Influence of soil composition on compressibility of Soils and correlations among parameters

Zhang Wengang
Key Laboratory of New Technology for Construction of Cities in Mountain Area, Chongqing University, Chongqing 400045, China
2School of Civil Engineering, Chongqing University, Chongqing 400045, China
3 National Joint Engineering Research Center of Geohazards Prevention in the Reservoir Areas, Chongqing University, Chongqing 400045, China
cheungwg@126.com
Han Liang[1], Wu Chongzhi[2], Yang Changyou[3], Zhou Xiaowan[4]
School of Civil Engineering, Chongqing University, Chongqing 400045, China

Goh ATC
School of Civil & Environmental Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798

ABSTRACT: Based on a field investigation report in Bukit Timah Granite (BTG) formation in Singapore, this paper studied the influence of soil composition on compressibility and the correlations among the soil physical and mechanical parameters. Firstly, BTG residual soils are composed of four different soil types – gravel, sand, silt, and clay, and their typical contents are 0 ~ 20%, 0 ~ 65%, 5 ~ 85%, and 0 ~ 50%. Then, the results show that sand and silt content plays a greater role in the compressibility of BTG residual soils, while the effect of gravel and clay content on the compressibility is less significant. With the help of conceptual model, it is implied that the plenty of void space created by gravel leads to the increase of C_c value, while C_c will decrease as the gravel content is so great (about 5%) that the void space is filled by finer-coursed gravels. In addition, based on the concept of "sand skeleton", the effect of sand on compressibility content is explained. Lastly, a correlation matrix was established among C_c and other parameters through the Person coefficient of correlation.

Keywords: Compressibility, Residual Soils, Soil composition (type), Sand Skeleton, Correlation

1. Introduction

Soil compressibility refers to the property that the volume compression of soil becomes smaller when it is compressed, and it is generally quantified using compression index C_c which can be used for calculating the settlement of ground surface [1]. Therefore, it is necessary to explore the compressibility of soils.

This study is based on the site investigation report during the construction of Mass Rapid Transit (MRT) line in Bukit Timah Granite (BTG) Formation in Singapore. Besides, in Singapore, lots of tunnels and underground malls were built in (BTG) Formation, which occupying one third of the land area of Singapore as shown in Fig. 1. Hence, BTG residual soils, produced by the weathering process of granite, should be paid much attention to the mechanical properties such as compressibility. In addition, as the probability analysis/reliability-based method is gradually introduced into geotechnical engineering, it is practical to take soil the relationship between soil composition and C_c into consideration and investigate the spatial viability of compressibility of residual soils. For example, cross correlation among parameters is generally considered in random field stability analysis [2], and the correlation matrix is an essential part for First Order Reliability Method (FORM)-based Spreadsheet method [3].

This paper firstly presents the relationship between C_c and different soil type content in BTG residual soils, and two conceptual models were put forward to illustrate the influence mechanisms of soil composition on compressibility. Secondly, a correlation matrix among C_c and other soil physical and mechanical parameters was established via the Person coefficient of correlation. Granite residual soils widely distribute all over the world, hence it is hoped that this research can provide some references in the future actual project related to granite residual soils.

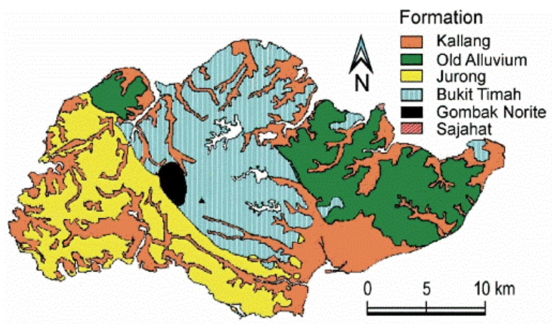


Fig. 1 Generalized geologi-cal map of Singapore (after reference [4])

