Geospatial distribution of unsaturated soil properties for slope stability assessment

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ABSTRACT: Rainfall-induced slope failures occur frequently in many tropical regions of the world. In Singapore, slope failures can often be observed in residual soils with a significant thickness of unsaturated zone above the groundwater table. The unsaturated zone is a dynamic interface of the slope with the environment. As a result, the factor of safety of residual soil slope is affected dynamically by the climate change. The coefficient of permeability and the shear strength of unsaturated soil are a function of matric suction that change significantly during rainfall. These unsaturated property changes affect stability of residual soil slope during rainfall and these changes can best be described using soil-water characteristic curve of the soil. The residual soil properties vary significantly and spatially due to the varying degrees of weathering. Therefore, it is important to understand the spatial variation of saturated and unsaturated soil properties in a particular area in order to assess the vulnerability of slopes to failure due to rainfall. In this study, geostatistical analyses were carried out to establish the geospatial distributions of soil properties of the residual soil from Bukit Timah Granite in Singapore. The geospatial distributions of soil properties were developed based on numerous data of the measured soil properties from site investigations on slopes at various locations. One failed slope was used to validate the accuracy of the developed geospatial distributions. Seepage and slope stability analyses were carried out for this validation slope using the soil properties measured from the laboratory tests of the soil obtained from the slope and the soil properties estimated from the developed geospatial distributions. The comparison results indicate that the developed geospatial distributions of saturated and unsaturated soil properties can be used to estimate factor of safety in the study zone.

1 INTRODUCTION

Residual soil is the product of the in-situ mechanical and chemical weathering of underlying rocks, which have lost their original rock fabrics (Wesley 1990). Thick layers of residual soil are commonly found in tropical regions with warm to hot climate. In Singapore, residual soils are also characterized based on rock formation and degree of weathering (Winn et al. 2001). The geology of Singapore consists essentially of three formations (see Figure 1): (i) igneous rocks of granite (Bukit Timah Granite) in the centre and northwest, (ii) sedimentary rocks (Jurong Formation) in the west, and (iii) a semi-hardened alluvium (Old Alluvium) which covers older rocks beneath in the east of Singapore (PWD 1976). Residual soils from Bukit Timah Granite are made up of mainly silt particles with some clay contents and they are usually medium to highly plastic. On the other hand, residual soils from sedimentary Jurong Formation have mainly clay contents with sands or silts and they are usually medium to highly plastic (Leong et al. 2002).

Residual soils are usually found unsaturated, since they are often observed above the ground water table where the pore-water pressures are negative (Rahardjo et al. 2013). During rainfall, water flows into the unsaturated zone, causing the pore-water pressure to increase and the shear strength of residual soil to decrease. As a result, rainfall-induced slope failures frequently happen in the tropical areas which are mainly covered with residual soils (Rahardjo et al. 2012a, Ng et al. 2003). In Singapore, 14 slope failures were observed between December 2006 and January 2007 during a heavy rainfall period (Figure 1). Majority of the slope failures occurred in the residual soil from Bukit Timah Granite. Therefore, this study focused on the site investigations of residual soils from Bukit Timah Granite.

Brand (1985) and Rahardjo et al. (2012b) observed that residual soils were difficult to test due to their heterogeneity. It is desirable to have tools to estimate soil heterogeneity in a quantitative scheme which is appropriate for engineering design. Classic statistical methods may be inadequate for interpolation of spatially dependent variables since these methods assume random variation and do not consider spatial correlation and relative locations of soil samples. Geostatistical analyses recognize these difficulties and provide tools to facilitate the geospatial distribution of residual soil properties. The main objective of this paper is to develop the geospatial distribution of the saturated and unsaturated soil properties of residual soils from Bukit Timah Granite.

