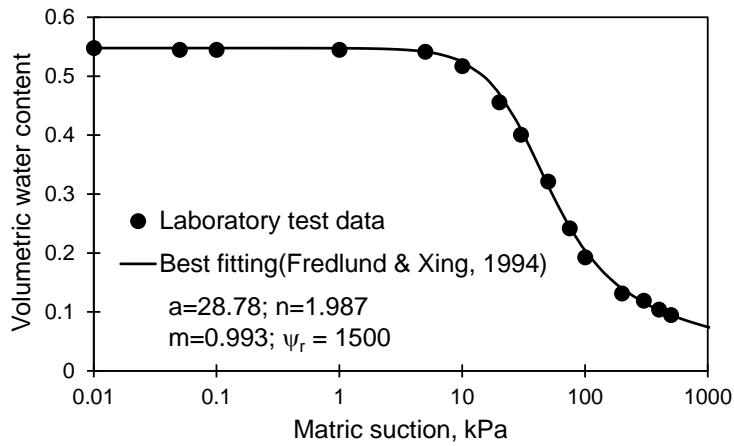
317 The numerical model of the slope near Yio Chu Kang Road is presented in Fig. 10. The
 318 soil properties used in stability analyses were obtained from a nearby borehole located at Ang
 319 Mo Kio St 21 (Rahardjo et al. 2012). The required SWCC and permeability function for the
 320 seepage analyses using SEEP/W are shown in Fig. 11. Three sets of rainfall loading were used.
 321 The first rainfall loading was Max. Daily rainfall with an intensity of 354 mm/day (maximum
 322 daily rainfall for periods of 1982-2017). The second rainfall loading was the 5-Day uniform
 323 rainfall with an intensity of 115 mm/day. The third rainfall loading was the 5-Day rainfall with
 324 four days of uniform rainfall (56 mm/day) and one day of high-intensity rainfall (354 mm/day).
 325 The pore-water pressure variations from seepage analyses were exported into SLOPE/W for
 326 slope stability analyses. The shear strength parameters of the soil are effective cohesion (c') of
 327 3 kPa, effective friction angle (ϕ') of 25° and ϕ^b angle of 11° .



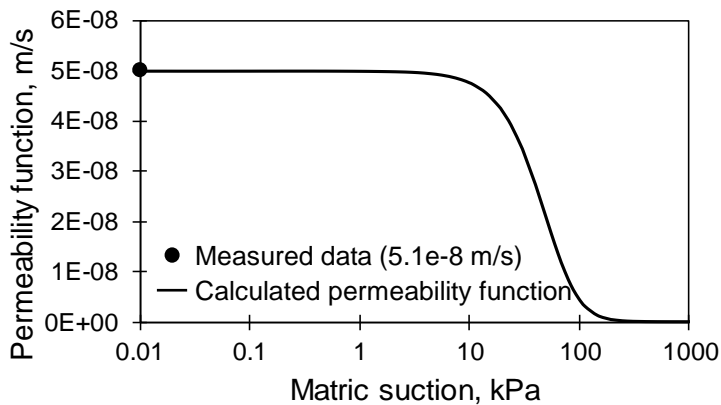
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 329 **Fig. 9** Location of slope failure near Yio Chu Kang Road and nearest rainfall station at
 330 Woodbridge Hospital Station
 331



332
333 **Fig. 10** Numerical model used in seepage analyses of the slope near Yio Chu Kang Road
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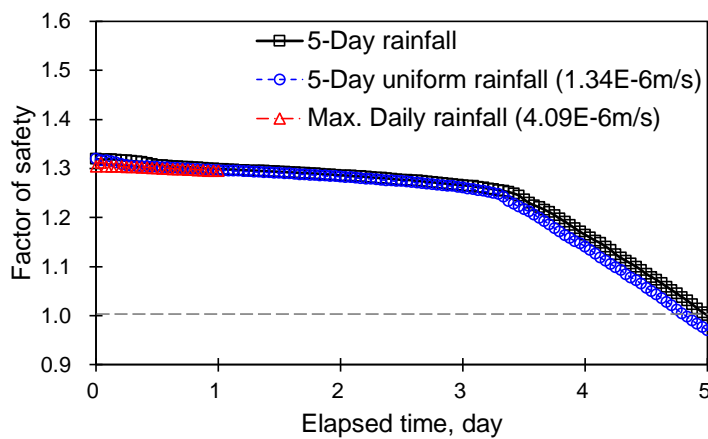
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336 (a) Soil-water characteristic curve



