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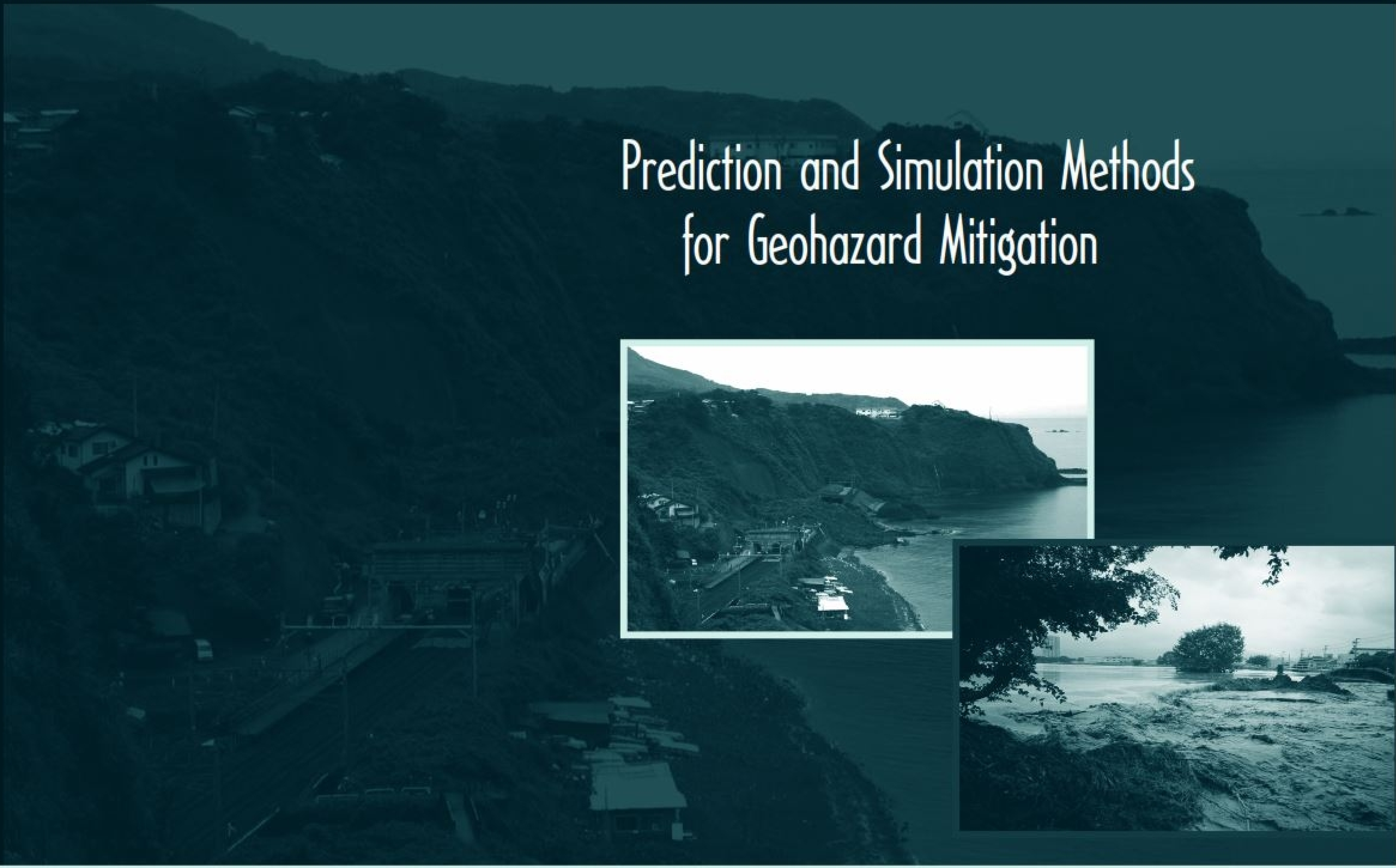

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Monitoring and non-destructive investigation methods

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Extreme rainfall for slope stability evaluation