2. Basic information about the database

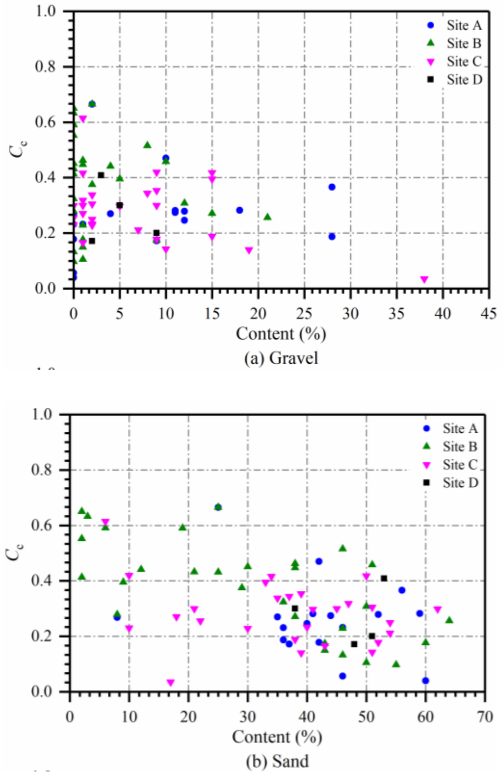
For this study, the database was extracted from a field investigation report in Singapore, and the compression index C_c was obtained by Oedometer settlement test under the ASTM standard as the Cc is the slope of the straight segment of e – log10(P) plot. This database consists of 178 data points from 106 boreholes in four different sites at the depth ranging from 0 to 25 m. To investigate the relationship between different soil type con-tent and C_c value, matching the C_c value with different soil type content at the same position in a same borehole. Besides, more characteristics of the BTG residual soils were given in the reference [5]

3. Results and Discussion

3.1. Relationship between soil type content and C_c

Previous studies have figured out that BTG residual soils is composed of four kind of soil ingredients-gravel, sand, silt, and clay [6,7]. Fig. 2 shows the variation of C_c value with different soil type contents.

As shown in Fig. 2(a), the typical gravel content in the BTG residual soil is much less than the other three, generally, typically ranging from 0 % to 20%. It can be seen that C_c value does not decrease until it reaches the peak value as gravel content is about 5%, then it decreases, as shown in Fig. 2 (a). Fig. 2 (b) shows that the typical sand content varies from 0% to 65% and there is a strong negative linear correlation rela-tionship between C_c value and sand content. From Fig. 2 (c), it is observed that the typical silt content ranges from 5 % to 85 % and there is a the strong positive linear correlation relationship between C_c value and silt content. From Fig. 2 (d), the typical clay content ranges from 0 to 50 %, and it is clear that the relationship between C_c and clay content is less salient. However, it can be still observed that there will be larger C_c value as clay content is relatively lower, as shown in Fig. 2 (d).



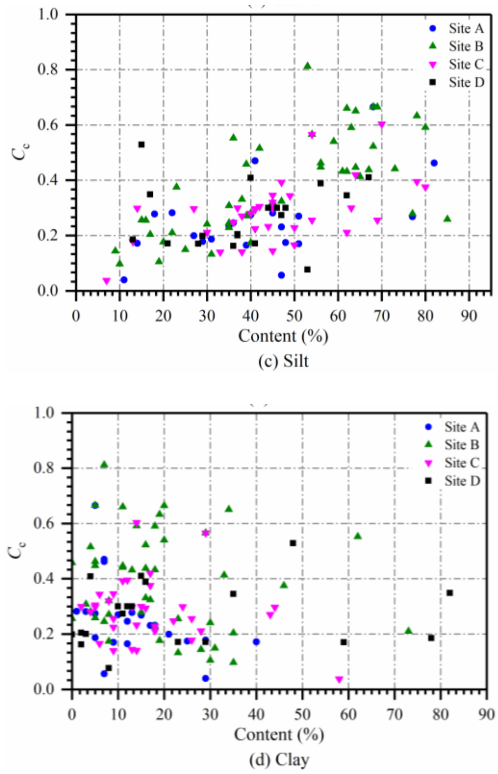


Fig. 2 Variation of Cc value with different soil type contents

3.2. Conceptual model of the effect of soil type on compressibility

Fig. 3 shows the effect of gravel content in residual soils on compressibility with a conceptual model. Fig. 3 (a) shows the soil without gravel. As gravel content increases slightly, its effect on compressibility can be neglected because of too much lower gravel content as shown in Fig. 3 (b). As the gravel content furtherly increases, more void spaces are created so that when the soil is compressed, the void space is com-pressed firstly as shown in Fig. 3 (c), which leads to that C_c value become larger than it is under lower gravel content condition. However, when the gravel content increases furtherly, the void spaces are filled by finer-coursed gravels as shown in Fig. 3 (d), leading to a decrease of C_c value.

