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Spatial Variations of Air-Entry Value for Residual Soils in Singapore

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ABSTRACT:

Rainfall-induced slope failures are commonly observed in residual soil. The slopes in Singapore are associated with deep groundwater table. As a result, residual soils in Singapore are commonly observed within unsaturated condition above groundwater table. The unsaturated soil properties (i.e. soil-water characteristic curve) are rarely used as parameters in the development of slope susceptibility map. To incorporate important unsaturated soil properties, such as air-entry value (AEV), in the slope stability analysis, the sampled soil data must be transformed into a continuous field output. Geostatistical methods of **ordinary kriging** (OK) and **simple kriging** (SK) were used to estimate the spatial variability of air-entry value for soils in Singapore. The effect of soils from different geological formations in Singapore was considered in the analyses. The first case of analysis assumed Singapore as one region whereas the second case of analysis assumed Singapore as two regions – (i) Jurong Formation (JF); and (ii) Bukit Timah Granite and Old Alluvium (BTG & OA). Leave-one-out cross validation and one additional sampling point were used to assess the performance of the kriging methods and determine a suitable method for digital soil mapping. OK and SK had similar root mean square error (RMSE), of 66.6 and 66.4 respectively, for analyses with the assumption of Singapore as one region. For analyses with the assumption of Singapore as two regions, the RMSE using OK was estimated at 32.6 and 85.6 for BTG & OA and JF, respectively. SK estimated the additional sampling point with greater accuracy

and was concluded as the better kriging method to estimate the AEV distribution of soils in Singapore as compared to OK method.

Keywords: spatial distribution, residual soil, statistical analysis, air-entry value

1. INTRODUCTION

Rainfall-induced slope failure is one of the potential natural hazards in Singapore's urban terrain. Most of the slope instabilities occurred in residual soils and were caused by long and heavy rainfall events (Regmi et al., 2014; Rahardjo et al., 2012a). The risk of rainfall-slope failure occurring in Singapore is elevated by climate change. Singapore has seen a statistically significant upward trend in annual rainfall over the past 30 years, possibly caused by climate change. Studies by Kristo et al. (2017) and Strauch et al. (2017) have shown an upward trend in both the intensity and frequency of heavy rainfall events. As such, it is important that slopes at risk of failure be identified and improved to prevent failure during a rain event.

A slope susceptibility map is required to identify areas that are prone to failure during rainfall event (Shahabi et al., 2014). A slope susceptibility map relies only on the intrinsic properties of an area to describe the possibility of landslides occurring. These intrinsic properties include important factors such as rock or soil strength and steepness of slope prior to failure. Other factors commonly used include fracture spacing for rock slopes, and the presence of faults and other geologic structures. Digital soil mapping is required to characterize the properties of residual soil at different locations.

Existing literatures provide various examples of digital soil mapping used to develop slope susceptibility maps. Roslee et al. (2012) and Jibson et. al (2000) used simple kriging when developing landslide susceptibility analyses of Kinabalu, Sabah, Malaysia and Oat

Mountain quadrangle, Los Angeles, California, respectively. Simple kriging was used for analysis as it could use either semi-variograms or covariances and allowed for measurement errors (Roslee et. al, 2012). Ordinary kriging has also been used to develop landslide prediction in Baichi watershed, Taiwan and the Kuohsing and Tungshih quadrangles in Taiwan (Chiang and Chang, 2009; Lee et. al, 2008). Chiang and Chang (2009) investigated the performance of inverse distance weightage, splines and ordinary kriging to produce rainfall maps. Ordinary kriging predictions were found to be the closest to radar rainfall estimates and performed better in predicting both landslides-prone and stable areas. Lee et al. (2008) determined the results from their model to be good for hilly terrain and mountainous terrain by plotting success rate curves and determining the accuracy of their event-based deterministic model.

Residual soils in Singapore are commonly observed in unsaturated condition due to deep groundwater table (Rahardjo et al., 2010), thus unsaturated soil properties need to be examined properly to estimate the stability of slope with respect to rainfall-induced slope failure (Antinoro et al., 2017). However, unsaturated soil properties are rarely incorporated into slope susceptibility maps.

The engineering behaviour of unsaturated soil is significantly controlled by soil-water characteristic curve (SWCC) of the soil (Fredlund et al., 2012). The soil-water characteristic curve shows the relationship between volumetric water content and matric suction of the soil. Water flow in unsaturated soil causes changes in matric suction which in turn affects the permeability and shear strength of the soil. Therefore, the use of the SWCC variables, such as air-entry value to represent the permeability of soil will be of value to the development of slope susceptibility map.

Air-entry value describes the matric suction at which air begins to enter a saturated soil. The soil behaviour at matric suctions lower than AEV is similar to the saturated soil

behaviour as suggested in various studies (Vanapalli et al., 1996; Satyanaga et al., 2013). The effects of soil types on SWCC were investigated by Fredlund and Xing (1994), Rahardjo et al. (2012b) and Zhai et al. (2016). They found that the air-entry value, the slope and water content of SWCC change significantly from gravelly soil to clayey soil. In general, a soil with a lower fines content has a lower initial water content, a lower air-entry value, a lower water content at a given matric suction, a lower residual matric suction and a steeper slope of the SWCC as compared to the SWCC of a soil with a higher fines content. Soils with high air-entry value are associated with high percentages of fine contents and low permeability of soil. Therefore, it will take longer time for rainwater to infiltrate into this soil and it may cause delay failure of the soil slope with high air-entry value (Rahardjo et al., 2012b).

No studies have been carried out to investigate the spatial distribution of air-entry value in Singapore. Therefore, geostatistical analyses were performed in this study to generate the spatial distribution of the air-entry value throughout Singapore island. The analyses include geostatistical analyses using **simple kriging** and **ordinary kriging**. The air-entry value mapping was evaluated using leave-one-out cross-validation and SWCC data obtained from small-scale centrifuge and dew point chilled mirror tests. **The effects of geomorphological factors were not included in this study. Only the spatial distribution of the air-entry value obtained from direct measurements of SWCC from different locations in Singapore was considered and the air-entry values deduced from other soil properties are not part of this study.**

2. MATERIALS AND METHODS

2.1 Study area

The study is located in Singapore and focused on its main island. Singapore is situated 15m above sea level with elevations ranging from 0 to **166 m** above sea level as shown in Figure 1

(PWD,1976). In terms of geology, Singapore is covered by residual soils from three main geological formations: (a) igneous rocks consisting of the Bukit Timah granite, occupying the north and central-north region; (b) sedimentary rocks of the Jurong formation, occupying the west and southwest region; and (c) Quarternary deposit of the Old Alluvium in the eastern region.

The Bukit Timah granite is generally an igneous rock formed during the Triassic period and is found at the centre of Singapore. Weathering of Bukit Timah granite is substantial, with an average depth of weathering of 30m primarily due to chemical decomposition under Singapore's humid tropical climate (Zhao et al., 1994). The sedimentary rocks of Jurong formation can be found extensively in southern, south western and western parts of Singapore. It consists of variations of conglomerate, sandstone and shale. The semi-hardened Old Alluvium was deposited by an ancient river system, probably in the Pleistocene epoch (PWD, 1976). The study by Winn et al. (2001) indicated that the residual soil from Bukit Timah Granite has the same characteristics as the residual soil from Old Alluvium.

Figure 1. Map of Singapore and locations of the investigated residual soil slopes in Singapore

2.2 Soil sampling and laboratory analysis

The undisturbed soil samples were collected from critical slopes. The selection of critical slopes investigated in this study is related to slopes with signs of instability, i.e. cracks on the slope surface, slope deformation, bulging and water ponding on the slope surface; steep and/or high slopes; slopes located in the proximity of residential areas or public facilities. The locations of the investigated slopes are presented in Figure 1. The undisturbed soil samples were collected using a Mazier sampler from depths of 2 to 5 m. The drilling of each borehole was carried out by rotary boring with foam to obtain the high quality Mazier samples. PVC tubes were used to store the samples and to maintain the natural water content of the soil samples. All samples were extruded from PVC tube and trimmed according to the required dimension for SWCC tests.