N. Gofar, M.L. Lee & A. Kasim
Universiti Teknologi Malaysia, Johor, Malaysia

ABSTRACT: Slopes in tropical region are prone to frequent rainfall-induced failures; hence the evaluation of slope stability has to consider the rainfall characteristics and other factors related to rainfall infiltration. This paper demonstrates the results of numerical simulation using Seep/W for the evaluation of rainfall-induced slope instability at five selected sites at Johor Bahru, Malaysia. The slopes were assigned with 1-day, 2-day, 3-day, 5-day, 7-day, 14-day and 30-day extreme rainfall of ten-year return period. A suction envelope was obtained for each site and slope stability analysis was performed for the corresponding suction envelope. The results show that the reduction in factor of safety is relatively more significant for fine-grained soil. The finding was verified by field observation after the slopes were subjected to a series of intense rainfalls in December 2006. The application of extreme rainfall in slope stability analysis gives a good prediction of rainfall-induced slope failure.

1 INTRODUCTION

Slope failures in tropical region, particularly Malaysia are commonly triggered by prolonged yet intense rainfalls during monsoon seasons. The mechanism of the slope failure is as follow: the prolonged rainfall infiltration reduces matric suction of soil which in turn decreases the soil shear strength, and subsequently triggers the slope failure (Li *et al*., 2005). It is thus essential to consider the rainfall characteristics and the suction profile of the soil slope for a more comprehensive evaluation of slope stability.

Studies relating the slope stability analysis with the extreme rainfall have been reported by a few researchers. Ng & Shi (1998) carried out a numerical simulation to study the influence of rainfall infiltration on the slope stability in Hong Kong. The rainfall applied in their study was based on the 10-year return period extreme rainfalls analyzed by Lam & Leung (1994). They suggested that the critical rainfall duration between three and seven days is required to cause failure. Pradel & Raad (1993) carried out a study on the equations governing the seepage and rainfall data in Southern California. They suggested that there was a threshold permeability of soil corresponding to an extreme rainfall. By applying a 50-year return period extreme rainfall, they found that the soils with permeability greater than 10^{-4} m/s will never become saturated; hence the surficial instability will not be developed.

It can be inferred from the previous studies that several attempts have been made to integrate the extreme rainfall into the slope stability analysis. In fact, the statistical prediction of extreme rainfall has played an integral role in the flood risk estimation and flood protection management. Development of the model for extreme rainfall application to slope stability analysis was presented by Gofar & Lee (2008).

The main objectives of this paper are to demonstrate the application of extreme rainfall in the slope stability evaluation and to prove its practicability by comparing the evaluation results with the observations of actual slope condition.

2 METHODOLOGY

Five sloping sites in the region of Johor Bahru, Malaysia (Figure 1) were selected for slope stability analysis and field observation. The slopes are made of different types of soil and the inclination of the slopes varies from 21° to 40° (Figure 2).

Intensity-Duration-Frequency (IDF) curve of Johor Bahru area (Figure 3) was used for the slope stability analysis. The 1-day, 2-day, 3-day, 5-day, 7-day, 14-day and 30-day extreme rainfalls were obtained from statistical analysis carried out by Gofar & Lee (2008). The properties of the soils retrieved from the study sites were determined through a series of laboratory tests and the results are summarized in Table 1. Figures 4, 5, and 6 shows the particle size distribution (PSD), soil water characteristic curve (SWCC) and hydraulic conductivity function of the soils.

Seep/W (GEO-SLOPE International Ltd., 2004a) was used to perform transient seepage analysis for each of the study sites. Prior to the analysis, the initial condition for each site was simulated based on the field suction measurements during dry period. In general, these suctions can be approximated to the suction corresponding to residual water content (Gofar *et al.*, 2007). Subsequently, the suction profiles generated from the seepage analyses were integrated into

Table 1. Properties of soil at the selected study sites.