337
338 (b) Permeability function
339 **Fig. 11** Unsaturated hydraulic properties of the slope near Yio Chu Kang Road
340

341 Figure 12 shows that the FS of the slope decreased to 1 after 5-Day rain. This happened
 342 due to the lower permeability of the soil, causing a slow rate of rainwater infiltration into a
 343 greater depth. The figure also indicates that the trend of decreases in FS due to the application
 344 of both 5-Day uniform and 5-Day rainfall was the same, and there was no significant drop in
 345 FS due to the application of Max. Daily rainfall. This might be attributed to the lower
 346 permeability of soil ($k_s = 5.0E-8$ m/s) as compared to the applied rainfall intensity. Hence, the
 347 same amount of rainwater infiltrated into the soil layer resulting in the same rate of decrease in
 348 factor of safety under both rainfall intensities.

349



350

351 **Fig. 12** Variations in factor of safety for the slope near Yio Chu Kang Road under different
 352 rainfall loading

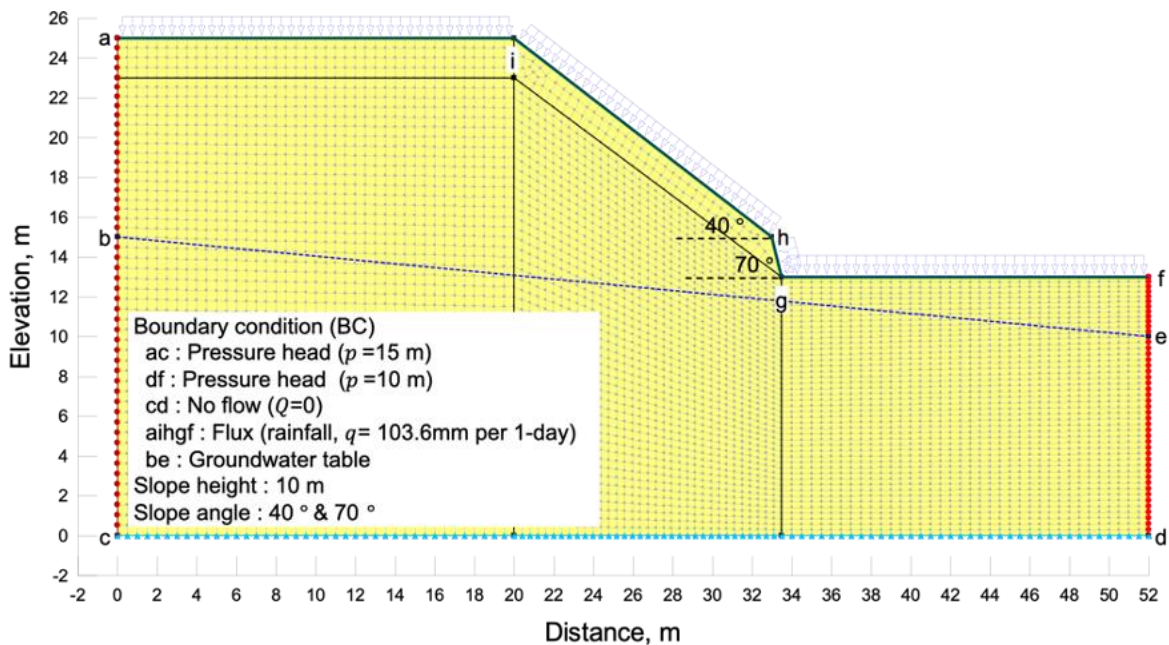
353

354 **Case 2: slope at Jalan Asas**

355 A slope failure occurred at Jalan Asas on 11 November 2018. The slope is located within
 356 residual soil from Bukit Timah Granite. The nearest rainfall station is at Bukit Panjang Telecom,
 357 which recorded a 1-Day rainfall of 103.6 mm prior to the failure event. The height and angle
 358 of slope at Jalan Asas are 10 m and 37°, respectively, as obtained from the DEM map. The
 359 groundwater table was located at 1.5 m below the toe of the slope. The numerical model of this
 360 slope is presented in Fig. 13.