Most of residual soils in Singapore have the degree of saturation varying from 50 % to 100 %. In term of soil skeleton, "Sand skeleton" and "void ratio of Sand skeleton" eg are applied by [8,9]. Sand skeleton refers to a soil structural pattern in which the sand particles form the main bearing structure as the loading reaches a certain level. And eg can be expressed as follows:

$$e_g = \frac{V_{other}}{V_{sand}} \tag{1}$$

where V_{sand} and V_{other} are the volume of sand and other type soils respectively in the mixed soils.

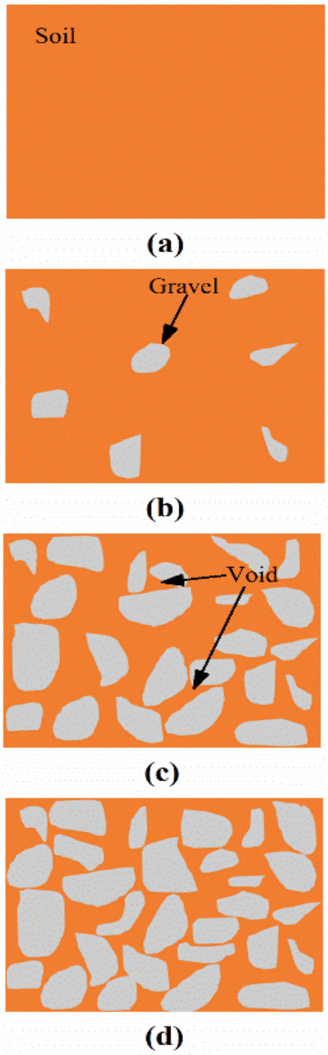
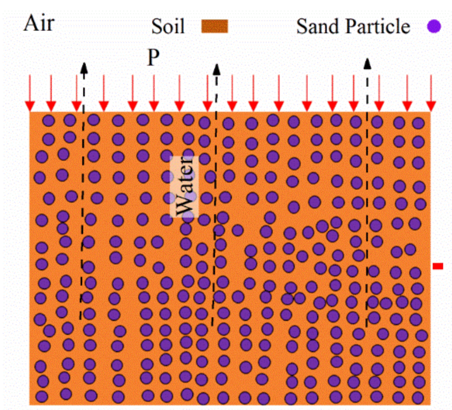
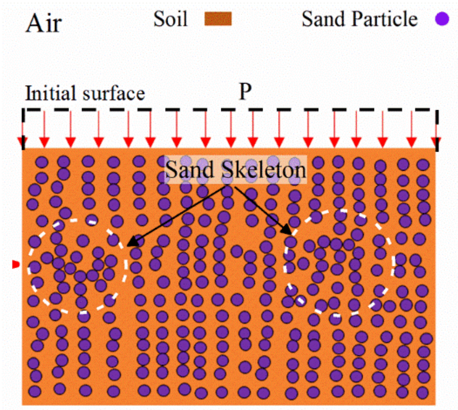


Fig. 3 Gravel content effect on compression property of soil

When the residual soil is compressed, pore water will be squeezed out and the void ratio will decrease gradually as shown in Fig. 4(a). In that case, if e_g is less than the maximum void ratio of sand e_{max}, it can be considered that the sand skeleton has formed and the stresses are mainly undertaken by the sand skeleton as shown in Fig. 4(b). According to the test result from [7,8], the compressibility of soil will be less sig-nificant due to the presence of sand skeleton, which is consistent with the result in Fig. 2 (b).



(a) Without sand skeleton



(b) Sand skeleton has formed

Fig. 1 Sand content effect on compressibility of soil

Apparently, the greater the gravel and sand content is, the smaller the silt and clay content in BTG residual soils. Therefore, the effect of silt content on compressibility can be implied by the gravel content and sand content indirectly in application. In terms of clay content, the effect mechanism may be attributed to the mineralogy. The biggest problem, however, is the absence of statistical of mineralogy in BTG soils.

4. Correlations between C_c and other soil property parameters

Ching and Phoon (2014) presented that the geotechnical literature is replete with pairwise correlations [10], which is to say that it is not realistic to assume that all soil parameters are uncorrelated. To keep notations concise, the physical random variables are denoted by Y1, Y2, …, Y13 as shown in Table 1. Hence, the next step is to evaluate the correlation between two soil parameters, Y1 and Y2, and each pairwise correlation has data points varying from 29 to 178. When evaluating the reliability index considering spatial variability, correlation matrix between physical random variables is essential as applied by Goh et al. (2019) [11]. As noted previously, compression property of soil is an important variable to calculate the ground settlement. Therefore, it is necessary to establish the correlation matrix for C_c with other physical random variables.