2.3 Best Fitting Soil-water Characteristic Curve

Many mathematical models have been developed to best fit soil-water characteristic curve (SWCC). In this study, the experimental data of SWCC was best fitted using the equation from Satyanaga et al. (2013) (Equation 1) since the parameters in this equation can be used to represent variables of SWCC. This equation is commonly used for best fitting SWCC data up to 1500 kPa (Zhai et al., 2016) for residual soils in Singapore. An iterative non-linear regression procedure provided in the Microsoft Excel software (Dodge and Stinson, 2007) was used to adjust all parameters to best fit the equation to the laboratory data of SWCC.

$$\theta_w = \left[\frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \right] \left[\theta_r + \left\{ (\theta_s - \theta_r) \left[1 - (\beta) \operatorname{erfc} \left(\frac{\ln\left(\frac{\psi_a - \psi}{\psi_a - \psi_m}\right)}{s} \right) \right] \right\} \right] \quad (\text{Equation 1})$$

where β is 0 when $\psi \leq \psi_a$; β is 1 when $\psi > \psi_a$, θ_w is calculated volumetric water content, θ_s is saturated volumetric water content, ψ is matric suction under consideration (kPa), ψ_a represents the air-entry value of soil (kPa), ψ_m represents the matric suction at the inflection

point of SWCC (kPa), s represents the geometric standard deviation of SWCC, S_r is the residual water content and ψ_r is the matric suction corresponding to residual water content (kPa)

2.4 Ordinary kriging

Ordinary kriging is a form of kriging that assumes the underlying random process to be intrinsically stationary with constant mean over a local area and that variation in the regionalised variable depends only on separation in distance and direction between points and not on absolute position (Goovaerts, 1997).

The kriging estimate is a linear weighted sum of observations from the surrounding area:

$$\hat{Z}_{OK}(\mathbf{x}_0) = \sum_{i=1}^N \lambda_{OK_i} z(\mathbf{x}_i) \quad (\text{Equation 2})$$

where $\hat{Z}_{OK}(\mathbf{x}_0)$ is the estimated soil property by ordinary kriging, N is the number of observations, $z(\mathbf{x}_i)$ is the observed soil parameter, λ_{OK_i} are the weights.

The ordinary kriging weights are chosen such that the kriging variance is minimised, and the estimate is unbiased through equations 2 and 3:

$$\sum_{i=1}^N \lambda_{OK_i} \gamma(\mathbf{x}_i, \mathbf{x}_j) + \psi(\mathbf{x}_0) = \gamma(\mathbf{x}_0, \mathbf{x}_j) \text{ for all } j \quad (\text{Equation 3})$$

$$\sum_{i=1}^N \lambda_{OK_i} = 1 \quad (\text{Equation 4})$$

where $\psi(\mathbf{x}_0)$ is the Lagrange multiplier, $\gamma(\mathbf{x}_i, \mathbf{x}_j)$ is the semivariance between observation locations and $\gamma(\mathbf{x}_j, \mathbf{x}_0)$ is the semivariance between the estimation location and the observation location.

Ordinary kriging is the most common form of kriging used for various reasons. It only requires knowledge of the spatial variation (from the variogram or covariance equation) and the measurements of data points and their geographic coordinates; its assumptions are easy to satisfy and it works well in most cases even if not all assumptions hold true (Webster and Oliver, 2007). However, ordinary kriging is known to be sensitive to short-range variation, which would lead the results of the spatial analyses to have a higher root mean square error (Laslett and McBratney, 1990).

2.5 Simple kriging

Simple kriging is a form of kriging that assumes the regionalised variable can be approached with a stationary random function, meaning that the mean is constant and known over the area of interest. The simple kriging system is given as:

$$\hat{Z}_{SK}(\mathbf{x}_0) = \sum_{i=1}^N \lambda_{SK_i} z(\mathbf{x}_i) + \left\{ 1 - \sum_{i=1}^N \lambda_{SK_i} \right\} \mu \quad (\text{Equation 5})$$

where $\hat{Z}_{SK}(\mathbf{x}_0)$ is the estimated soil property by simple kriging, N is the number of observations, $z(\mathbf{x}_i)$ is the observed soil parameter, λ_{OK_i} are the simple kriging weights and μ is the global mean.

$$\sum_{i=1}^N \lambda_{SK_i} C(\mathbf{x}_i, \mathbf{x}_j) = C(\mathbf{x}_0, \mathbf{x}_j) \quad (\text{Equation 6})$$

where $C(\mathbf{x}_i, \mathbf{x}_j)$ is the covariance between observation locations and $C(\mathbf{x}_0, \mathbf{x}_j)$ is the covariance between the estimation location and the observation locations.

As simple kriging assumes stationarity, the covariance and variogram are equivalent and both can be used to describe spatial variability. Simple kriging results in lower variances compared to ordinary kriging. This is caused by having no uncertainty in the mean. However, simple

kriging can only be used in cases where the mean for the whole region of interest is known and can be assumed to be stationary. As such, it cannot be used for intrinsic only processes, and a variogram with an upper bound is necessary. Furthermore, the mean of a region is seldom known and therefore, this method is not always applicable (Webster and Oliver, 2007).

The weights in simple kriging are not constrained to sum to 1, thus the second term on the right-hand side of equation 5 is included to ensure unbiased predictions. This implies that as the weightage of the mean increases, the predicted values will tend more towards the mean. Generally, poorly sampled regions have been shown to result in larger weightage of the mean and will have predictions that are drawn towards the mean value (Boufassa and Armstrong, 1989; Remacre, 1987; Daniel and Remacre, 1984).

3. RESULTS & DISCUSSION

3.1 Laboratory analyses

Slope A located in the residual soil from Bukit Timah Granite was used to verify the results from kriging analyses (Figure 1), were investigated in this study. Laboratory analyses were carried out to determine the index properties of the soil sample. The index properties of the soil sample are summarized in Table 1 and the grain-size distribution is presented in Figure 2.

Table 1. Index properties of the investigated residual soils from Bukit Timah Granite

Properties	Values	ASTM Standard
Liquid Limit, LL (%)	41	ASTM D4318 - 17
Plastic Limit, PL (%)	23	
Plasticity Index, PI (%)	18	
Sand (%)	45	ASTM D6913
Silt (%)	16	
Clay (%)	39	
Total density, ρ (Mg/m ³)	1.87	ASTM D7263 - 09

Water content, w (%)	31	ASTM D2216 - 10
Unified Soil Classification System (USCS)	CL	ASTM D2487 - 11

The Soil-Water Characteristics Curve (SWCC) was obtained using combined methods of dew-point chilled mirror and small-scale centrifuge. Each test was carried out on 2 specimens for a total of 4 soil specimens. In this study, the small-scale centrifuge was used for measurement of SWCC from 0.6 kPa to 250 kPa while the chilled-mirror hygrometer was used for measurement of SWCC from 500 kPa to 5000 kPa. Shrinkage tests were also carried out to incorporate volume change into the SWCC and to determine the degree of saturation. Small-scale centrifuge test was carried out by applying a high gravity field to the soil specimen using a centrifuge (Khanzode et al., 2000). It is described as Method E for the measurement SWCC (ASTM D6838-02, 2008). This method yields SWCC in terms of matric suction. The specimen is subjected to a centrifugal force using a centrifuge chamber. By varying the angular velocity of the centrifuge, different matric suctions are applied to the specimen. The specimen is weighed after every spin to measure the amount of water displaced from the soil at a given angular velocity.

Figure 2. Particle size distribution curve

230 Dew point test was carried out based on the equilibration of liquid-phase water in a soil
231 specimen and vapour-phase water (relative humidity) in the surrounding air space in a sealed
232 chamber (Gee et al., 1992). It is classified as Method D for measurement of SWCC in
233 reference (ASTM D6838-02, 2008) and it is generally used to determine the SWCC
234 corresponding to high suctions and low water contents. The chilled mirror hygrometer uses
235 the dew point technique to determine the water potential of a soil specimen. The water
236 potential of the specimen is equilibrated with the water potential of the air in the headspace of
237 a sealed chamber, containing a mirror. Water Potential 4C (WP4C) was used as the chilled
238 mirror hygrometer in this study.

