STABILITY OF RESIDUAL SOIL SLOPES BASED ON SPATIAL DISTRIBUTION OF SOIL PROPERTIES

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Residual soils are highly heterogeneous with highly variable properties in nature due to the spatial variation of degrees of weathering. In this study, the geostatistical method was used as a preliminary attempt to model the spatial distribution of residual soils in Singapore. The stability analyses were carried out to understand the variations of factor of safety within several zones of residual soils from three different rock formations in Singapore.

Keywords: residual soil, geostatistical method, factor of safety, spatial distribution

INTRODUCTION

Residual soils are formed by the in situ weathering of rocks (Wesley, 1990) and they can be found in large areas of the world. Residual soil slopes are commonly unsaturated since water table in the residual soil is generally quite deep (Rahardjo et al., 2004). The negative pore-water pressure or matric suction of the unsaturated soil contributes to the shear strength and overall stability of the slope (Fredlund and Rahardjo, 1993). The infiltration of rainwater into residual soil slopes causes the changes in negative pore-water pressure and consequently in the shear strength of unsaturated soil and the stability of the residual soil slope during rainfall (Rahardjo et al., 2008; Fredlund et al., 2012). The problems associated with infiltration and slope stability variation during rainfall are complex due to the highly non-linear analyses involving unsaturated soil properties (Ng et al., 2001; Rahardjo et al., 2013). In addition, the variability in degree of weathering contributes to the non-homogeneity of residual soil and the spatial distribution of its properties. As a result, the stability analyses of residual soil slopes can be quite complex. 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 spatial distribution of residual soil properties. The objective of this study is to perform geostatistical analyses for the development of soil property and factor of safety zonation map for Singapore.

METHODOLOGY

The study consisted of four stages of research works. In the first part of the study, the characteristics of residual soil properties from different locations within a selected zone were investigated through saturated and unsaturated laboratory tests. In the second part of the study, geostatistical analyses were carried out using Kriging method to estimate the spatial distribution of residual soil properties. As a result, the appropriate boundary of the selected zone could be established. In the third part of the study, stability analyses were conducted using typical saturated and unsaturated shear strength data to generate variations of factor of safety within each of the established zones. In the fourth part of the study, analytical hierarchy process was performed to determine the weight value of each factor contributing to slope stability. Thereafter, the spatial analyses were carried out to generate the preliminary slope susceptibility map of Singapore.

SOIL CHARACTERIZATION

Forty-four slopes in Singapore were selected for site investigations which are located in the residual soils from the sedimentary Jurong Formation (JF), Bukit Timah Granite (BTG) and Old Alluvium (OA) (see Fig. 1). Laboratory tests were performed on the undisturbed soil samples obtained from site investigations of the forty-four slopes. The laboratory tests comprised of 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). SWCC was obtained from combination of three different tests using Tempe cell and pressure plate following procedures explained in Fredlund et al. (2012). Saturated permeability was measured using a triaxial permeameter with two back-pressure systems as described by Head (1986). Saturated shear strength parameters (i.e. c' and 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).