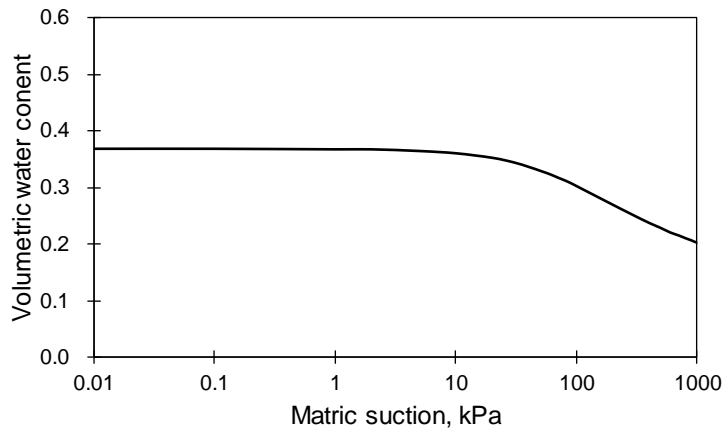
361 The soil properties used in the stability analyses were obtained from a nearby borehole
 362 located at Orchard Boulevard (Rahardjo et al. 2018). The required SWCC and permeability
 363 function for the seepage analyses using SEEP/W are shown in Fig. 14. The pore-water pressure
 364 variations from seepage analyses were exported into SLOPE/W for stability analyses. The
 365 shear strength parameters of the soil are effective cohesion (c') of 9 kPa, effective friction angle
 366 (ϕ') of 30° and ϕ^b angle of 20° . The variations in FS are presented in Fig. 15. The condition
 367 of slope prior to rainfall is considered to be safe since the initial FS is higher than 1.5. After
 368 one day of rainfall, the FS dropped to 1.2. The value of 1.2 is likely to be considered as unstable
 369 condition in accordance with Building Construction Authority (2018), which was proven by
 370 the fact that the slope failure occurred on 11 November 2018.

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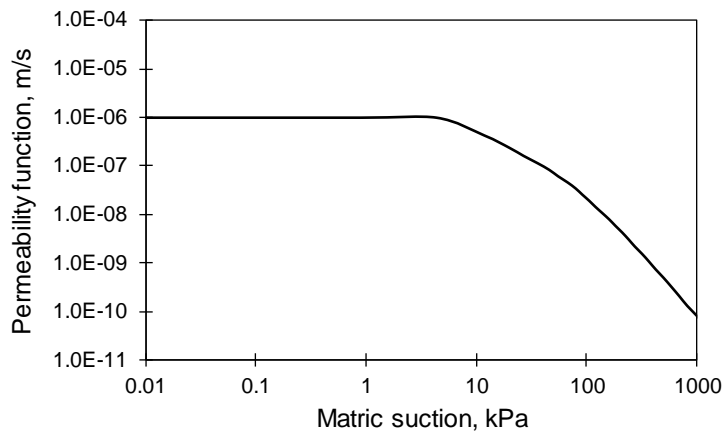


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Fig. 13 Numerical model used in seepage analyses of the slope at Jalan Asas

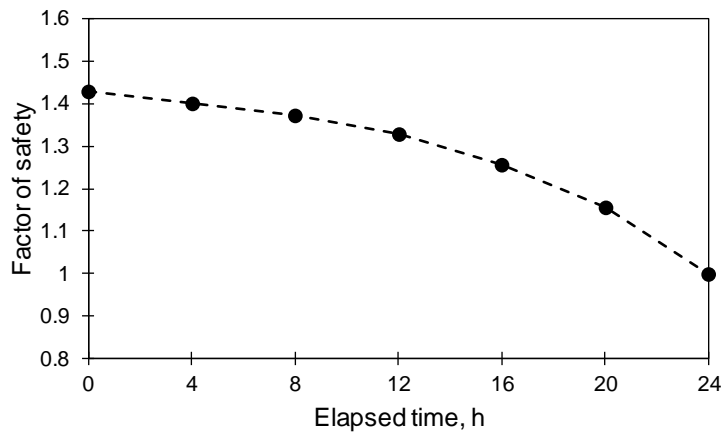


375
376 (a) Soil-water characteristic curve



377
378 (b) Permeability function

379 **Fig. 14** Unsaturated hydraulic properties for seepage analyses of the slope at Jalan Asas
380



381
382 **Fig. 15** Variation in factor of safety for the slope at Jalan Asas
383