239 All the specimens from dew-point chilled mirror and small-scale centrifuge tests were dried
240 in an oven at 105 °C for 24 hours after testing. The dry weights were measured and recorded
241 to determine the gravimetric water content of the specimens. Degree of saturation is required
242 to obtain an accurate SWCC for determination of parameters including air-entry value,
243 inflection point, residual suction and residual water content. Shrinkage test was performed to
244 obtain the total volume of the soil specimens at various suction values. Shrinkage tests rely
245 on measuring volume change of the soil specimens as water evaporates from it. The soil
246 specimens were air dried slowly under a controlled room temperature of 25 °C and were
247 covered at various time intervals until reaching their equilibrium condition. The volumes of
248 the soil specimens were measured twice daily and directly using a Vernier Caliper. The void
249 ratios at different water contents were calculated and a plot between void ratio and
250 gravimetric water content (e versus w plot) is generated. The shrinkage curve can be best-fit
251 using the hyperbolic curve proposed by Fredlund et al. (1996).

252 The results from shrinkage test were combined with the results from dew-point method and
253 small-scale centrifuge tests to establish SWCC with respect to degree of saturation up to
254 matric suction of 5000 kPa. The experimental data of SWCC was best fitted using equation 1.

The results of SWCC tests in terms of degree of saturation are presented in Figure 3. The fitting parameters of the SWCCs are summarized in Table 2. Air-entry value of the tested soil specimens was 30 kPa.

Table 2. Fitting parameters of SWCC for Specimens 1 and 2

Fitting Parameters	
ψ_a (kpa)	30
ψ_m (kpa)	55000
s	4.00
ψ_r (kpa)	100000
S_r	0.00

Figure 3. SWCC with respect to Degree of Saturation

3.2 Geospatial analysis considering Singapore as 1 region

36 samples obtained from residual soil slopes located in three different formations in Singapore were used in the geospatial analysis of air-entry value (AEV). The air-entry values and the locations of the investigated residual soil slopes are presented in Table 3 and Figure 1, respectively. Summary statistics of the AEV data are presented in Table 4. Geostatistical analyses were carried out using simple kriging and ordinary kriging to estimate the spatial distribution of the AEV of residual soils in Singapore. Statistical computation was performed in R software environment (R Core Team, 2016) using the RStudio IDE (RStudio Team,

2016). The following packages were applied: gstat (Pebesma, 2004; Gräler et al., 2016) and sp (Pebesma and Bivand, 2005; Bivand et al., 2013). A spherical variogram model with a partial sill of 25.0, range of 8000 and nugget of 0, was used for the simple and ordinary kriging analyses, shown in Figure 4. The results from kriging analyses and the variances for simple kriging and ordinary kriging are presented in Figures 5 and 6, respectively. The points in Figures 5 and 6 indicate the locations of the investigated residual soil slopes used for the analyses.

Table 3. Air-entry values of the investigated residual soils in Singapore

No	Location	Geological Formation	Air-entry value (kPa)	Latitude (°)	Longitude (°)
1	Ang Mo Kio Ave 4	Bukit Timah Granite	70	1.3752	103.8384
2	Ang Mo Kio St 21	Bukit Timah Granite	9	1.3684	103.8331
3	Ang Mo Kio St 52	Bukit Timah Granite	60	1.3727	103.8525
4	Bukit Batok East Ave 5	Bukit Timah Granite	110	1.3490	103.7544
5	Bukit Batok St 52	Bukit Timah Granite	4	1.3518	103.7536
6	Marsiling Rd	Bukit Timah Granite	20	1.4386	103.7762
7	Thomson Rd	Bukit Timah Granite	50	1.3281	103.8409
8	Teck Whye Lane Blk 15	Bukit Timah Granite	19	1.3790	103.7543
9	Lorong_Asrama	Bukit Timah Granite	30	1.412446	103.775027
10	Yishun	Bukit Timah Granite	25	1.439824	103.821043
11	Stephen Lee Rd 1	Bukit Timah Granite	10	1.412869	103.762537
12	Stephen Lee Rd 2	Bukit Timah Granite	30	1.419956	103.77553
13	Jalan Minyak	Jurong Formation	110	1.287432	103.837405
14	Jalan Rumah Tinggi	Jurong Formation	200	1.288396	103.809189
15	Mei Ling Street	Jurong Formation	85	1.293069	103.804108
16	NTU 1	Jurong Formation	250	1.350715	103.67611
17	NTU 2	Jurong Formation	370	1.339899	103.679354
18	NTU 3	Jurong Formation	250	1.347878	103.690517
19	NTU 4	Jurong Formation	340	1.356286	103.68863
20	NTU CEE bottom	Jurong Formation	150	1.345834	103.678555
21	NTU CEE top	Jurong Formation	200	1.345731	103.678741
22	Commonwealth Crescent	Jurong Formation	200	1.3045	103.7993
23	Bukit Merah View	Jurong Formation	25	1.2845	103.8224
24	Bukit Purmei	Jurong Formation	12	1.2737	103.8282
25	Depot Rd	Jurong Formation	40	1.2815	103.8098
26	Havelock Rd	Jurong Formation	15	1.2890	103.8360
27	Jalan Bukit Ho Swee	Jurong Formation	20	1.2874	103.8298
28	Jalan Bukit Merah Blk 14	Jurong Formation	0.3	1.2878	103.8076
29	Jalan Kukoh	Jurong Formation	36	1.2877	103.8395
30	Jalan Klinik	Jurong Formation	11	1.2880	103.8287

31	Commonwealth Close	Jurong Formation	50		
32	Telok Blangah Rise	Jurong Formation	45	1.2726	103.8213
33	Bedok North St 4	Old Alluvium	15	1.3321	103.9397
34	CBS	Old Alluvium	1	1.2797	103.8499
35	Joo Seng Rd	Old Alluvium	70	1.3360	103.8816
36	Tampines St 34	Old Alluvium	15	1.3561	103.9599

Figure 4. Variogram of and Spherical model used for Singapore as 1 region

b)

Figure 5. a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using simple kriging of 36 samples

a)

b)

Figure 6. a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using ordinary kriging of 36 samples

Comparing the ordinary kriging and simple kriging variances, it can be observed that simple kriging has a smaller range of variances than ordinary kriging. The variance for OK ranges from 0.05 to 27.45, while the variance for SK ranges from 0.05 to 25.00. The variances of points clustered around the sampled points are also larger for ordinary kriging. However, this may be attributed to the fact that the global mean was assumed as the mean of the sampled datasets shown in Table 3. Therefore, the simple kriging results may not be more accurate than the ordinary kriging results.

Table 4. Summary statistics of air-entry values (kPa) of the investigated residual soils

Summary Statistics	All geological formations	Jurong Formation	Bukit Timah Granite & Old Alluvium
Mean	78.68	120.50	26.44
Minimum	0.30	0.30	1.00
Maximum	370.00	370.00	70.00
Standard deviation	98.92	116.53	19.79
Sample	36	20	16

size

3.3 Geospatial analyses considering Singapore as 2 regions

Singapore has 3 main geological formations, namely Jurong Formation, Bukit Timah Granite and Old Alluvium. The effects of the different formations were incorporated into the kriging analysis by grouping samples based on their soil formation and kriging each group separately. Bukit Timah Granite and Old Alluvium have been shown to have similar ranges of AEV (Rahardjo, 2012c). As such, the samples for Bukit Timah Granite and Old Alluvium were combined and Kriged together. Summary statistics for AEV data in Jurong Formation (JF) region; and Bukit Timah Granite and Old Alluvium region (BTG & OA) are presented in Table 4.

The 36 samples were divided into samples from (i) Jurong Formation and (ii) Bukit Timah Granite and Old Alluvium. An exponential model with a partial sill of 5.5, range of 1680 and nugget of 0.9, was used to model the JF variogram and a Gaussian model with a partial sill of 21.4, range of 10770 and nugget of 0.5, was used to model the BTG&OA variogram shown in Figure 8 and 9, respectively. Figures 10 and 11 present the results of simple kriging and ordinary kriging considering Singapore as 2 regions, respectively.