To eliminate the effect of units of different parameters, standard normal random variable with zero mean and unit standard deviation is applied, and it is calculated by equation (2) as following:

$$X_i = \frac{Yi - Y_i^*}{SD_{Y_i}}, \text{ i=1, 2,…, m.} \tag{2}$$

where Yi is the physical random variable of soils, Yi^* is the mean value of Yi, SD_{Yi} is the standard variation of Yi, Xi is the standard normal random variable with zero mean and unit standard deviation, m is the number of the physical random variable of soils (m=12 in this study).

When considering the correlation between two variables, there for type of correlation coefficients are applied in statistical analysis: (i) the Pearson product-moment correlation coefficient between the physical non-normal variables; (ii) the Spearman rank correlation coefficient;

(iii) the Kendall's tau rank correlation coefficient; and (iv) the Pearson product-moment correlation coefficient between the standard normal variables. According to Ching and Phoon (2014) [10], it is observed that the effect of the Spearman rank correlation coefficient and the Kendall's tau rank correlation coefficient is not significant comparing with the Pearson product-moment correlation coefficient. Hence, the Pearson product-moment correlation is applied in this study, and it is defined as:

$$\rho_{ij} = \frac{C_{ij}}{\sqrt{SD_i}\sqrt{SD_j}} \tag{3}$$

where C_{ij} is the covariance between two variables, SD_i and SD_j are the standard variations of two variables respectively, and ρ_{ij} is the Pearson correlation coefficient.

As the standard normal random variable has zero mean and unit standard deviation, C_{ij} can be simply defined as:

$$C_{ij} = \rho_{ij} \tag{4}$$

Simply, if it is assumed that m=3, the correlation matrix (***C***) of variables can be obtained by equation (4):

$$C = \begin{bmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \rho_{13}\sigma_1\sigma_3 \\ \rho_{21}\sigma_1\sigma_2 & \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 \\ \rho_{31}\sigma_1\sigma_3 & \rho_{23}\sigma_2\sigma_3 & \sigma_3^2 \end{bmatrix} = \begin{bmatrix} 1 & \rho_{12} & \rho_{13} \\ \rho_{21} & 1 & \rho_{23} \\ \rho_{31} & \rho_{23} & 1 \end{bmatrix} \tag{5}$$

Based on above analysis, the correlation between C_c and other random variables is calculated, and the correlation matrix is given as shown in Table 2. It is clear that C_c is strongly related with ω, e_0, ρ_d, sand content and silt content, and there might be strongly correlation among other physical random variables such as between ω and e_0, ω and ρ_d, e_0 and ρ_d, ρ_d and sand content, and sand content and silt content.

Table 1. Definition of physical random variables

Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
C_c	ω	*LL*	*LI*	S_0	e_0	ρ_d	Gravel content	Sand content	Silt content	Clay content	SPT *N*

Note: ω : Water content; *LL*: Liquid limit; *LI*: Liquid index; S_0: Saturatation degree; ρ_d: Dry density; SPT N: Blow count number of Standard penetration.

Table 2. Correlation matrix for C_c and other physical random variables

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
X1	1	0.673	0.331	0.465	0.236	0.708	-0.688	-0.227	-0.518	0.572	-0.105	-0.109
X2		1	0.535	0.692	0.594	0.897	-0.870	-0.073	-0.649	0.472	0.190	-0.350
X3			1	-0.117	0.383	0.443	-0.419	0.056	-0.498	0.007	0.536	-0.381
X4				1	0.408	0.613	-0.608	-0.028	-0.292	0.297	-0.090	-0.395
X5					1	0.218	-0.195	-0.257	-0.366	0.205	0.209	-0.323
X6						1	-0.983	0.001	-0.581	0.508	0.053	-0.231
X7							1	0.007	0.554	-0.498	-0.051	0.226
X8								1	0.249	-0.321	-0.436	0.126
X9									1	-0.793	-0.298	0.215
X10										1	-0.392	-0.038
X11											1	-0.373
X12												1

5. Conclusions

Based on a field investigation report, several conclusions are obtained about the relationship between compressibility and soil types in BTG residual soils in Singapore:

(1) The C_c value increases with gravel content firstly and then decreases with gravel content. When the gravel content increases to a certain level (about 5%), where plenty of void space are created, the C_c value has the maximum value.