	Site 1	Site 2	Site 3	Site 4	Site 5
Composition					
Gravel (%)	48	21	7	1	1
Sand (%)	15	39	37	26	16
Silt (%)	20	13	40	64	63
Clay (%)	17	27	16	9	20
LL (%)	53.2	64.8	61.9	60.2	64.6
PL (%)	35.5	42.2	41.9	45.4	40.0
PI	17.7	22.6	20.0	14.8	24.6
Classification BSCS	GMH	SMH	MHS	MHS	MHS
ρ_b (kg/m^3)	1805	1833	1724	1550	1704
Natural MC (%)	24.3	29.1	35.0	42.5	27.3
Saturated Permeability (m/s)	1.23×10^{-5}	1.44×10^{-5}	3.25×10^{-8}	8.36×10^{-8}	2.22×10^{-8}
Shear Strength,					
c'(kPa)	3.3	6.3	2.6	2.1	5.7
ϕ'(°)	39.5	28.4	24.6	20.4	22.3

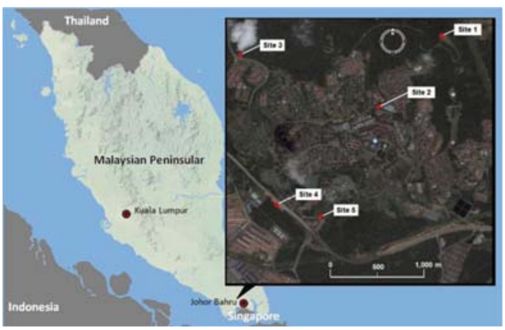

Figure 1. Locations of the selected study sites.

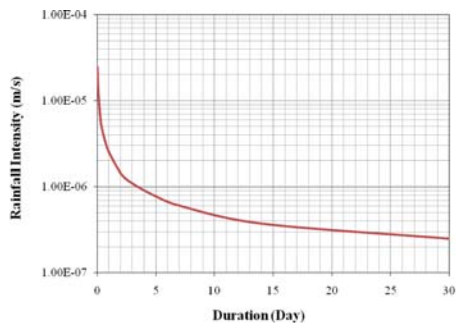

Figure 3. Intensity-Duration-Frequency (IDF) curve of Johor Bahru, Malaysia.

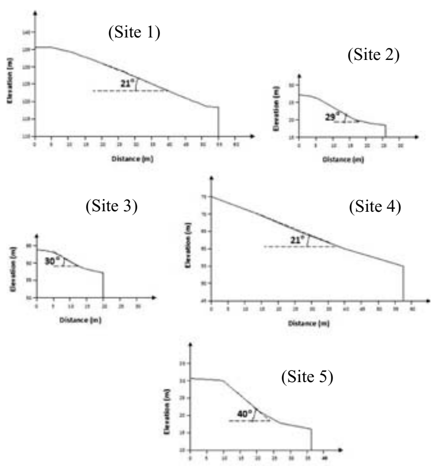

Figure 2. Geometry of the slopes.

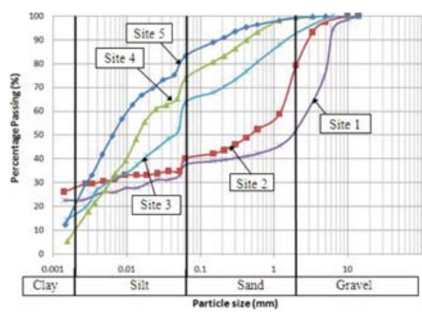

Figure 4. Particle size distribution.

Slope/W (GEO-SLOPE International Ltd., 2004b) for the slope stability analysis.

Field observation was made after the southern part of the Malaysian Peninsular experienced excessive rainfall for four continuous days in December 2006.

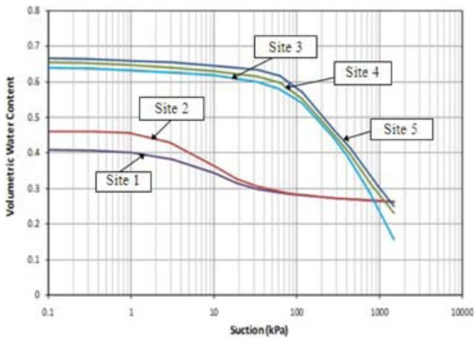

Figure 5. Soil Water Characteristic curves.