Figure 7. Variogram of and Exponential model used for Jurong Formation region

Figure 8. Variogram of and Gaussian model used for Bukit Timah Granite and Old Alluvium region

a)

b)

Figure 9. a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using simple kriging considering Singapore as 2 regions

336

a)

b)

Figure 10. (a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using **ordinary kriging** considering Singapore as 2 regions

Similar to the previous case taking Singapore as 1 region, the **simple kriging** variance is observed to have a smaller range than the variance of **ordinary kriging**. This is once again attributed to assuming the global mean to be the mean of the sampled soils. Kriging by taking Singapore as two regions has lower variance than kriging by taking Singapore as one region for both **simple and ordinary kriging**. This is especially true for the BTG&OA region where variance is generally between 0 and 3 except at the edges where extrapolation of data is required. On the other hand, the variance for this region is above 8 when taking Singapore as 1 region. As such, the Gaussian variogram model is effective in kriging the BTG&OA region.

3.4 Validation

To determine if incorporating Singapore's different soil formations improved the accuracy and precision of the kriged AEV prediction, leave-one-out cross-validation was performed on all four kriging analyses. The mean prediction error (ME), root mean square error (RMSE) and normalised root mean square error (RMNSE) are tabulated in Table 5 and their equations are presented below (Hengl, 2009, Webster & Oliver, 2007).

$$ME = \frac{1}{l} \sum_{j=1}^l [\hat{z}(x_j) - z^*(x_j)] \quad (\text{Equation 7})$$

$$RMSE = \sqrt{\frac{1}{l} \sum_{j=1}^l [\hat{z}(x_j) - z^*(x_j)]^2} \quad (\text{Equation 8})$$

$$RMNSE = \sqrt{\frac{1}{l} \sum_{j=1}^l \left[\frac{\hat{z}(x_j) - z^*(x_j)}{\hat{\sigma}_j} \right]^2} \quad (\text{Equation 9})$$

where l is the number of validation points while $\hat{z}(x_j)$, $z^*(x_j)$ and $\hat{\sigma}_j$ are the estimated values, actual observations and kriging variances respectively at the validation points. For an unbiased interpolation method, the ME should ideally be zero. The RMNSE should be small and should equal the kriging standard error for an accurate variogram. As such, the RMNSE should be equal to 1.

Kriging analyses indicated that the ME, RMSE and RMNSE of OK analyses considering Singapore as two regions are smaller than that considering Singapore as one region. On the other hand, SK analyses considering Singapore as one region are slightly better as compared to that considering Singapore as two regions. The similarity of the diagnostic statistics between the two spatial interpolation models suggests the difference in the methods, namely

the assumption of a stationary mean, does not strongly impact the accuracy of the predicted maps. On the other hand, the differences in diagnostic statistics of the analyses results from two kriging methods considering Singapore as two regions suggest a lack of a stationary mean within each region. The assumption of using a constant and known mean throughout the kriging area for SK analyses may lead to higher ME and RMNSE.

Since the three sets of data (Singapore as a whole, JF and BTG & OA) have different standard deviations, only the RMNSE can be used to compare the performance of interpolation methods between the regions. For all the regions, RMNSE was greater than 1. This suggests that the variability in the predictions is being underestimated (Robinson & Metternicht, 2006). The high RMNSE were caused by around 2-5 validation points where the mean error was at least 4 times higher than the kriging variance. These validation points were mainly locations with outlier data as compared to other nearby locations. For example, soil sample locations 3 and 5 (as shown in Table 3) in BTG which had vastly different AEV values (60 kPa vs 4 kPa) but were spatially close to each other. This suggests that the variogram model is unable to predict these outliers, leading to high errors, or there are other geological factors causing high variation of AEV in these areas.

Kriging analyses considering Singapore as 2 regions resulted in lower RMNSE as compared to that considering Singapore as 1 region. The variogram models for each region describes the spatial distribution of AEV within the region more reasonably as compared to the variogram models from the whole of Singapore. This indicated that the spatial distribution of AEV within the JF region is significantly different as compared to the spatial distribution of AEV within BTG & OA region. The RMNSE for JF region is smaller than that of BTG & OA region, which is attributed to the high variability in BTG & OA region. On the other

hand, the high variance of the JF region reduces the impact of outliers in the data such as soil sample location 28 (0.3 kPa).

Table 5. Comparison of mean error and root mean square error between different kriging and regions

Case	Kriging Method	Region	ME	RMSE	RMNSE
Singapore as 1 region	SK	-	-7.24	66.36	3.10
	OK	-	-8.56	66.58	3.10
	SK	BTG & OA	3.99	37.29	2.67
Singapore as 2 regions	SK	JF	-23.31	87.30	1.80
	OK	BTG & OA	1.21	32.57	2.61
	OK	JF	-19.65	85.63	1.79

For Singapore as a whole and the JF region, the RMSE of both OK and SK is higher than the standard deviation of the data used in the interpolation. This means that the estimation of the AEV using Kriging analyses is more accurate than that using the mean of the soil data for the entire region. However, for the BTG & OA regions, RMSE of both kriging methods performs worse as compared to estimating the whole region as having a constant AEV value of the mean of the data. This implies that the geostatistical modelling process is not capturing the spatial variation of the data, which may be caused by poor sampling. The data for BTG & OA have the smallest number of sampling locations and have multiple occurrences of nearby sampling locations having significantly different AEV values.

The comparison of the performance between the kriging methods and cases was carried out based on the estimated results of AEV from each kriging method. In addition, the experimental data of AEV was used to verify the results from kriging analyses. All the sampled datasets were obtained from depths ranging from 1 to 3 m. Thus, the AEV of the residual soils from the experimental works in this study (2-3 m depth) can be compared with the AEV of the sampled datasets. The investigated soil in this study is located at latitude and longitude of 1.303264 ° and 103.825207 ° and is represented by the square data point in Figure 1. The estimated air-entry value of the tested soils based on spatial analyses using simple kriging and ordinary kriging and kriging Singapore as 1 region and as 2 regions are

presented in Table 6. Simple kriging by taking Singapore as two region is the most effective model to estimate the AEV of the experimental soil sample out of the 4 interpolation methods used in this study since the estimated air-entry value of the investigated soil based on this method was closest to the actual air-entry value of the tested soil, 30 kPa. Kriging Singapore as one region overestimates the AEV of the experimental soil sample to more than twice the actual value. This may be due to nearby datapoints of JF with high AEV value. On the other hand, kriging Singapore as two regions performs better, likely due to the arrangement of the sampling grid being more spread out and because the effects of JF datapoints are removed.

Table 6. Estimated air-entry value of the investigated soil using Simple Kriging and Ordinary Kriging taking Singapore as 1 region and 2 regions

Predicted AEV (kPa)	Simple Kriging	Ordinary Kriging
Singapore as 1 region	69.0	68.5
Singapore as 2 regions	17.5	17.3

4. CONCLUSIONS

In this study, simple kriging and ordinary kriging were used to map the spatial variation of air-entry value in Singapore. The effects of different geological formations were explored by dividing Singapore into two regions: the Jurong Formation region; and the Bukit Timah Granite and Old Alluvium region. Validation of the kriging maps was performed through two methods: leave-one-out cross-validation and one additional sampling point from the BTG & OA region. Overall, both SK and OK gave similar RMSE values using the cross-validation method. The similar performance suggested that the difference between the kriging methods has no major impact on the accuracy of the map when kriging Singapore as a whole. When kriging the two regions separately, OK performed slightly better when comparing the

summary statistics, which suggested that within each region the assumption of a stationary mean did not hold as strongly. Kriging Singapore as 2 regions using simple kriging performed better at estimating the air-entry value of the additional sampling point.

