Measuring Hydraulic Conductivity Using Geotechnical Centrifuge

Nur Aishah Zarime and Wan Zuhairi Wan Yaacob

Geology Programme, School of Environmental Sciences and Natural Resources, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

Abstract: This study investigated the validity of hydraulic conductivity value using Mini Column Infiltration Test. Granitic residual soils from Broga Selangor, Malaysia were tested to obtain the hydraulic conductivity value in relatively shorter time. Soil samples were physically characterized before being tested using Centrifuge Mini Column Infiltration Technique. A normal 1-g Falling Head Permeability Test \( K_f \) was also being performed as a comparison with hydraulic conductivity value from Centrifuge Test \( K_{cen} \). For centrifuge test \( K_{cen} \), there were three factors involved: rotation speed, soil thickness and type of solution (single or mixture solution). Hydraulic conductivity value from Centrifuge Test \( K_{cen} \) also was highly depending on the Scale Factor Value (SFV). The results from Centrifuge Test showed that the higher rotation speed, the lower SFV would be. Hydraulic conductivity was decreasing with an increasing of rotation speed. The increment of soil thickness also contributed to the decrement of SFV and hydraulic conductivity value. Thus, the hydraulic conductivity value would be more accurate when higher rotation speed and higher soil thickness were applied. Hydraulic conductivity, \( K_{cen} \) for a single solution also showed higher values compared to mixture solutions. However, some of hydraulic conductivity value \( K_{cen} \) showed overestimated values due to the presence of cracks in the soil (mudcakes). Most of the scale factors gave low values \( (x<1.00) \) which meant \( x \) values were close to unity. The value of hydraulic conductivity for 1-g Permeability Test \( K_f \) was \( 2.08 \times 10^{-6} \) m/s. While for 10mm soil thickness and 2500 RPM \( (1440 \cdot g) \) velocity of a single solution, the value of hydraulic conductivity \( K_{cen} \) was \( 6.82 \times 10^{-4} \) m/s. Since the scale factor obtained was less than 1 \( (x = 0.74) \), the value of \( K_{cen} \) could be used as a valid number to replace the value of \( K_f \) from 1-g Permeability Test. This study concluded that by using scale factor, the relationship between HCV from Centrifuge Tests and Falling Head Permeability Tests could be known; thus, Centrifuge modeling could be developed as a valid method in determining the hydraulic conductivity of the soils.

Keywords: Hydraulic Conductivity, Mini Column Infiltration Test, Granitic Residual Soil

Introduction

Centrifuge modeling has been used over the decades in many aspects to characterize the soil behaviors (Culligan, 1996). This method was chosen because of its ability to model complex natural systems in a controlled laboratory environment (Wan Zuhairi and Muchlis, 2012). By using a centrifugation, Darcy’s velocity in a Centrifuge model was tested at N times, Earth’s gravitational acceleration \( (g) \) was N times the unit discharged in the prototype provided that the soil in the model and the prototype soil had the same intrinsic permeability (Arunanand et al., 1988; Emidio et al., 2002). According to Di Emidio et al. (2012; Singh and Gupta, 2002), Centrifuge Test could also be used to estimate the hydraulic conductivity of geotechnical materials in accelerated gravity conditions, reproduce the prototype vertical effective
stresses in the soil samples and reduce the testing time. The purpose of this research was to validate hydraulic conductivity value obtained from mini column infiltration using mathematical model.

Materials and Methods

This study utilized geologic material which was granitic residual soil (BGR) taken from Broga, Selangor. This soil was air-dried and later sieved to 0.125 mm before it could be used for other analysis.

Falling Head Permeability Test

The falling head Permeability Test was conducted according to ASTM D-2434 (1984) method.

Mini Column Infiltration Test

Mini column infiltration by using a small geotechnical Centrifuge was conducted based on Antoniadis et al. (2007) method. A standard solution with 500±25 mg L⁻¹ concentration of Cadmium Nitrate; Cd(NO₃)₂ was prepared. Soil sample weighed 20g has been added with de-ionized water to make it slurry. It was left overnight before transferred to the column cell. Sample was centrifuged and sedimented soil layer called ‘mudcake’ layer. This procedure has been continued until all parts of solution passed through the ‘mudcake’ layer. This procedure has been continued until 60 pores water volume was reached. For this test, different G-forces (230-g, 520-g, 920-g and 1440-g) and soil thicknesses (10g, 15g and 20g) were applied. The effluent solutions were collected and measured using Couple Plasma Mass Spectroscopy (Perkin Elmer Model OPTIMA 3000 with auto sampler).