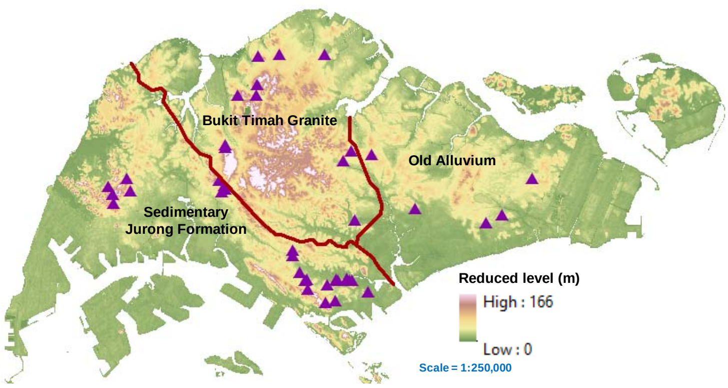


Fig. 1 Location of soil investigations in Singapore

SPATIAL DISTRIBUTION OF SOIL PROPERTIES

Geostatistical analyses were carried out using Ordinary Kriging method to create the spatial variations of soil properties (digital soil mapping) in Singapore. R software package (RStudio v0.98.1102) was used for statistical computation in this study since this software is commonly used for sophisticated spatial data analyses (Brundson and Comber, 2015; Bivand et al., 2013). Ordinary Kriging was used in the analyses since it is the simplest form of Kriging, but it is also the most robust (Li and Heap, 2014). The spatial analyses results from R software were exported into Quantum Geographical Information System (QGIS v2.10 Pisa) for data viewing and analysis. The input for the spatial analyses consisted of basic map of Singapore and the soil properties data which included variables of SWCC (i.e. air-entry value), Fredlund and Xing (1994) fitting parameter (i.e. *a*, *n* and *m*), shear strength parameters (i.e. *c'*, ϕ' and ϕ^b). Study by Zhai et al. (2016) showed that the upper and the lower bounds of the saturated permeability (k_s) and the saturated volumetric water content (θ_s) were found to be in the narrow band. Therefore, the envelopes of k_s and θ_s for the JF, BTG and OA residual soils were assigned to all zones of JF, BTG and OA, respectively in Fig 3. Georeferenced map used in this study was based on a coordinate reference system. Based on the spatial distributions of air-entry value, effective cohesion (*c'*), effective friction angle (ϕ') and ϕ^b angle, the preliminary zonation of soil properties in Singapore was established (see Fig. 3). Figs. 2a to 2c present the results of the Ordinary Kriging analyses on the shear strength parameters, *c'*, ϕ' and ϕ^b.

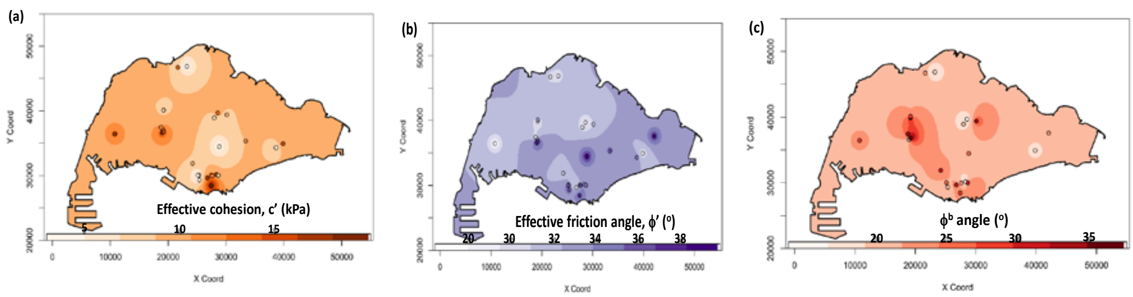
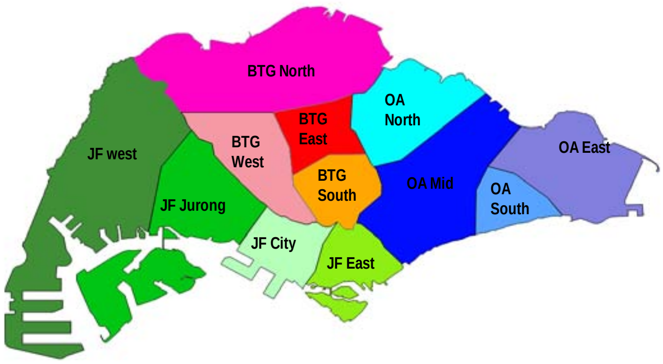


Fig. 2 Spatial distribution of (a) effective cohesion, (b) effective friction angle and (c) ϕ^b angle in Singapore



	Name		AEV [kPa]	c' [kPa]	ϕ' [°]	ϕ^b [°]
Bukit Timah Granite	BGT east		9-34	5-11	28-33	17-22
	BGT south		33-50	0-5	32-40	21-22
	BGT west		19-43	10-13	29-33	23-33
	BGTnorth		20-33	0-9	29-33	17-22
Jurong Formation	JF city		47-69	0-15	31-37	21-25
	JF east		50-67	0-14	31-35	20-25
	JF jurong		56-60	5-14	32-37	16-23
	JF west		19-110	5-13	29-33	23-27
Old Alluvium	OA east		15-33	10-14	33-39	21-22
	OA mid		33-53	7-9	32-35	21-22
	OA north		33-53	4-9	29-33	22-28
	OA south		15-30	0-4	29-34	18-21

Fig. 3 Preliminary digital soil mapping of Singapore

SLOPE STABILITY ANALYSES

Seepage analyses were conducted using Seep/W (Geoslope, 2012a) to obtain variations of pore-water pressures under dry and rainy periods for different soil zonations in Singapore. The upper and lower bounds of air-entry value as well as Fredlund and Xing (1993) fitting parameters a, n and m were used to generate upper and lower bounds of SWCC for each zonation in Fig. 3. The upper and lower bounds of saturated permeability and SWCC were used to generate the unsaturated permeability for each zonation. Then, these soil properties were incorporated in the seepage analyses under an extreme rainfall of 22 mm/h for 24 hours. Typical groundwater table position and geometry of residual soil slope in Singapore (see Fig. 4) were used in the analyses. The results from seepage analyses were exported to Slope/W (Geoslope, 2012b) for slope stability analyses. The upper and lower bounds of shear strength parameters were used in these analyses to establish the upper and lower bounds of the variations in factor of safety, respectively for different zonations in Singapore. The results from slope stability analyses of slope at BTG North are presented in Fig. 5.