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Spatial Variations of Air-Entry Value for Residual Soils in Singapore

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ABSTRACT:

Rainfall-induced slope failures are commonly observed in residual soil. The slopes in Singapore are associated with deep groundwater table. As a result, residual soils in Singapore are commonly observed within unsaturated condition above groundwater table. The unsaturated soil properties (i.e. soil-water characteristic curve) are rarely used as parameters in the development of slope susceptibility map. To incorporate important unsaturated soil properties, such as air-entry value (AEV), in the slope stability analysis, the sampled soil data must be transformed into a continuous field output. Geostatistical methods of ordinary kriging (OK) and simple kriging (SK) were used to estimate the spatial variability of air-entry value for soils in Singapore. The effect of soils from different geological formations in Singapore was considered in the analyses. The first case of analysis assumed Singapore as one region whereas the second case of analysis assumed Singapore as two regions – (i) Jurong Formation (JF); and (ii) Bukit Timah Granite and Old Alluvium (BTG & OA). Leave-one-out cross validation and one additional sampling point were used to assess the performance of the kriging methods and determine a suitable method for digital soil mapping. OK and SK had similar root mean square error (RMSE), of 66.6 and 66.4 respectively, for analyses with the assumption of Singapore as one region. For analyses with the assumption of Singapore as two regions, the RMSE using OK was estimated at 32.6 and 85.6 for BTG & OA and JF, respectively. SK estimated the additional sampling point with greater accuracy

and was concluded as the better kriging method to estimate the AEV distribution of soils in Singapore as compared to OK method.

Keywords: spatial distribution, residual soil, statistical analysis, air-entry value

1. INTRODUCTION

Rainfall-induced slope failure is one of the potential natural hazards in Singapore's urban terrain. Most of the slope instabilities occurred in residual soils and were caused by long and heavy rainfall events (Regmi et al., 2014; Rahardjo et al., 2012a). The risk of rainfall-slope failure occurring in Singapore is elevated by climate change. Singapore has seen a statistically significant upward trend in annual rainfall over the past 30 years, possibly caused by climate change. Studies by Kristo et al. (2017) and Strauch et al. (2017) have shown an upward trend in both the intensity and frequency of heavy rainfall events. As such, it is important that slopes at risk of failure be identified and improved to prevent failure during a rain event.

A slope susceptibility map is required to identify areas that are prone to failure during rainfall event (Shahabi et al., 2014). A slope susceptibility map relies only on the intrinsic properties of an area to describe the possibility of landslides occurring. These intrinsic properties include important factors such as rock or soil strength and steepness of slope prior to failure. Other factors commonly used include fracture spacing for rock slopes, and the presence of faults and other geologic structures. Digital soil mapping is required to characterize the properties of residual soil at different locations.

Existing literatures provide various examples of digital soil mapping used to develop slope susceptibility maps. Roslee et al. (2012) and Jibson et. al (2000) used simple kriging when developing landslide susceptibility analyses of Kinabalu, Sabah, Malaysia and Oat

Mountain quadrangle, Los Angeles, California, respectively. Simple kriging was used for analysis as it could use either semi-variograms or covariances and allowed for measurement errors (Roslee et. al, 2012). Ordinary kriging has also been used to develop landslide prediction in Baichi watershed, Taiwan and the Kuohsing and Tungshih quadrangles in Taiwan (Chiang and Chang, 2009; Lee et. al, 2008). Chiang and Chang (2009) investigated the performance of inverse distance weightage, splines and ordinary kriging to produce rainfall maps. Ordinary kriging predictions were found to be the closest to radar rainfall estimates and performed better in predicting both landslides-prone and stable areas. Lee et al. (2008) determined the results from their model to be good for hilly terrain and mountainous terrain by plotting success rate curves and determining the accuracy of their event-based deterministic model.

Residual soils in Singapore are commonly observed in unsaturated condition due to deep groundwater table (Rahardjo et al., 2010), thus unsaturated soil properties need to be examined properly to estimate the stability of slope with respect to rainfall-induced slope failure (Antinoro et al., 2017). However, unsaturated soil properties are rarely incorporated into slope susceptibility maps.

The engineering behaviour of unsaturated soil is significantly controlled by soil-water characteristic curve (SWCC) of the soil (Fredlund et al., 2012). The soil-water characteristic curve shows the relationship between volumetric water content and matric suction of the soil. Water flow in unsaturated soil causes changes in matric suction which in turn affects the permeability and shear strength of the soil. Therefore, the use of the SWCC variables, such as air-entry value to represent the permeability of soil will be of value to the development of slope susceptibility map.

Air-entry value describes the matric suction at which air begins to enter a saturated soil. The soil behaviour at matric suctions lower than AEV is similar to the saturated soil

behaviour as suggested in various studies (Vanapalli et al., 1996; Satyanaga et al., 2013). The effects of soil types on SWCC were investigated by Fredlund and Xing (1994), Rahardjo et al. (2012b) and Zhai et al. (2016). They found that the air-entry value, the slope and water content of SWCC change significantly from gravelly soil to clayey soil. In general, a soil with a lower fines content has a lower initial water content, a lower air-entry value, a lower water content at a given matric suction, a lower residual matric suction and a steeper slope of the SWCC as compared to the SWCC of a soil with a higher fines content. Soils with high air-entry value are associated with high percentages of fine contents and low permeability of soil. Therefore, it will take longer time for rainwater to infiltrate into this soil and it may cause delay failure of the soil slope with high air-entry value (Rahardjo et al., 2012b).

No studies have been carried out to investigate the spatial distribution of air-entry value in Singapore. Therefore, geostatistical analyses were performed in this study to generate the spatial distribution of the air-entry value throughout Singapore island. The analyses include geostatistical analyses using simple kriging and ordinary kriging. The air-entry value mapping was evaluated using leave-one-out cross-validation and SWCC data obtained from small-scale centrifuge and dew point chilled mirror tests. The effects of geomorphological factors were not included in this study. Only the spatial distribution of the air-entry value obtained from direct measurements of SWCC from different locations in Singapore was considered and the air-entry values deduced from other soil properties are not part of this study.

2. MATERIALS AND METHODS

2.1 Study area

The study is located in Singapore and focused on its main island. Singapore is situated 15m above sea level with elevations ranging from 0 to 166 m above sea level as shown in Figure 1

(PWD,1976). In terms of geology, Singapore is covered by residual soils from three main geological formations: (a) igneous rocks consisting of the Bukit Timah granite, occupying the north and central-north region; (b) sedimentary rocks of the Jurong formation, occupying the west and southwest region; and (c) Quarternary deposit of the Old Alluvium in the eastern region.

The Bukit Timah granite is generally an igneous rock formed during the Triassic period and is found at the centre of Singapore. Weathering of Bukit Timah granite is substantial, with an average depth of weathering of 30m primarily due to chemical decomposition under Singapore's humid tropical climate (Zhao et al., 1994). The sedimentary rocks of Jurong formation can be found extensively in southern, south western and western parts of Singapore. It consists of variations of conglomerate, sandstone and shale. The semi-hardened Old Alluvium was deposited by an ancient river system, probably in the Pleistocene epoch (PWD, 1976). The study by Winn et al. (2001) indicated that the residual soil from Bukit Timah Granite has the same characteristics as the residual soil from Old Alluvium.

Figure 1. Map of Singapore and locations of the investigated residual soil slopes in Singapore

2.2 Soil sampling and laboratory analysis

The undisturbed soil samples were collected from critical slopes. The selection of critical slopes investigated in this study is related to slopes with signs of instability, i.e. cracks on the slope surface, slope deformation, bulging and water ponding on the slope surface; steep and/or high slopes; slopes located in the proximity of residential areas or public facilities. The locations of the investigated slopes are presented in Figure 1. The undisturbed soil samples were collected using a Mazier sampler from depths of 2 to 5 m. The drilling of each borehole was carried out by rotary boring with foam to obtain the high quality Mazier samples. PVC tubes were used to store the samples and to maintain the natural water content of the soil samples. All samples were extruded from PVC tube and trimmed according to the required dimension for SWCC tests.