Relationship for Hydraulic Conductivity in Centrifuge and 1-g Permeability Test

The relationships between hydraulic conductivity for both Centrifuge Test (KCen) and 1-g Permeability Test (Kf) were shown in equation 1 and 2:

\[ \frac{K_{cen}}{K_f} = N^x \]  

(1)

where, KCen and Kf are the values of hydraulic conductivity obtained from Centrifuge Test and Falling Head Permeability Test respectively. N is an achieved acceleration level, x is the scale factor for hydraulic conductivity respects to 1-g:

\[ x = \frac{\ln K_{cen}}{\ln N} \]  

(2)

Equation 2 are derived from equation 1 in order to calculate the scale factor; x. Based on Singh and Gupta (2002), by obtaining the scale factor, the correlation between KCen and Kf could be identified.

Results and Discussion

Physical properties of the soil have been tested according to British Standard Method, BS1377 (1990) to investigate the physical characteristics of it. All the physical tests were tabulated in Table 1 and were run a prior Mini Column Infiltration Test. Granitic residual soil (BGR) had higher percentages of sand ranged between 54%-63% and according to Unified Soil Classification System (USCS), it was classified as sandy silt material. According to Zarime et al (2014), coarse-grained soils exhibited a lower heavy metal absorption tendency compared to fine-grained soil. The granitic residual soil was chosen to be tested due to its low permeability. The Atterberg limit (plasticity index), specific gravity, maximum dry density and 1-g Permeability Test also showed moderate values ranged between 9.90%-11.99%, 2.50-2.59, 1.75 g/cm³ and 2.08×10⁻⁶ respectively.

High plasticity indicates higher absorption capability (Zulfihami et al., 2011). Moderate value of specific gravity (2.50-2.59) shows granitic residual soil to have a moderate particle size (Chalermprayanat et al., 2009).

Table 2 shows the hydraulic conductivity values and scaling factors in a Mini Geotechnical Centrifuge. The results showed that the hydraulic conductivity (Kcen) was highly depended on the SFV. For 10mm soil thickness in 500ppm mixture solution, increased rotation speed from 1000 RPM to 2500 RPM, showed the decreased of scale factors; x = 1.07 (1000 RPM), x = 0.94 (1500 RPM), x = 0.71 (2000 RPM) and; x = 0.63 (2500 RPM). Hydraulic conductivity of the soil also decreased with the increasing of rotation speed. The reason of this behaviour was due to the decreased of the soil’s void ratio (Di Emidio et al., 2012). According to Poulos (1988), the increased of the rotation speed in the centrifuge would increase the driving force applied on the samples, thus the void ratio would decrease. Therefore, when the rotation speed increased, hydraulic conductivity of the samples would be decreased.

Table 1. Physical properties of granitic residual soil

| Physical characteristics | BGR       |
|--------------------------|-----------|
| Particle size distribution |          |
| Sand (%)                 | 54-63     |
| Silt (%)                 | 32-42     |
| Clay (%)                 | 1-6       |
| Atterberg limit          |           |
| Plastic limit (%)        | 38.01-38.61 |
| Liquid limit (%)         | 48.50-50.00 |
| Plasticity index (%)     | 9.90-11.99 |
| Specific gravity         | 2.50-2.59  |
| Max dry density (g/cm³)  | 1.75      |
| Soil classification (USCS)| Sandy silt|
| Permeability (m/s)       | 2.08×10⁻⁶  |
For 1500 RPM rotation speed of a 500 ppm single solution, an increment of soil thickness showed the decrement of scale factors and hydraulic conductivity values; (10mm: \( x = 1.37 \), \( K_{cen} = 4.51 \times 10^{-2} \) m/s, 15mm: \( x = 0.87 \), \( K_{cen} = 1.25 \times 10^{-3} \) m/s and 20mm: \( x = 0.63 \), \( K_{cen} = 2.09 \times 10^{-4} \) m/s). Increasing of soil thickness has decreased the high energy sites where low energy sites were filled with larger ions fractions and caused the decreasing of metal adsorption from pollutants, q, and hydraulic conductivity values, \( K_{cen} \). Hydraulic conductivity, \( K_{cen} \) for a single solution also showed a higher value compared to mixture solutions. For example, for 1500 RPM rotation speed and 10mm soil thickness, hydraulic conductivity value for single solution was \( K_{cen} = 4.51 \times 10^{-2} \) m/s while for mixture solution was \( K_{cen} = 2.07 \times 10^{-3} \) m/s. This was due to the competition for heavy metal ions adsorption in mixture solutions. Thus, it reduced the adsorption of heavy metal and subsequently lowered the \( K_{cen} \) values. For single solution, there is no competition for adsorption of metals, thus the value of \( K_{cen} \) increases (Wan Zuhairi and Abdul Rahim, 2007).