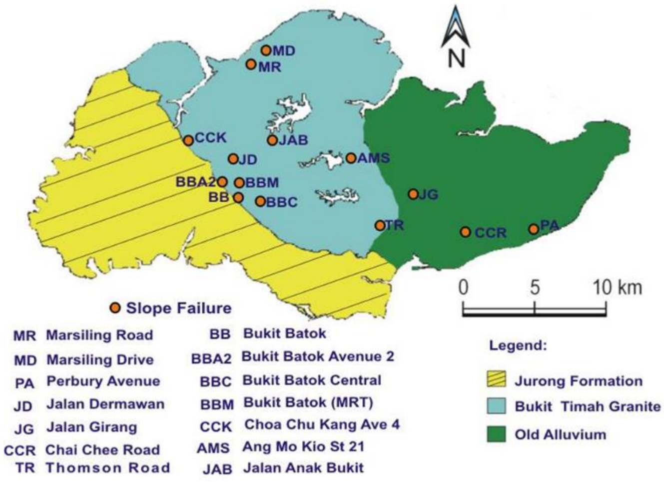


Figure 1. Slope failures in Singapore between December 2006 and January 2007 (Rahardjo et al. 2007).

2 SITE INVESTIGATION

Site investigations were conducted on 14 slopes within residual soils from Bukit Timah Granite in Singapore (Figure 2). Thirteen (13) slopes were used for the development of geospatial distributions of saturated and unsaturated soil properties whereas one (1) slope at Ang Mo Kio St 21 was used for the validation of the developed geospatial distributions.

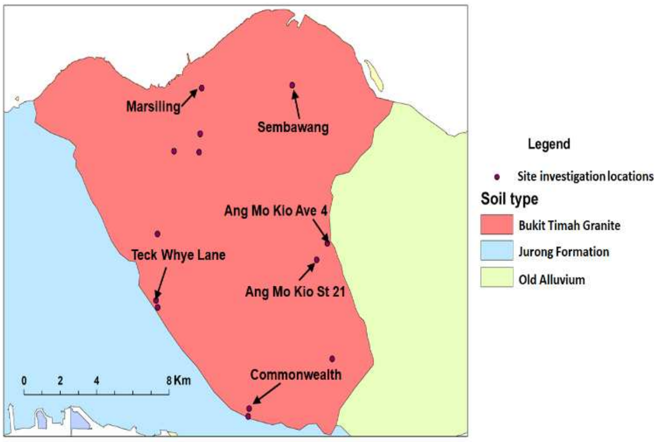


Figure 2. Location of soil sampling on slopes used in the geostatistical analyses.

Laboratory tests were performed on the undisturbed soil samples obtained from site investigations of the fourteen slopes. The laboratory tests comprised index properties tests, saturated permeability, soil-water characteristic curves (SWCC), saturated and unsaturated triaxial tests. The soil samples were classified under the Unified Soil Classification System (USCS) using the information from the index properties tests (ASTM D2487-10). The SWCC was obtained from combination of two different tests using Tempe cell and pressure plate apparatus following the procedures explained in Fredlund et al. (2012). Saturated permeability was measured using a triaxial permeameter with two back-pressure systems as described in Head (1986). Saturated shear strength parameters (i.e. effective cohesion, c' and effective friction angle, ϕ') were obtained from consolidated undrained triaxial tests with pore-water pressure measurements (ASTM D4767-04) whereas unsaturated shear strength parameter, ϕ^b, was obtained from consolidated drained triaxial tests using a modified triaxial apparatus (Fredlund and Rahardjo 1993).

3 GEOSPATIAL DISTRIBUTION OF SOIL PROPERTIES

Geostatistical analyses provide methods for processing data in digital soil mapping. The core elements of geostatistical analyses are the interpolation methods. One commonly used method is Kriging which is an interpolation method based on the distance-weighting and semivariogram function approach to find the unknown data between measured/known locations. Li and Heap (2011) observed that Ordinary Kriging is the most popular Kriging method. It is the simplest form of Kriging (e.g., no trend, no stratification etc.) since it requires only a single variable (univariate method). However, this type of Kriging is also the most robust among all types of Kriging. In this study, Ordinary Kriging was used in the development of geospatial distribution of the saturated and unsaturated properties of residual soil from Bukit Timah Granite. The geostatistical analyses were carried out using ArcGIS software (McCoy and Johnston 2002). Georeferenced map used in this study was based on a coordinate reference system.

