Effect of grain-size distribution on hydraulic anisotropy of unsaturated soils

H. Rahardjo i) and A. Satyanaga ii)

i) Professor, School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, chrahamj@ntu.edu.sg
ii) Senior Research Fellow, School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, alfrendo@ntu.edu.sg

ABSTRACT

As slope failures induced by rainfall are universal problems, especially in areas covered by residual soils, slope preventive system is necessary to avoid casualties. One effectively-proven alternative method is capillary barrier system (CBS) which utilizes the principles of unsaturated soil mechanics to minimize rainwater infiltration into soil layer. Previous studies indicated that the efficiency of CBS could be enhanced further by incorporating different hydraulic conductivities in two different directions. This study investigated hydraulic anisotropy by using two different types of soil layering, horizontal-layering (HL) and vertical-layering (VL), with two main soil compositions such as sandy silt and silty sand. The hydraulic anisotropy ratio observed in this study was then correlated with various soil properties, such as percentages of fines, dry density, plastic limit and liquid limit in order to find the relationship between hydraulic anisotropy ratio and soil properties. This study showed that percentages of fines and dry density of soils exhibit non-linear relationship with hydraulic anisotropy ratio, while plastic limit and liquid limit of soils exhibit linear relationship with hydraulic anisotropy ratio.

Keywords: grain-size distribution, soil-water characteristic curve, hydraulic anisotropy, horizontal-layering, vertical-layering

1 INTRODUCTION

Climate change contributes significantly towards one of the most frequently occurring failures around the world: that is rainfall-induced slope failure (Rahardjo et al., 2012a). Cases of slope failure almost always have significant consequences, such as the loss of life, loss of infrastructure and slope restoration costs. Hence, there is a need to develop rainfall-induced slope failure preventive measures. A rainfall-induced slope failure preventive measure termed the Capillary Barrier System (CBS) has attracted significant interest over the past decade (Tami et al., 2004; Rahardjo et al., 2012b). Principally, CBS is a slope cover system that consists of a fine-grained soil layer overlying a coarse-grained soil layer in order to prevent rainfall infiltration into the slope (Krisdani et al., 2006).

A good understanding of soil-water characteristic curve (SWCC) and unsaturated permeability is essential in improving the performance of CBS. One aspect of the hydraulic properties of soil that is not fully understood is anisotropy, which indicates the directional-dependence of a property. Hydraulic anisotropy represents the permeability ratio in parallel and perpendicular direction to soil layering as designated as kparallel/kperpendicular (Bear and Cheng, 2010), where high ratio value implies higher flow rate in parallel direction. Past study by Priono et al. (2016) showed that both unsaturated and saturated coefficients of permeability parallel to the flow direction are greater than the respective values perpendicular to the flow direction. Priono et al. (2017) also observed that the SWCC of unsaturated soils is almost identical regardless of its layering. However, the time taken to reach the corresponding equilibrium condition at a particular matric suction (i.e. equalization time) is different. The ratio between equalization times was found to reflect the value of hydraulic anisotropy obtained from the direct measurement.

The previous research works on hydraulic anisotropy of unsaturated soil focused on one composition of compacted soil mixtures. The hydraulic anisotropy behaviour of unsaturated soil with different grain-size distributions has not been explored very well. Therefore, the main objective of this study is to investigate the effect of grain-size distribution on the hydraulic anisotropy of the unsaturated soil. The scope of works includes the direct measurement of SWCC and the direct measurement of the unsaturated permeability of different composition of soil mixtures.
2 LABORATORY TESTING

In this study three different compacted soil mixtures (Table 1) were utilized to investigate the effect of grain-size distribution on the hydraulic anisotropy. L2-grade coarse kaolin and ASTM 20-30 grade Ottawa sand were used in the study since both materials have non-excessive volume change and non-collapsing characteristics. Static compaction (following procedures by Ong, 1999) was carried out to establish the compacted soil mixtures to ensure the homogeneity and reproducibility of the specimens tested for SWCC and unsaturated permeability measurements. The compaction was performed in terms of horizontal-layering (HL) and vertical-layering (VL) orientations to develop the hydraulic anisotropy behaviour following study by Priono et al. (2016).

Table 1. Compacted sand-kaolin mixtures

| Soil Specimen Description | Initial Condition |
|---------------------------|-------------------|
| 30% sand – 70% kaolin     | 95% \( \rho_{d, \text{max}} \) (wet of optimum) |
| 50% Sand – 50% Kaolin     | 95% \( \rho_{d, \text{max}} \) (wet of optimum) |
| 70% Sand – 30% Kaolin     | 95% \( \rho_{d, \text{max}} \) (wet of optimum) |

All of the specimens were prepared according to a standard size of 50 mm in diameter and 30 mm in height. To produce HL and VL specimens with the same static compactor, it is required to have two sets of compaction moulds with different sizes. The mould has a block shape with a circular tunnel at the center of its plane. The mould for HL specimen has 50 mm diameter tunnel while the mould for VL specimen has a 100 mm diameter tunnel. This is because preparation of VL specimen requires cutting of a larger soil block into the standard size.