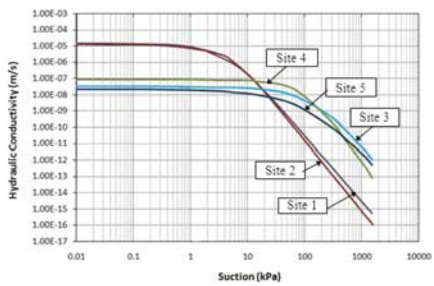

Figure 6. Hydraulic conductivity curves.

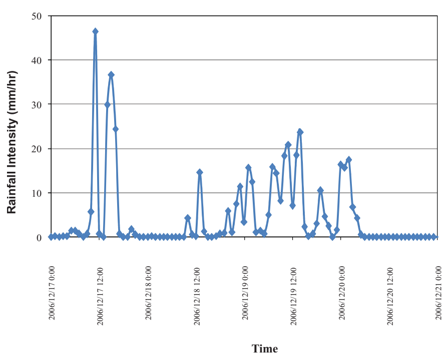

Figure 7. Hourly Rainfall Recorded at Johor Bahru from 17 to 20 December 2006.

As shown in Figure 7, the hourly rainfall measured at Johor Bahru within these four days was 450.4 mm, which was much higher than the average monthly rainfall of the Malayisan Peninsular (250.2 mm). Several slope failure incidents were reported following the rainfall events. The incident provided a unique opportunity to validate and evaluate the practicability of the model developed for slope stability analysis using extreme rainfall (Gofar & Lee, 2008).

3 RESULTS AND ANALYSIS

Figure 8 shows the suction profiles developed in soil mass at the selected sites computed by Seep/W. These suction envelopes indicate the worst suction condition that may occur in the corresponding soil slope under extreme rainfall. The figure indicates that there are two distinctive types of soil response to rainfall infiltration. Suction envelopes for Site 1 and 2 are formed by all the extreme rainfalls while the suction envelopes for Site 3, 4 and 5 were formed by the suction profile caused by the 30-day extreme rainfall only. The reason for this observation was that the slopes at Site 3, 4, and 5 consisted of fine-grained soils with the saturated permeability lower than the intensity of extreme rainfalls. Thus, the infiltration was controlled by the saturated permeability and the extreme rainfall with the longest duration would definitely result in the worst suction profile.

Figure 9 shows the factor of safety computed from the initial suction condition (dry condition) and the suction envelope (extreme rainfall condition). Apparently, the differences in the factor of safety between the two suction conditions were relatively less significant for Site 1 and 2 as compared with Site 3, 4, and 5. This was because the initial suction existed in the coarse-grained soil was considerably low (20 kPa to 30 kPa),

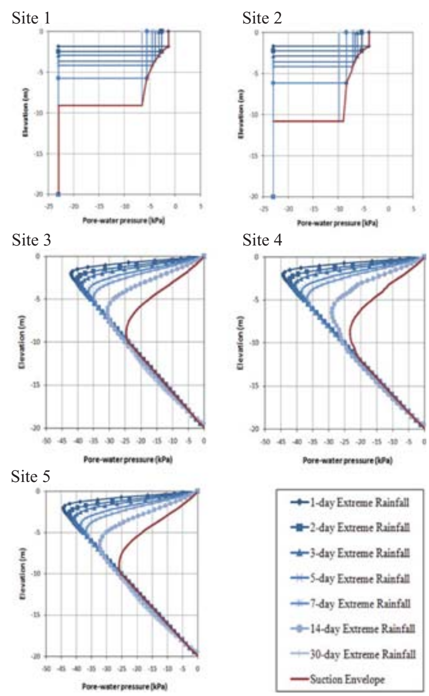

Figure 8. Suction envelopes as the result of extreme rainfalls.