2.3 Best Fitting Soil-water Characteristic Curve

Many mathematical models have been developed to best fit soil-water characteristic curve (SWCC). In this study, the experimental data of SWCC was best fitted using the equation from Satyanaga et al. (2013) (Equation 1) since the parameters in this equation can be used to represent variables of SWCC. This equation is commonly used for best fitting SWCC data up to 1500 kPa (Zhai et al., 2016) for residual soils in Singapore. An iterative non-linear regression procedure provided in the Microsoft Excel software (Dodge and Stinson, 2007) was used to adjust all parameters to best fit the equation to the laboratory data of SWCC.

$$\theta_w = \left[\frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \right] \left[\theta_r + \left\{ (\theta_s - \theta_r) \left[1 - (\beta) \operatorname{erfc} \left(\frac{\ln\left(\frac{\psi_a - \psi}{\psi_a - \psi_m}\right)}{s} \right) \right] \right\} \right] \quad (\text{Equation 1})$$

where β is 0 when $\psi \leq \psi_a$; β is 1 when $\psi > \psi_a$, θ_w is calculated volumetric water content, θ_s is saturated volumetric water content, ψ is matric suction under consideration (kPa), ψ_a represents the air-entry value of soil (kPa), ψ_m represents the matric suction at the inflection

point of SWCC (kPa), s represents the geometric standard deviation of SWCC, S_r is the residual water content and ψ_r is the matric suction corresponding to residual water content (kPa)

2.4 Ordinary kriging

Ordinary kriging is a form of kriging that assumes the underlying random process to be intrinsically stationary with constant mean over a local area and that variation in the regionalised variable depends only on separation in distance and direction between points and not on absolute position (Goovaerts, 1997).

The kriging estimate is a linear weighted sum of observations from the surrounding area:

$$\hat{Z}_{OK}(\mathbf{x}_0) = \sum_{i=1}^N \lambda_{OK_i} z(\mathbf{x}_i) \quad (\text{Equation 2})$$

where $\hat{Z}_{OK}(\mathbf{x}_0)$ is the estimated soil property by ordinary kriging, N is the number of observations, $z(\mathbf{x}_i)$ is the observed soil parameter, λ_{OK_i} are the weights.

The ordinary kriging weights are chosen such that the kriging variance is minimised, and the estimate is unbiased through equations 2 and 3:

$$\sum_{i=1}^N \lambda_{OK_i} \gamma(\mathbf{x}_i, \mathbf{x}_j) + \psi(\mathbf{x}_0) = \gamma(\mathbf{x}_0, \mathbf{x}_j) \text{ for all } j \quad (\text{Equation 3})$$

$$\sum_{i=1}^N \lambda_{OK_i} = 1 \quad (\text{Equation 4})$$

where $\psi(\mathbf{x}_0)$ is the Lagrange multiplier, $\gamma(\mathbf{x}_i, \mathbf{x}_j)$ is the semivariance between observation locations and $\gamma(\mathbf{x}_j, \mathbf{x}_0)$ is the semivariance between the estimation location and the observation location.

Ordinary kriging is the most common form of kriging used for various reasons. It only requires knowledge of the spatial variation (from the variogram or covariance equation) and the measurements of data points and their geographic coordinates; its assumptions are easy to satisfy and it works well in most cases even if not all assumptions hold true (Webster and Oliver, 2007). However, ordinary kriging is known to be sensitive to short-range variation, which would lead the results of the spatial analyses to have a higher root mean square error (Laslett and McBratney, 1990).

2.5 Simple kriging

Simple kriging is a form of kriging that assumes the regionalised variable can be approached with a stationary random function, meaning that the mean is constant and known over the area of interest. The simple kriging system is given as:

$$\hat{Z}_{SK}(\mathbf{x}_0) = \sum_{i=1}^N \lambda_{SK_i} z(\mathbf{x}_i) + \left\{ 1 - \sum_{i=1}^N \lambda_{SK_i} \right\} \mu \quad (\text{Equation 5})$$

where $\hat{Z}_{SK}(\mathbf{x}_0)$ is the estimated soil property by simple kriging, N is the number of observations, $z(\mathbf{x}_i)$ is the observed soil parameter, λ_{SK_i} are the simple kriging weights and μ is the global mean.

$$\sum_{i=1}^N \lambda_{SK_i} C(\mathbf{x}_i, \mathbf{x}_j) = C(\mathbf{x}_0, \mathbf{x}_j) \quad (\text{Equation 6})$$

where $C(\mathbf{x}_i, \mathbf{x}_j)$ is the covariance between observation locations and $C(\mathbf{x}_0, \mathbf{x}_j)$ is the covariance between the estimation location and the observation locations.

As simple kriging assumes stationarity, the covariance and variogram are equivalent and both can be used to describe spatial variability. Simple kriging results in lower variances compared to ordinary kriging. This is caused by having no uncertainty in the mean. However, simple

kriging can only be used in cases where the mean for the whole region of interest is known and can be assumed to be stationary. As such, it cannot be used for intrinsic only processes, and a variogram with an upper bound is necessary. Furthermore, the mean of a region is seldom known and therefore, this method is not always applicable (Webster and Oliver, 2007).

The weights in simple kriging are not constrained to sum to 1, thus the second term on the right-hand side of equation 5 is included to ensure unbiased predictions. This implies that as the weightage of the mean increases, the predicted values will tend more towards the mean. Generally, poorly sampled regions have been shown to result in larger weightage of the mean and will have predictions that are drawn towards the mean value (Boufassa and Armstrong, 1989; Remacre, 1987; Daniel and Remacre, 1984).

3. RESULTS & DISCUSSION

3.1 Laboratory analyses

Slope A located in the residual soil from Bukit Timah Granite was used to verify the results from kriging analyses (Figure 1), were investigated in this study. Laboratory analyses were carried out to determine the index properties of the soil sample. The index properties of the soil sample are summarized in Table 1 and the grain-size distribution is presented in Figure 2.

Table 1. Index properties of the investigated residual soils from Bukit Timah Granite

Properties	Values	ASTM Standard
Liquid Limit, LL (%)	41	ASTM D4318 - 17
Plastic Limit, PL (%)	23	
Plasticity Index, PI (%)	18	
Sand (%)	45	ASTM D6913
Silt (%)	16	
Clay (%)	39	
Total density, ρ (Mg/m ³)	1.87	ASTM D7263 - 09

Water content, w (%)	31	ASTM D2216 - 10
Unified Soil Classification System (USCS)	CL	ASTM D2487 - 11

The Soil-Water Characteristics Curve (SWCC) was obtained using combined methods of dew-point chilled mirror and small-scale centrifuge. Each test was carried out on 2 specimens for a total of 4 soil specimens. In this study, the small-scale centrifuge was used for measurement of SWCC from 0.6 kPa to 250 kPa while the chilled-mirror hygrometer was used for measurement of SWCC from 500 kPa to 5000 kPa. Shrinkage tests were also carried out to incorporate volume change into the SWCC and to determine the degree of saturation. Small-scale centrifuge test was carried out by applying a high gravity field to the soil specimen using a centrifuge (Khanzode et al., 2000). It is described as Method E for the measurement SWCC (ASTM D6838-02, 2008). This method yields SWCC in terms of matric suction. The specimen is subjected to a centrifugal force using a centrifuge chamber. By varying the angular velocity of the centrifuge, different matric suctions are applied to the specimen. The specimen is weighed after every spin to measure the amount of water displaced from the soil at a given angular velocity.

Figure 2. Particle size distribution curve

230 Dew point test was carried out based on the equilibration of liquid-phase water in a soil
231 specimen and vapour-phase water (relative humidity) in the surrounding air space in a sealed
232 chamber (Gee et al., 1992). It is classified as Method D for measurement of SWCC in
233 reference (ASTM D6838-02, 2008) and it is generally used to determine the SWCC
234 corresponding to high suctions and low water contents. The chilled mirror hygrometer uses
235 the dew point technique to determine the water potential of a soil specimen. The water
236 potential of the specimen is equilibrated with the water potential of the air in the headspace of
237 a sealed chamber, containing a mirror. Water Potential 4C (WP4C) was used as the chilled
238 mirror hygrometer in this study.