(2) The C_c value decreases with sand content, while it increases with silt content. This phenomenon is explained by the concept of "sand skeleton".

(3)The effect of clay on compressibility of residual soils is less significant, but it is still can be seen that the C_c is relatively greater as the clay content is lower.

(4) C_c is strongly related with ω, e0, ρd, sand content and silt content, and there exists strongly correlation among other physical random variables such as between ω and e0, ω and ρd, e0 and ρd, ρd and sand content, and sand content and silt content.

Acknowledgement

This work was supported by Chongqing Construction Science and Technology Plan Project (2019-0045), Chongqing Engineering Research Center of Disaster Prevention and Control for Banks and Structures in Three Gorges Reservoir Area (SXAPGC18ZD01), and Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJZD-K201900102). The financial supports are gratefully acknowledged.

References

[1] Feng, W.Q., Yin, J. H. "Development and Verification of a New Simplified Method for Calculating Settlement of a Thick Soil Layer with Nonlinear Compressibility and Creep", International Journal of Geomechanics, 20 (3), pp. 04019184-1-13, 2020. https://doi.org/ 10.1061/(ASCE)GM.1943-5622.0001562.

[2] Cai, J. S., Yeh, T. C. J., Yan, E.C., Hao, Y. H., Huang, S. Y., Wen J.C. "Uncertainty of rainfall-induced landslides considering spatial variability of parameters", Computers and Geotechnics, 87 (2017), pp. 149-162, 2017. https://doi.org/10.1016/j.compgeo.2017.02.009

[3] Zhang, W., Goh, A.T.C., Zhang, Y. "Probabilistic Assessment of Serviceability Limit State of Diaphragm Walls for Braced Excavation in Clays", Asce-Asme Journal of Risk and Uncertainty in Engineering Systems Part a-Civil Engineering, 1 (3), pp. 06015001-7, 2015. https://doi.org/ 10.1061/AJRUA6.0000827.

[4] Rahardjo, H., Aung, K. K., Leong, E. C., Rezaur, R. B. "Characteristics of residual soils in singapore as formed by weathering", Engineering Geology 73(1), pp. 157-169, 2004. https://doi.org/ 10.1016/j.enggeo.2004.01.002.

[5] Zhang, W. G., Zhang, R. H., Han, L., Goh, A. T. C. "Engineering properties of the Bukit Timah Granitic residual soil in Singapore", Underground Space, 4(2), pp. 98-108, 2018. https://doi.org/ 10.1016/j.undsp.2018.07.001.

[6] Rahardjo, H., Satyanaga, A., Leong, E. C., Ng, Y. S., Pang, H. T. C. "Variability of residual soil properties", Engineering Geology, (2012), pp. 141-142, 2012. https://doi.org/ 10.1016/j.enggeo.2012.05.009.

[7] Ip, C. Y. S., Rahardjo, H., & Satyanaga, A. "Spatial variations of air-entry value for residual soils in Singapore", Catena 174, pp. 259-268, 2019. https://doi.org/ 10.1016/j.catena.2018.11.012.

[8] Sun, W. J.，Sun, D. A.，Meng, D. L. "Compression deformation characteristics of saturated bentonite and sand-bentonite mixtures". Rock and Soil Mechanics 30(11), pp. 3249-3255, 2009. (in Chinese) https://doi.org/10.16285/j.rsm.2009.11.029.

[9] Wu, Z. L., Zhu, X. Y., Deng, Y. F., Liu, H. S. "Compression behavior of sand-clay mixtures and formation mechanism of coarse granulesand skeleton". China Civil Engineering Journal 49(2), pp. 121-128, 2016. (in Chinese) https://doi.org/ 10.15951/j.tmgcxb.2016.02.012.

[10] Ching, JY., Phoon, KK. "Correlations among some clay parameters - the multivariate distribution", Canadian Geotechnical Journal. 51(6), pp. 686-704, 2014. doi:10.1139/cgj-2013-0353 https://doi.org/

[11] Goh, ATC., Zhang, WG., Wong, KS. "Deterministic and reliability analysis of basal heave stability for excavation in spatial variable soils", Computers and Geotechnics. 108, pp. 152-160, 2019. https://doi.org/10.1016/j.compgeo.2018.12.015.