The input for the Kriging analyses consisted of basic map of Singapore and the soil properties data which included variables of SWCC (i.e. air-entry value, AEV), saturated permeability (k_s), shear strength parameters (i.e. c', ϕ' and the angle indicating the increase in shear strength due to the increase in matric suction, ϕ^b angle). The soil properties from 13 slopes used in this study are presented in Table 1.

Table 1. Soil properties from site investigation of 13 slopes used in the geospatial analyses of this study.

Location	k_s (m/s)	AEV (kPa)	c' (kPa)	ϕ' (°)	ϕ^b (°)
Sembawang Road	5.6e-6	5	9	28	19
Ang Mo Kio Ave 4	2.5e-6	40	11	28	17
Ang Mo Kio St 52	4.7e-5	25	6	31	28
Bukit Batok East Ave 5	8.3e-7	60	12	28	17
Bukit Batok St 52	5.2e-4	4	12	33	25
Lorong Asrama	3.8e-5	30	6	30	21
Marsiling Road	1.7e-6	20	9	30	21
Stephen Lee Rd 1	2.8e-5	10	7	32	23
Stephen Lee Rd 2	9.7e-7	30	11	28	18
Teck Whye Lane	5.6e-5	19	13	27	23
Thomson Rd	3.2e-7	50	12	30	22
Yishun	2.8e-5	25	8	28	18
Commonwealth	3.9e-7	50	8	31	24

Three cases of geostatistical analyses were conducted in this study to investigate the effect of the number of site investigation locations on the accuracy of the geospatial distribution of soil properties. All cases were validated using the actual soil properties obtained from laboratory tests on soils from Ang Mo Kio St 21 (k_s = 8.5e-5 m/s, AEV = 9 kPa, c' = 5 kPa, ϕ' = 30° and ϕ^b = 18°). Case 1 corresponded to the geostatistical analyses of soil properties of 13 slopes from Table 1. Case 2 corresponded to the geostatistical analyses of soil properties of 11 slopes from Table 1 excluding 2 slopes at Commonwealth and Ang Mo Kio Ave 4. Case 3 corresponded to the geostatistical analyses of soil properties of 9 slopes from Table 1 excluding 4 slopes at Commonwealth, Ang Mo Kio Ave 4, Marsiling and Teck Whye Lane. As an example, Figure 3 presents the geospatial distribution of soil properties obtained from Case 1 based on the Ordinary Kriging analyses.

4 SEEPAGE AND SLOPE STABILITY ANALYSES FOR VALIDATION OF GEOSPATIAL DISTRIBUTION

The geospatial distributions of AEV, k_s, c', ϕ' and ϕ^b obtained from Cases 1, 2 and 3 were validated through seepage and slope stability analyses of slope at Ang Mo Kio St 21 that was used as the validation slope. Four seepage and slope stability analyses were conducted in this study using the geometry, boundary condition and groundwater table of slope at Ang Mo Kio St 21 (Figure 4). The slope height and the slope angle for the residual soil slope from Bukit Timah Granite at Ang Mo Kio St 21 were obtained from a topographical survey of the slope. Analysis V (analysis for validation) consisted of the seepage and slope stability analyses using the measured soil properties from laboratory tests of the residual soil sampled from slope at Ang Mo Kio St 21. Analyses 1, 2 and 3 consisted of the seepage and slope stability analyses using the soil properties estimated for the location at Ang Mo Kio St 21 by geospatial distributions obtained from Cases 1, 2 and 3, respectively. The measured soil properties and the estimated soil properties to be used as the input parameters for the numerical analyses of slope at Ang Mo Kio St 21 are presented in Table 2.