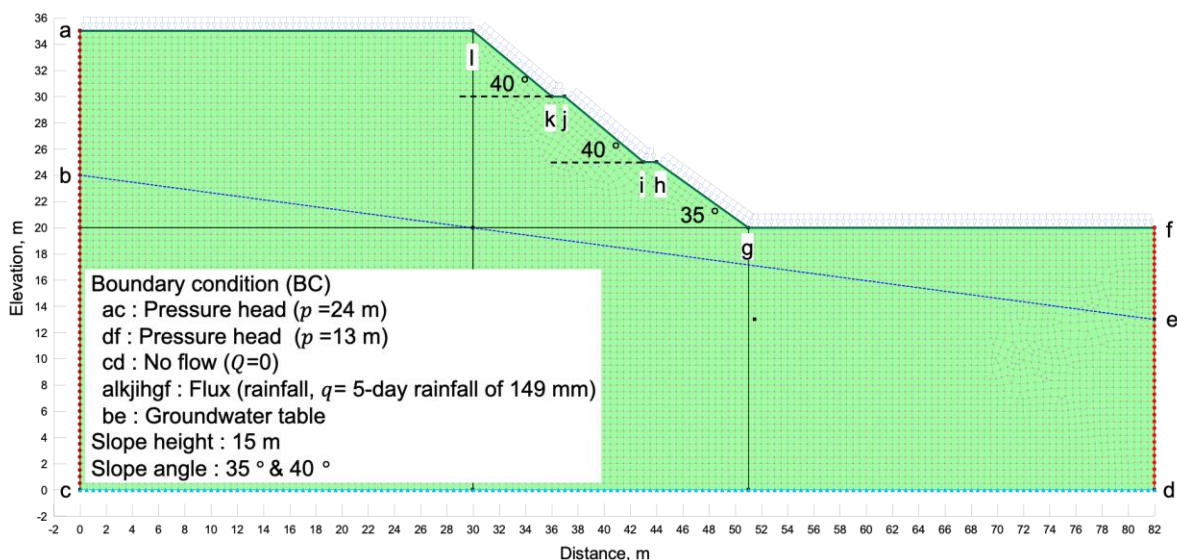
384 **Case 3: slope at Kent Ridge**

385 A slope failure was recorded within the slope National University Singapore campus (Kent
386 Ridge) on 11 January 2006. The slope is located within the residual soil from Jurong Formation.

387 The rainfall data prior to failure event were obtained from the closest rainfall station located at
 388 Ulu Pandan station. A 5-Day antecedent rainfall of 149 mm was observed prior to the failure
 389 event. The height and angle of slope at Kent Ridge are 11 m and 40°, respectively, as obtained
 390 from the DEM map. The groundwater table was located at 1.5 m below the toe of the slope.
 391 The numerical model of this slope is presented in Fig. 16.

392 The soil properties used in the seepage and stability analyses were obtained from a
 393 nearby borehole located at the commonwealth area (Rahardjo et al. 2012). The required SWCC
 394 and permeability function for the seepage analyses using SEEP/W are shown in Fig. 17. The
 395 pore-water pressure variations from the seepage analyses were exported into SLOPE/W for
 396 slope stability analyses. The shear strength parameters used in the slope stability analyses are
 397 effective cohesion (c') of 7 kPa, effective friction angle (ϕ') of 27° and ϕ^b angle of 20°. The
 398 variations in FS are presented in Fig. 18. The condition of slope prior to rainfall was considered
 399 to be safe since the initial FS was higher than 1.5. After five days of rainfall, the FS dropped
 400 to 0.98. The value of 0.98 corresponds to an unstable condition and this is supported by the fact
 401 that the slope failed on 11 January 2006.