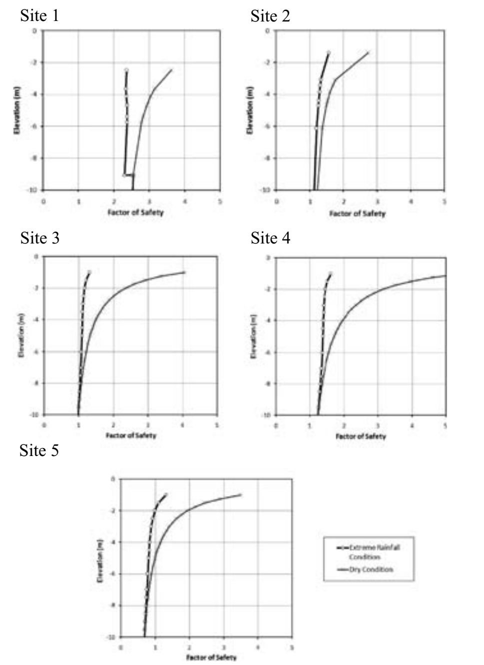

Figure 9. Factor of safety of the slopes for extreme rainfall condition and dry condition.

indicating the shear strength properties of the soil play a more crucial role than the suction towards the stability of the slope.

Conversely, greater variations in the factor of safety were observed for the slopes consisting of fine-grained soils (i.e. Site 3, 4 and 5). The huge differences between the initial suction condition (50 kPa) and the critical suction condition (0 kPa) should explain the result.

From the factor of safety chart, it can be noted that the influence of rainfall infiltration on the stability of the slope of fine-grained soil was particularly significant at shallow depth (i.e. within top 5 m). In other words, the potential failure for a slope consisting of fine-grained soil should be a shallow to intermediate-depth failure. This result contested the findings from previous studies which suggested that the failure of fine-grained soil should be comparatively deep-seated due to high cohesion.

4 DISCUSSION

The stability of a slope is governed by several parameters including slope geometry, shear strength properties and the suction profile of soil. Slope stability analysis is a way of assessing the factor of safety of the slope by assuming that the ultimate magnitudes for these parameters are known. In reality, however, these parameters are exposed to uncertainties due to the inhomogeneity of soil and slope environment.

The use of extreme rainfall in the evaluation of slope stability could minimize the uncertainties associated with the conventional slope stability analysis through a statistical approach. It is not a method to obtain the ultimate factor of safety of the slope, but to compare the relative factor of safety between dry and extreme rainfall condition. It offers an advantage of better understanding of the mechanism of rainfall-induced slope failure.

In the present study, the factors of safety for the five selected study sites were computed for both dry and extreme rainfall conditions (Figure 9). Consistencies were revealed through the comparison between the analysis results and the slope conditions observed at the actual sites (Figure 10) under extreme rainfall condition.

For Site 1 and 2, the reductions in the factor of safety as the result of extreme rainfall were relatively less significant, thus only minor surface erosions were observed at the actual slopes. On the other hand, the reductions in factor of safety as the result of extreme rainfall for Site 3, 4 and 5 were significant, particularly within top 5 m of the soil slopes. The observations at the actual slopes confirmed these findings with the failure plane of these slopes are 2 to 3 m depths. It is noted that the factor of safety obtained for Site 4 was slightly higher than one but still the slope failed. This may be due to the inconsistency of the actual shear strength of the soil with the value used in the analysis. Nonetheless, the analysis showed that

Figure 10. Slope conditions at the selected sites under prolonged intense rainfall in December 2006.

the effect of extreme rainfall on this slope is significant. In this study, the mechanism of rainfall-induced slope failure was clearly revealed through numerical analysis as well as field observation. The integration of extreme rainfall in rainfall induced slope stability analysis provides a tool to analyse the susceptibility of any slope to rainfall infiltration.

5 CONCLUSIONS

The following conclusions can be drawn from the slope stability evaluation using extreme rainfalls for five selected sloping sites in Johor Bahru, Malaysia:

1. The extreme rainfall was integrated successfully into the slope stability evaluation to serve as an alternative approach to the conventional method of slope stability analysis. The field observation proved the viability of the method.
2. Despite the fact that the ultimate factor of safety of a slope is governed by several parameters including slope geometry, shear strength properties and suction profile of soil, the use of extreme rainfall in the slope stability evaluation could compare the relative factor of safety during dry and extreme rainfall conditions, hence provides an insight to the mechanism of rainfall-induced slope failure.
3. The potential depth of failure plane can be predicted from the slope stability evaluation using extreme rainfall. In general, the potential failure plane for fine-grained soil is within 5 m depths. The effect of extreme rainfall on the stability of coarse-grained soil slope is less significant.

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