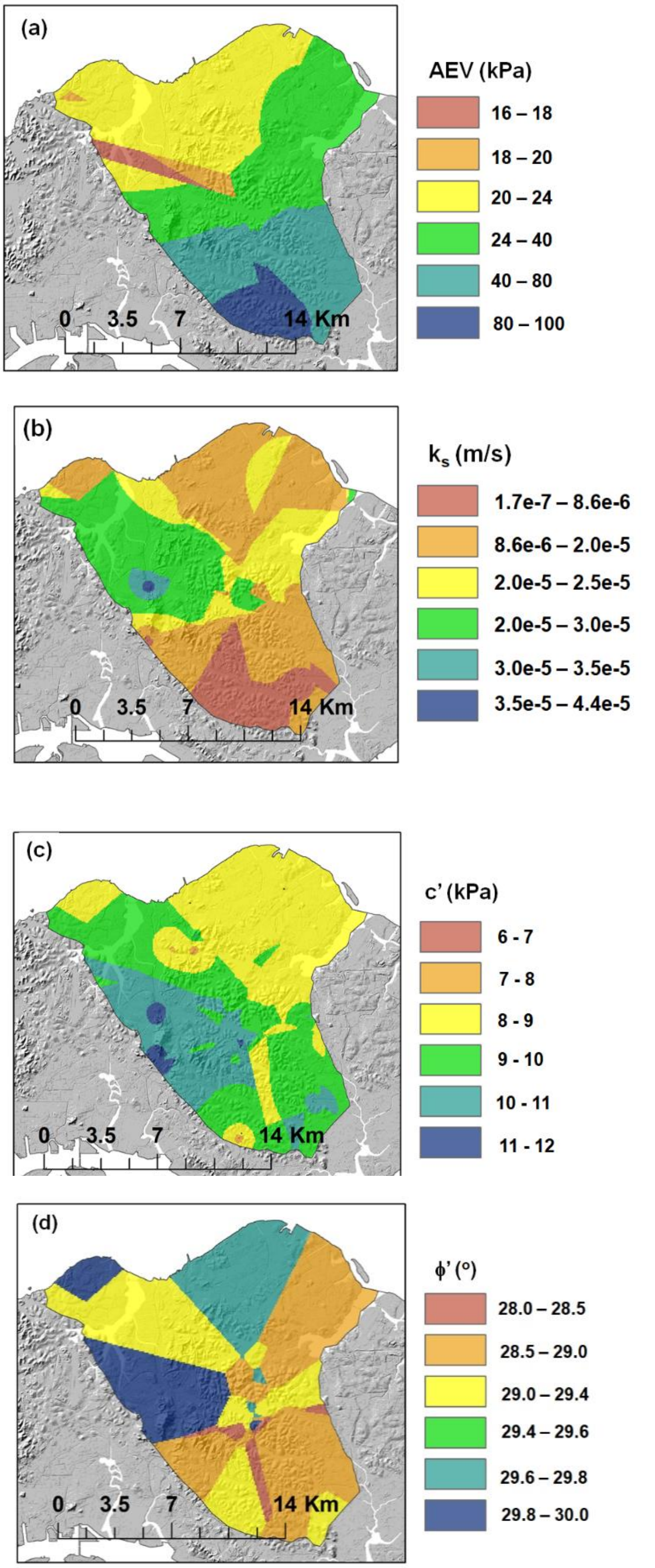
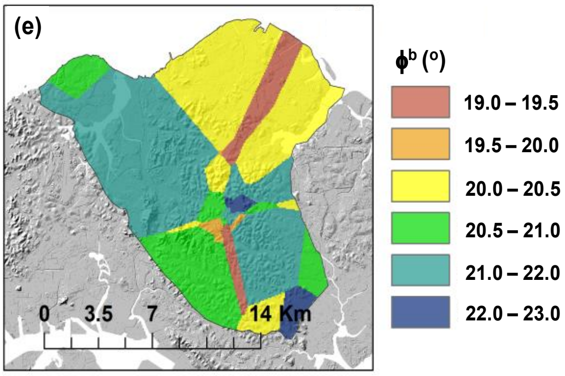


Figure 3. Geospatial distributions of (a) air-entry value, (b) saturated permeability, (c) effective cohesion; and (d) effective friction angle.



(Con't) Figure 3. Geospatial distributions of (e) ϕ^b angle.

The estimated AEV and k_s from the geospatial distribution of Case 1 were higher than the estimated values from the geospatial distributions of Cases 2 and 3. As a result, water will infiltrate faster within the slope layer in Case 1 as compared to the slope layer in Cases 2 and 3. The estimated c' from the geospatial distribution of Case 1 was higher than the estimated values from the geospatial distributions of Cases 2 and 3. The estimated effective friction angle ϕ' and ϕ^b angle were similar for all cases. Hence, the slope in analysis 1 (using shear strength from Case 1) will have higher factor of safety as compared to the slope in analyses 2 and 3 (using shear strength from Cases 2 and 3). The comparison between the measured and the estimated soil properties (Table 2) indicated that only the saturated permeability had a clear trend with respect to the number of site investigation locations used in obtaining the geospatial distribution. The estimated saturated permeability decreased with the decrease in the number of site investigation locations.