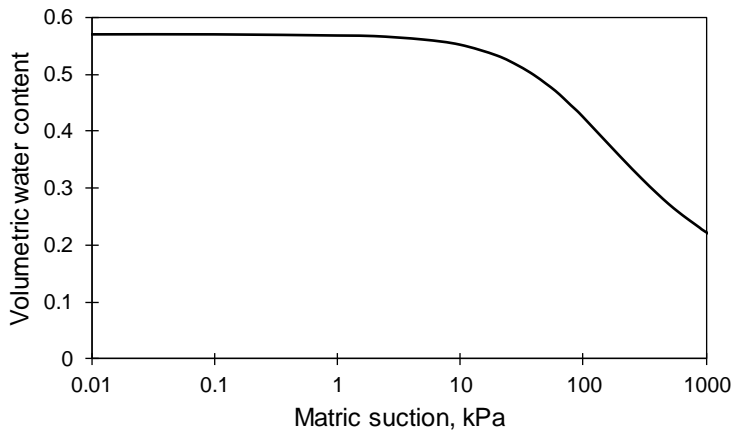
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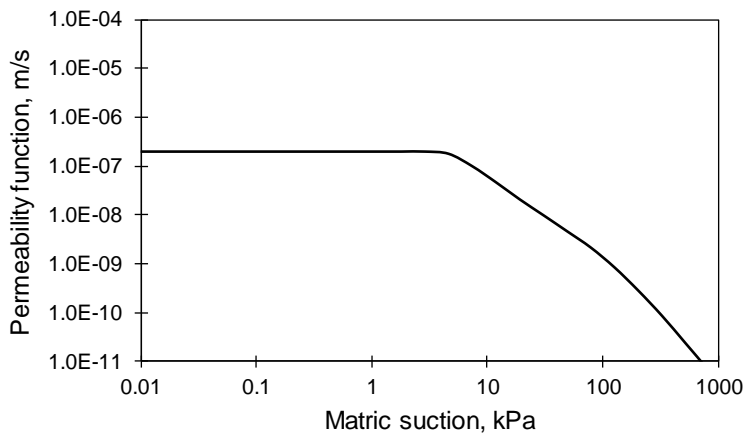
404 **Fig. 16** Numerical model used in seepage analyses of slope at Kent Ridge

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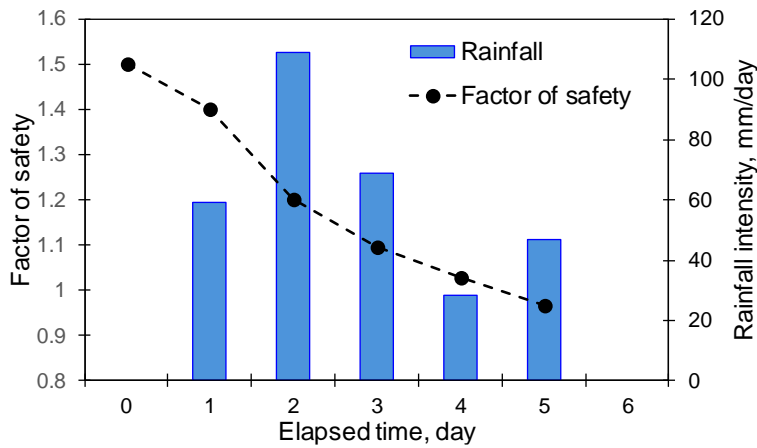
(a) Soil-water characteristic curve



408
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(b) Permeability function

410 **Fig. 17** Unsaturated hydraulic properties for seepage analyses of the slope at Kent Ridge
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413 **Fig. 18** Variation in factor of safety and corresponding rainfall for the slope at Kent Ridge
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416

417 **Conclusions**

418 The following conclusions can be made based on the assessment of rainfall scenarios for slope
419 stability analyses in Singapore.

420 Rainfall scenarios with the incorporation of antecedent rainfall (Scenarios 2 to 4)
421 affected the stability of the slope with low permeability soil by lowering the factor of safety of
422 the slope before the occurrence of the maximum daily rainfall. In other words, the antecedent
423 rainfall controlled the rate of decrease in factor of safety, particularly under 5-Day rainfall
424 scenario, resulting in the critical factor of safety of 1.0.

425 The instability of slopes was controlled by the amount of infiltrated rainwater into the
426 slope as represented by the decrease in factor of safety. Maximum daily rainfall scenarios based
427 on the historical rainfall data from 1982 to 2017 in Singapore affected the stability of the slope
428 with high permeability soil more significantly because the amount of infiltrated rainwater was
429 the highest.

430 Consequently, the slope with low permeability soil is mainly affected by 5-Day rainfall,
431 while the slope with high permeability soil is mainly affected by Maximum daily rainfall in
432 Singapore. Combined with the historical rainfall data and numerical analyses, these
433 observations give insight into instability of slopes subjected to prolonged rainfalls.

434

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438 of the project on The Development of Slope Management and Susceptibility Geographical
439 Information System.

440

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