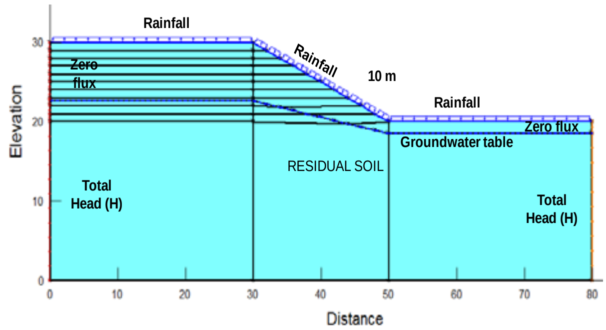


Fig. 4 Slope model for stability analyses

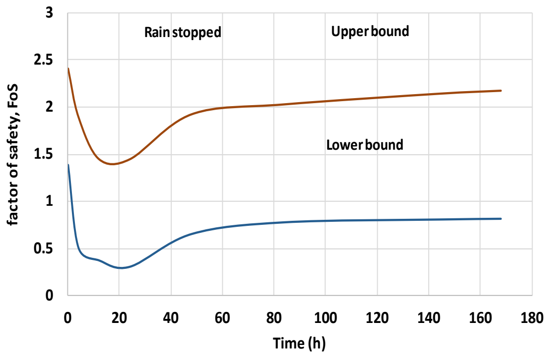


Fig 5. Upper and lower bounds of variations of factor of safety for BTG North

SLOPE SUSCEPTIBILITY MAP

The upper and the lower bounds of the initial and the minimum factor of safety as well as the differences between the initial and the minimum factor of safety were used as the main factors in the development of slope susceptibility map. The other factors were the gradient and the elevation of the slope. Analytical hierarchy process (AHP) developed by Satty (1980) was used in generating the hierarchical structure of these 8 factors. While applying AHP, factors are compared with each other to determine the relative preference of each factor in accomplishing the overall goal. Numerical values are assigned to each pair of the factors using the guidelines established in Fundamental Satty‘s Scale (Satty, 1980). The calculated weighted values were as follows: 2.4 % for slope gradient, 2.4 % for slope elevation, 7.6 % for the lower bound of the initial factor of safety, 6.8 % for the upper bound of the initial factor of safety, 87.4 % for the lower bound of the minimum factor of safety, 22.2 % for the upper bound of the minimum factor of safety, 11.8 % for the lower bound of the differences in the factor of safety and 10.8 % for the upper bound of the differences in the factor of safety. After assigning the weight values to these main factors , the cumulative weight value for each grid in the slope susceptibility map was calculated using the landslide hazard zonation model developed by Esmali (2003). Figure 6 presents the preliminary slope susceptibility map of Singapore. It shows that the majority of very high risk areas are located in the west-north location of Singapore. This result is in agreement with the locations of slope failures in Singapore which occurred during periods of heavy rainfalls in December 2006 and January 2007 by Rahardjo et al. (2007) (see Fig. 6).

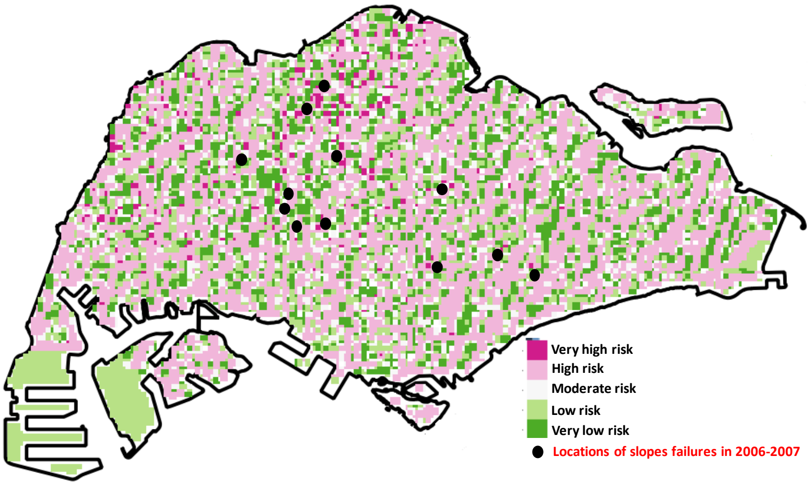


Fig. 6 Preliminary slope susceptibility map with location of previous slope failures in Singapore

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