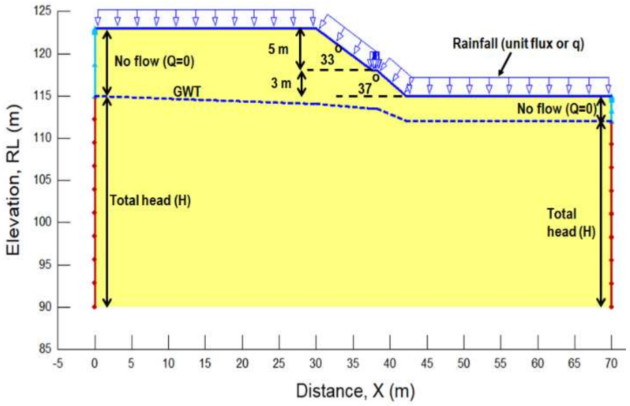


Figure 4. Numerical model of residual soil slope at Ang Mo Kio St 21.

Transient seepage analyses were carried out using finite element software, SEEP/W (Geoslope 2012a). Based on the Code of Practice of Power and Utilities Board, Singapore (PUB 2000) for drainage system design, the maximum total amount of rainfall in a day is 533.2 mm. Therefore, a rainfall intensity of 22 mm/hr for 24 hours (equivalent to a daily rainfall of 528 mm) was applied to the ground surface in all the seepage analyses. The slope has a total height of 8 m with a slope angle of 37° at the toe of the slope and 33° at the 5-m height of the upper part of the slope. The SWCCs and permeability functions generated from the statistical analyses and used in the seepage analyses are shown in Figures 5 and 6, respectively.

Table 2. Summary of soil properties used in all analyses of residual soil slope at Ang Mo Kio St 21.

	No. of site	k_s (m/s)	*AEV* (kPa)	*c'* (kPa)	ϕ' (°)	ϕ^b (°)
Analysis V (measured)	1	8.5e-5	9	5	30	18
Analysis 1 (estimated-Case 1)	13	5.2e-5	56	9.2	28.8	21.4
Analysis 2 (estimated-Case 2)	11	2.3e-5	44	7.5	28.7	23
Analysis 3 (estimated-Case 3)	9	2.4e-5	48	7.6	28.6	21

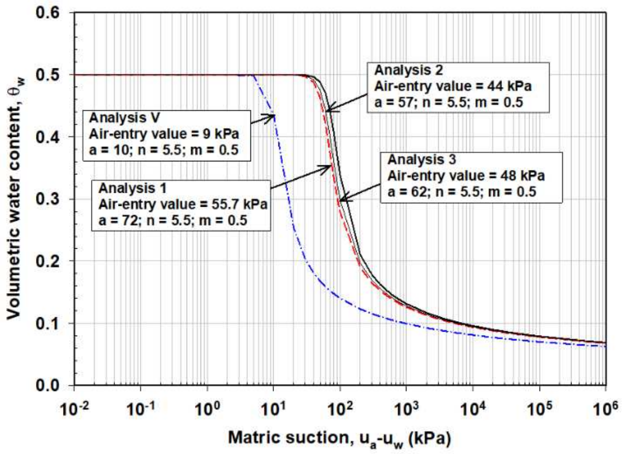


Figure 5. SWCCs used in seepage analyses of residual soil slope at Ang Mo Kio St 21.