239 All the specimens from dew-point chilled mirror and small-scale centrifuge tests were dried
240 in an oven at 105 °C for 24 hours after testing. The dry weights were measured and recorded
241 to determine the gravimetric water content of the specimens. Degree of saturation is required
242 to obtain an accurate SWCC for determination of parameters including air-entry value,
243 inflection point, residual suction and residual water content. Shrinkage test was performed to
244 obtain the total volume of the soil specimens at various suction values. Shrinkage tests rely
245 on measuring volume change of the soil specimens as water evaporates from it. The soil
246 specimens were air dried slowly under a controlled room temperature of 25 °C and were
247 covered at various time intervals until reaching their equilibrium condition. The volumes of
248 the soil specimens were measured twice daily and directly using a Vernier Caliper. The void
249 ratios at different water contents were calculated and a plot between void ratio and
250 gravimetric water content (e versus w plot) is generated. The shrinkage curve can be best-fit
251 using the hyperbolic curve proposed by Fredlund et al. (1996).

252 The results from shrinkage test were combined with the results from dew-point method and
253 small-scale centrifuge tests to establish SWCC with respect to degree of saturation up to
254 matric suction of 5000 kPa. The experimental data of SWCC was best fitted using equation 1.

The results of SWCC tests in terms of degree of saturation are presented in Figure 3. The fitting parameters of the SWCCs are summarized in Table 2. Air-entry value of the tested soil specimens was 30 kPa.

Table 2. Fitting parameters of SWCC for Specimens 1 and 2

Fitting Parameters	
ψ_a (kpa)	30
ψ_m (kpa)	55000
s	4.00
ψ_r (kpa)	100000
S_r	0.00

Figure 3. SWCC with respect to Degree of Saturation

3.2 Geospatial analysis considering Singapore as 1 region

36 samples obtained from residual soil slopes located in three different formations in Singapore were used in the geospatial analysis of air-entry value (AEV). The air-entry values and the locations of the investigated residual soil slopes are presented in Table 3 and Figure 1, respectively. Summary statistics of the AEV data are presented in Table 4. Geostatistical analyses were carried out using simple kriging and ordinary kriging to estimate the spatial distribution of the AEV of residual soils in Singapore. Statistical computation was performed in R software environment (R Core Team, 2016) using the RStudio IDE (RStudio Team,

2016). The following packages were applied: gstat (Pebesma, 2004; Gräler et al., 2016) and sp (Pebesma and Bivand, 2005; Bivand et al., 2013). A spherical variogram model with a partial sill of 25.0, range of 8000 and nugget of 0, was used for the simple and ordinary kriging analyses, shown in Figure 4. The results from kriging analyses and the variances for simple kriging and ordinary kriging are presented in Figures 5 and 6, respectively. The points in Figures 5 and 6 indicate the locations of the investigated residual soil slopes used for the analyses.

Table 3. Air-entry values of the investigated residual soils in Singapore

No	Location	Geological Formation	Air-entry value (kPa)	Latitude (°)	Longitude (°)
1	Ang Mo Kio Ave 4	Bukit Timah Granite	70	1.3752	103.8384
2	Ang Mo Kio St 21	Bukit Timah Granite	9	1.3684	103.8331
3	Ang Mo Kio St 52	Bukit Timah Granite	60	1.3727	103.8525
4	Bukit Batok East Ave 5	Bukit Timah Granite	110	1.3490	103.7544
5	Bukit Batok St 52	Bukit Timah Granite	4	1.3518	103.7536
6	Marsiling Rd	Bukit Timah Granite	20	1.4386	103.7762
7	Thomson Rd	Bukit Timah Granite	50	1.3281	103.8409
8	Teck Whye Lane Blk 15	Bukit Timah Granite	19	1.3790	103.7543
9	Lorong_Asrama	Bukit Timah Granite	30	1.412446	103.775027
10	Yishun	Bukit Timah Granite	25	1.439824	103.821043
11	Stephen Lee Rd 1	Bukit Timah Granite	10	1.412869	103.762537
12	Stephen Lee Rd 2	Bukit Timah Granite	30	1.419956	103.77553
13	Jalan Minyak	Jurong Formation	110	1.287432	103.837405
14	Jalan Rumah Tinggi	Jurong Formation	200	1.288396	103.809189
15	Mei Ling Street	Jurong Formation	85	1.293069	103.804108
16	NTU 1	Jurong Formation	250	1.350715	103.67611
17	NTU 2	Jurong Formation	370	1.339899	103.679354
18	NTU 3	Jurong Formation	250	1.347878	103.690517
19	NTU 4	Jurong Formation	340	1.356286	103.68863
20	NTU CEE bottom	Jurong Formation	150	1.345834	103.678555
21	NTU CEE top	Jurong Formation	200	1.345731	103.678741
22	Commonwealth Crescent	Jurong Formation	200	1.3045	103.7993
23	Bukit Merah View	Jurong Formation	25	1.2845	103.8224
24	Bukit Purmei	Jurong Formation	12	1.2737	103.8282
25	Depot Rd	Jurong Formation	40	1.2815	103.8098
26	Havelock Rd	Jurong Formation	15	1.2890	103.8360
27	Jalan Bukit Ho Swee	Jurong Formation	20	1.2874	103.8298
28	Jalan Bukit Merah Blk 14	Jurong Formation	0.3	1.2878	103.8076
29	Jalan Kukoh	Jurong Formation	36	1.2877	103.8395
30	Jalan Klinik	Jurong Formation	11	1.2880	103.8287

31	Commonwealth Close	Jurong Formation	50		
32	Telok Blangah Rise	Jurong Formation	45	1.2726	103.8213
33	Bedok North St 4	Old Alluvium	15	1.3321	103.9397
34	CBS	Old Alluvium	1	1.2797	103.8499
35	Joo Seng Rd	Old Alluvium	70	1.3360	103.8816
36	Tampines St 34	Old Alluvium	15	1.3561	103.9599

Figure 4. Variogram of and Spherical model used for Singapore as 1 region

a)

b)

Figure 5. a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using simple kriging of 36 samples

a)

b)

Figure 6. a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using ordinary kriging of 36 samples

Comparing the ordinary kriging and simple kriging variances, it can be observed that simple kriging has a smaller range of variances than ordinary kriging. The variance for OK ranges from 0.05 to 27.45, while the variance for SK ranges from 0.05 to 25.00. The variances of points clustered around the sampled points are also larger for ordinary kriging. However, this may be attributed to the fact that the global mean was assumed as the mean of the sampled datasets shown in Table 3. Therefore, the simple kriging results may not be more accurate than the ordinary kriging results.

Table 4. Summary statistics of air-entry values (kPa) of the investigated residual soils

Summary Statistics	All geological formations	Jurong Formation	Bukit Timah Granite & Old Alluvium
Mean	78.68	120.50	26.44
Minimum	0.30	0.30	1.00
Maximum	370.00	370.00	70.00
Standard deviation	98.92	116.53	19.79
Sample	36	20	16

size

3.3 Geospatial analyses considering Singapore as 2 regions

Singapore has 3 main geological formations, namely Jurong Formation, Bukit Timah Granite and Old Alluvium. The effects of the different formations were incorporated into the kriging analysis by grouping samples based on their soil formation and kriging each group separately. Bukit Timah Granite and Old Alluvium have been shown to have similar ranges of AEV (Rahardjo, 2012c). As such, the samples for Bukit Timah Granite and Old Alluvium were combined and Kriged together. Summary statistics for AEV data in Jurong Formation (JF) region; and Bukit Timah Granite and Old Alluvium region (BTG & OA) are presented in Table 4.

The 36 samples were divided into samples from (i) Jurong Formation and (ii) Bukit Timah Granite and Old Alluvium. An exponential model with a partial sill of 5.5, range of 1680 and nugget of 0.9, was used to model the JF variogram and a Gaussian model with a partial sill of 21.4, range of 10770 and nugget of 0.5, was used to model the BTG&OA variogram shown in Figure 8 and 9, respectively. Figures 10 and 11 present the results of simple kriging and ordinary kriging considering Singapore as 2 regions, respectively.