Most of the scale factors were showed to be low values (\( x<1.00 \)) which meant \( x \) values were close to unity. For the scale factor (\( x > 1.00 \)), the hydraulic conductivity (\( K_{cen} \)) the values were overestimated due to the presence of cracks in the soil (mudcakes) during centrifugation. For 10mm soil thickness and 2500 RPM (1440 -g) speed rotation of a single solution, the values of hydraulic conductivity (\( K_{cen} \)) and scale factor were \( 6.82 \times 10^{-4} \) m/s and 0.74 respectively. While hydraulic conductivity for 1-g Permeability Test (\( K_{f} \)) provided value of \( 2.08 \times 10^{-6} \) m/s. This indicated that 1-g permeability (\( K_{f} \)) had good correlations with permeability from Centrifuge Test (\( K_{cen} \)) since the scale factor obtained was less than 1 (\( x = 0.74 \)). This study proved the Hydraulic Conductivity Values from the Centrifuge Tests can be developed as a valid method in determining the hydraulic conductivity of the soil in a short period.

**Conclusion**

This study highlighted the capability of Centrifuge modeling in measuring the hydraulic conductivity (\( K_{cen} \)) in a short period of time. Results have shown that hydraulic conductivity (\( K_{cen} \)) was highly depending on the SFV. Hydraulic conductivity was decreasing with an increasing of rotation speed, while increment of soil thickness decreased the SFV and hydraulic conductivity value. Hydraulic conductivity, \( K_{cen} \) for a single solution also showed higher value compared to mixture solutions. The low values of scale factor (\( x<1.00 \)) showed that \( x \) values were close to unity, while for scale factor (\( x > 1.00 \)), it showed the overestimated hydraulic conductivity values (\( K_{cen} \)). This was due to the presence of cracks in the soil (mudcakes) during the centrifugation. The study also concluded 1-g permeability (\( K_{f} \)) to has good correlations with permeability obtained from Centrifuge Test (\( K_{cen} \)). Thus, Centrifuge modeling can be developed as a valid method to determine the hydraulic conductivity of the soil.

**Acknowledgement**

This research project was funded by Fundamental Research Grant Scheme, Project No: FRGS/1/2012/STWN06/UKM/02/2. Authors acknowledge Geology Department, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), Malaysia for their assistance in conducting the study and writing this paper.

**Funding Information**

Fundamental Research Grant Scheme, Project No: FRGS/1/2012/STWN06/UKM/02/2.

**Author’s Contributions**

Nur Aishah Zarime: Conducting the experimental work and drafting this paper.

880
Wan Zuhairi Wan Yaacob: Is the main supervisor of the study and revise the article.

Ethics
This article is an original and contains unpublished materials. All authors have read and approved this manuscript and no ethical issues involved.

References
Antoniadis, V., J.D. Mckinley and W.Y.W. Zuhairi, 2007. Single-element and competitive metal mobility measured with column infiltration and batch tests. J. Environ. Quality, 60: 53-60. DOI: 10.2134/jeq2006.0134
Arulanandan, K., P.Y. Thompson, B.L. Kutter, N.J. Meegoda and K.K. Mureleetharan et al., 1988. Centrifuge modeling of transport processes for pollutants in soil. J. Geotechnical Eng., 114: 185-205.
Chalermyanont, T., S. Arrykul and N. Charoenthaison, 2009. Potential use of lateritic and marine clay soils as landfill liners to retain heavy metals. Waste Manage., 29: 117-27. DOI: 10.1016/j.wasman.2008.03.010
Culligan, P.J., 1996. Centrifuge modelling of contaminant transport process. Electronic J. Geotechnical Eng.
Di Emidio, G., H. Peiffer, B. Malengier, P. Kison and A. Bezuijen, 2012. Bench-scale centrifuge testing to determine the hydraulic conductivity of clayey soils. Pro European Conference on Physical Modelling in Geotechnics, (PMG’ 12).
Poulos, H.G., 1988. Modified calculation of pile group settlement interaction. J. Geotechnical Eng., 114: 697-706. DOI: 10.1061/(ASCE)0733-9410(1988)114
Singh, D.N. and A.K. Gupta, 2002. Modelling hydraulic conductivity in a small Centrifuge. Canadian Geotechnical J., 39: 486-487. DOI: 10.1139/t01-105
Wan Zuhairi, W.Y. and Muchlis, 2012. Migration of toluene and PCE in porous medium using mini geotechnical centrifuge technique. Proceedings of the 5th Engineering Conference, Engineering Towards Change - Empowering Green Solutions, (EGS’ 12), pp: 309-314.
Wan Zuhairi, W.Y. and A.R. Samsudin, 2007. Sorption parameters of Pb and Cu on natural clay soils from Selangor, Malaysia. Sains Malaysian, 36: 149-157.
Zarime, N.A., W.Y. Wan Zuhairi and S. Krishna, 2014. Adsorption of nickel and zinc by residual soils. Am. J. Environ. Sci., 10: 523-529. DOI: 10.3844/ajessp.2014.523.529
Zulfahmi, A.R., H. Umar and A. Noorulakma 2011. Engineering geological properties of oil-contaminated granitic and metasedimentary soils. Sains Malaysian, 40: 293-300.