Stability analyses were carried out using Slope/W (Geoslope 2012b) by incorporating the pore-water pressures at different time steps as obtained from the seepage Analyses V, 1, 2 and 3. The factors of safety at different time steps were calculated using Bishop's simplified method. The measured and the estimated *c'*, ϕ' and ϕ^b shown in Table 2 were used in slope stability Analyses V, 1, 2 and 3 using the same slope geometry from Ang Mo Kio St 21. The variations of factor of safety (FoS) from Analyses V, 1, 2 and 3 are shown in Figure 7. The minimum FoS obtained from slope stability Analysis V was the highest as compared to FoS from the other Analyses. This could be attributed to the lowest permeability of soil under unsaturated condition (prior to rainfall event) used in the seepage Analysis V (see Figure 6). As a result, the rainwater percolated down soil layer at a slower rate in seepage Analysis V than the rates computed in seepage Analyses 1, 2 and 3.

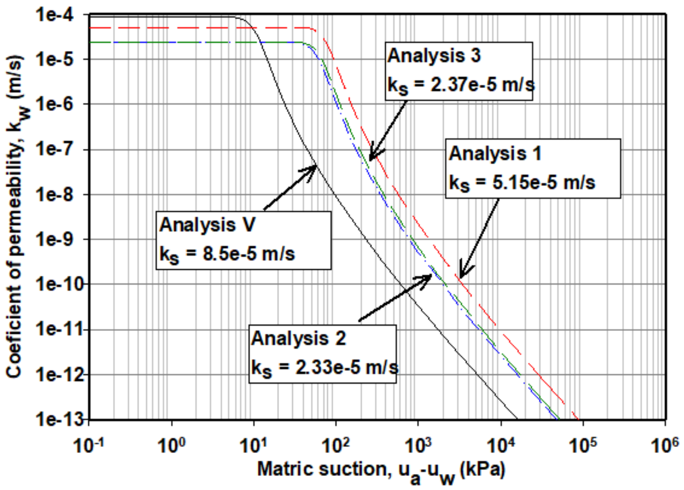


Figure 6. Permeability functions used in seepage analyses of residual soil slope at Ang Mo Kio St 21

The difference between the minimum FoS from slope stability Analyses V and 1 was minimal (around 0.1). On the other hand, the difference between the minimum FoS from Analyses V and 2 as well as the difference between the minimum FoS from Analyses V and 3 was significant (around 0.3). This indicated that the difference in the minimum FoS increased with the decrease in the number of site investigation locations used in the geostatistical analyses. On the other hand, the minimum FoS obtained from Analyses 2 and 3 were about the same. This indicated that the reduction of 2 and 4 numbers of site investigation locations used in this geostatistical analysis generated a similar geospatial distribution of soil properties. In other words, the reduction of 2 and 4 numbers of site investigation locations resulted in similar inaccuracy of the minimum factor of safety calculation.

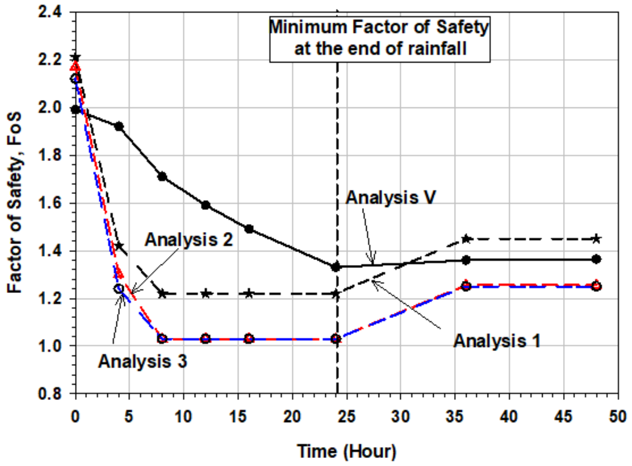


Figure 7. Factor of safety variations of residual soil slope at Ang Mo Kio.

The results of this study indicated that the larger the number of soil data used in the geospatial analyses, the higher the accuracy of the estimation of the factor of safety in the stability analysis. In this paper, the estimated factor of safety based on soil properties obtained from the geospatial analysis using 13 soil data were closer to the actual factor of safety as compared to that obtained from the geospatial analyses using 11 or 9 soil data.

5 CONCLUSION

The results of the study indicate that geospatial distributions of the appropriate number of saturated and unsaturated properties together with topographical map can be used to estimate factor of safety of slopes within the zone of study.

6 ACKNOWLEDGEMENTS

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