Figure 7. Variogram of and Exponential model used for Jurong Formation region

Figure 8. Variogram of and Gaussian model used for Bukit Timah Granite and Old Alluvium region

a)

b)

Figure 9. a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using simple kriging considering Singapore as 2 regions

336

a)

b)

Figure 10. (a) Spatial distribution and b) Variances of the air-entry value obtained from geospatial analyses using ordinary kriging considering Singapore as 2 regions

Similar to the previous case taking Singapore as 1 region, the simple kriging variance is observed to have a smaller range than the variance of ordinary kriging. This is once again attributed to assuming the global mean to be the mean of the sampled soils. Kriging by taking Singapore as two regions has lower variance than kriging by taking Singapore as one region for both simple and ordinary kriging. This is especially true for the BTG&OA region where variance is generally between 0 and 3 except at the edges where extrapolation of data is required. On the other hand, the variance for this region is above 8 when taking Singapore as 1 region. As such, the Gaussian variogram model is effective in kriging the BTG&OA region.

3.4 Validation

To determine if incorporating Singapore's different soil formations improved the accuracy and precision of the kriged AEV prediction, leave-one-out cross-validation was performed on all four kriging analyses. The mean prediction error (ME), root mean square error (RMSE) and normalised root mean square error (RMNSE) are tabulated in Table 5 and their equations are presented below (Hengl, 2009, Webster & Oliver, 2007).

$$ME = \frac{1}{l} \sum_{j=1}^l [\hat{z}(x_j) - z^*(x_j)] \quad (\text{Equation 7})$$

$$RMSE = \sqrt{\frac{1}{l} \sum_{j=1}^l [\hat{z}(x_j) - z^*(x_j)]^2} \quad (\text{Equation 8})$$

$$RMNSE = \sqrt{\frac{1}{l} \sum_{j=1}^l \left[\frac{\hat{z}(x_j) - z^*(x_j)}{\hat{\sigma}_j} \right]^2} \quad (\text{Equation 9})$$

where l is the number of validation points while $\hat{z}(x_j)$, $z^*(x_j)$ and $\hat{\sigma}_j$ are the estimated values, actual observations and kriging variances respectively at the validation points. For an unbiased interpolation method, the ME should ideally be zero. The RMNSE should be small and should equal the kriging standard error for an accurate variogram. As such, the RMNSE should be equal to 1.

Kriging analyses indicated that the ME, RMSE and RMNSE of OK analyses considering Singapore as two regions are smaller than that considering Singapore as one region. On the other hand, SK analyses considering Singapore as one region are slightly better as compared to that considering Singapore as two regions. The similarity of the diagnostic statistics between the two spatial interpolation models suggests the difference in the methods, namely

the assumption of a stationary mean, does not strongly impact the accuracy of the predicted maps. On the other hand, the differences in diagnostic statistics of the analyses results from two kriging methods considering Singapore as two regions suggest a lack of a stationary mean within each region. The assumption of using a constant and known mean throughout the kriging area for SK analyses may lead to higher ME and RMNSE.

Since the three sets of data (Singapore as a whole, JF and BTG & OA) have different standard deviations, only the RMNSE can be used to compare the performance of interpolation methods between the regions. For all the regions, RMNSE was greater than 1. This suggests that the variability in the predictions is being underestimated (Robinson & Metternicht, 2006). The high RMNSE were caused by around 2-5 validation points where the mean error was at least 4 times higher than the kriging variance. These validation points were mainly locations with outlier data as compared to other nearby locations. For example, soil sample locations 3 and 5 (as shown in Table 3) in BTG which had vastly different AEV values (60 kPa vs 4 kPa) but were spatially close to each other. This suggests that the variogram model is unable to predict these outliers, leading to high errors, or there are other geological factors causing high variation of AEV in these areas.

Kriging analyses considering Singapore as 2 regions resulted in lower RMNSE as compared to that considering Singapore as 1 region. The variogram models for each region describes the spatial distribution of AEV within the region more reasonably as compared to the variogram models from the whole of Singapore. This indicated that the spatial distribution of AEV within the JF region is significantly different as compared to the spatial distribution of AEV within BTG & OA region. The RMNSE for JF region is smaller than that of BTG & OA region, which is attributed to the high variability in BTG & OA region. On the other

hand, the high variance of the JF region reduces the impact of outliers in the data such as soil sample location 28 (0.3 kPa).

Table 5. Comparison of mean error and root mean square error between different kriging and regions

Case	Kriging Method	Region	ME	RMSE	RMNSE
Singapore as 1 region	SK	-	-7.24	66.36	3.10
	OK	-	-8.56	66.58	3.10
	SK	BTG & OA	3.99	37.29	2.67
Singapore as 2 regions	SK	JF	-23.31	87.30	1.80
	OK	BTG & OA	1.21	32.57	2.61
	OK	JF	-19.65	85.63	1.79

For Singapore as a whole and the JF region, the RMSE of both OK and SK is higher than the standard deviation of the data used in the interpolation. This means that the estimation of the AEV using Kriging analyses is more accurate than that using the mean of the soil data for the entire region. However, for the BTG & OA regions, RMSE of both kriging methods performs worse as compared to estimating the whole region as having a constant AEV value of the mean of the data. This implies that the geostatistical modelling process is not capturing the spatial variation of the data, which may be caused by poor sampling. The data for BTG & OA have the smallest number of sampling locations and have multiple occurrences of nearby sampling locations having significantly different AEV values.

The comparison of the performance between the kriging methods and cases was carried out based on the estimated results of AEV from each kriging method. In addition, the experimental data of AEV was used to verify the results from kriging analyses. All the sampled datasets were obtained from depths ranging from 1 to 3 m. Thus, the AEV of the residual soils from the experimental works in this study (2-3 m depth) can be compared with the AEV of the sampled datasets. The investigated soil in this study is located at latitude and longitude of 1.303264 ° and 103.825207 ° and is represented by the square data point in Figure 1. The estimated air-entry value of the tested soils based on spatial analyses using simple kriging and ordinary kriging and kriging Singapore as 1 region and as 2 regions are

presented in Table 6. Simple kriging by taking Singapore as two region is the most effective model to estimate the AEV of the experimental soil sample out of the 4 interpolation methods used in this study since the estimated air-entry value of the investigated soil based on this method was closest to the actual air-entry value of the tested soil, 30 kPa.

Kriging Singapore as one region overestimates the AEV of the experimental soil sample to more than twice the actual value. This may be due to nearby datapoints of JF with high AEV value. On the other hand, kriging Singapore as two regions performs better, likely due to the arrangement of the sampling grid being more spread out and because the effects of JF datapoints are removed.

Table 6. Estimated air-entry value of the investigated soil using Simple Kriging and Ordinary Kriging taking Singapore as 1 region and 2 regions

Predicted AEV (kPa)	Simple Kriging	Ordinary Kriging
Singapore as 1 region	69.0	68.5
Singapore as 2 regions	17.5	17.3

4. CONCLUSIONS

In this study, simple kriging and ordinary kriging were used to map the spatial variation of air-entry value in Singapore. The effects of different geological formations were explored by dividing Singapore into two regions: the Jurong Formation region; and the Bukit Timah Granite and Old Alluvium region. Validation of the kriging maps was performed through two methods: leave-one-out cross-validation and one additional sampling point from the BTG & OA region. Overall, both SK and OK gave similar RMSE values using the cross-validation method. The similar performance suggested that the difference between the kriging methods has no major impact on the accuracy of the map when kriging Singapore as a whole. When kriging the two regions separately, OK performed slightly better when comparing the

summary statistics, which suggested that within each region the assumption of a stationary mean did not hold as strongly. Kriging Singapore as 2 regions using simple kriging performed better at estimating the air-entry value of the additional sampling point.

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Highlight

- Simple Kriging (SK) and Ordinary Kriging (OK) were used in the spatial analyses
- Spatial variation of air-entry value (AEV) for Jurong Formation region
- Spatial variation of AEV for Bukit Timah Granite and Old Alluvium regions
- Cross-validation method was performed based on Root Mean Square Error
- Singapore should be considered as 2 regions in the AEV estimation using SK analysis