Standard Proctor Compaction Test (ASTM D698-12e1) was performed to obtain the compaction curve and to determine the initial conditions of the specimen prior to SWCC and permeability tests. 95% of the maximum dry density (95% \( \rho_{d, \text{max}} \)) associated with the wet optimum side was selected as the initial condition for each specimen (Table 1). The specimens compacted at the wet of optimum side are expected to produce unimodal SWCC. Index properties tests were carried out in order to classify the soil mixtures based on the Unified Soil Classification System (USCS) (ASTM D2487-11). The tests included specific gravity tests (ASTM D854-14), Atterberg limits tests (ASTM D4318-10e1), and grain-size distribution tests (ASTM D422-63e2). Saturated permeability tests were conducted based on ASTM D5084-10 Standards.

Tempe Cell with ceramic disc of 1 Bar was used for SWCC tests less than 100 kPa, whereas pressure plate with ceramic disc of 15 Bar was used for SWCC tests between 100 and 1500 kPa. The ceramic disc was submerged into de-oxygenated purified water in the vacuum desiccator for days to make it completely saturated. Prior to the application of matric suction, the saturation of soil specimen was performed. Based on the axis-translation technique (Hilf, 1956), matric suction was applied to soil specimen inside Tempe cell and pressure plate. Hourly and daily recording of the mass of the specimens was taken at the initial and later stages of the test, respectively. The matric suction was increased by increasing the air pressure inside the Tempe cell and pressure plate when no significant change in the mass of specimen was observed.

Triaxial permeameter following the design by Goh et al. (2010) was used in the unsaturated permeability test. The test procedure of the unsaturated permeability test involves saturation, matric suction application, and unsaturated permeability measurement. Prior to the test, the ceramic disks on the pedestals were saturated by filling the cell with de-aired water and applying a pressure of 50 kPa for a minimum duration of 24 hours. The unsaturated permeability test was carried out by creating a hydraulic gradient of matric suction within the soil specimen. Inflow and outflow rates were continuously recorded with an interval of 5 minutes. The test was ceased when both flow rates were approximately the same (i.e. steady-state condition). The measurement of unsaturated permeability was influenced significantly by the ceramic disks on the bottom and top pedestals. The calculation of permeability of the whole specimen setup still follows Darcy’s Law, however due to the three-layered system of the setup (i.e. Disk-Soil-Disk) (Figure 1), the equation used to determine the unsaturated permeability coefficient is modified as shown in Equation 1.

\[
\frac{k_{w}}{k} = \frac{L_{t}}{L_{s}} = \frac{L_{t} + \frac{L_{s}}{k_{b}}}{L_{s}} \\
\]

where:
- \( k_{w} \) = coefficient of unsaturated permeability (m/s)
- \( k \) = measured coefficient of permeability of setup (m/s)
- \( k_{b} \) = coefficient of permeability of bottom disk (m/s)
3 RESULTS

The compaction curves of three different soil mixtures are presented in Figure 2. The maximum dry density and the optimum water content of specimen 1 are 1.61 Mg/m$^3$ and 19.5 %, respectively. The maximum dry density and the optimum water content of specimen 2 are 1.83 Mg/m$^3$ and 14.1 %, respectively. The maximum dry density of specimen 1 is lower than those of specimens 2 and 3. Therefore, specimen 1 has a lower dry density at a given initial condition compared to specimens 2 and 3.

The index properties of soil mixtures in this study are shown in Table 2. Specimen 1 is classified as silt with high plasticity (MH) due to the abundance of kaolin in the soil mixture. Specimen 2 is classified as silty sand to sandy silt with low plasticity (SM-ML) due to the balanced composition of sand and kaolin. Specimen 3 is classified as silty sand to sandy silt with low plasticity (SM-ML) due to the balanced composition of sand and kaolin. Specimen 3 has a higher air-entry value (40 kPa) as compared to specimen 2 (20 kPa) and specimen 3 (4 kPa). This is attributed to the higher percentage of silt content within specimen 1 as compared to specimens 2 and 3. The presence of hydraulic anisotropy in each specimen is shown by the difference in HL and VL coefficients of permeability. For each type of specimen, VL orientation had a higher water coefficient of permeability compared to HL specimen. This observation is in agreement with study by Priono et al. (2016, 2017). In addition, hydraulic anisotropy value of specimen 1 is lower than those of specimens 2 and 3.

### Table 2. Index Properties of Soil Mixtures 1, 2 and 3

| Index properties | 1   | 2   | 3   |
|------------------|-----|-----|-----|
| Specific gravity | 2.63| 2.59| 2.65|
| Liquid Limit, LL | 53  | 46.7| 26.8|
| Plastic Limit, PL| 31  | 27.4| 11.6|
| Plasticity Index | 22  | 19.3| 15.2|
| Dry Density, $\rho_d$ (Mg/m$^3$) | 1.53 | 1.75 | 1.85 |
| Water Content, w (%) | 24.5 | 17.5 | 4.0 |
| Sand (%)          | 30.0 | 50.0 | 70.0 |
| Silt (%)          | 63.4 | 37.5 | 25.3 |
| Clay (%)          | 6.6  | 12.5 | 4.7  |

### Table 3. Saturated Permeability Coefficient of Specimen 1 to 3

| Specimen | $k_{sat, HL}$ (m/s) | $k_{sat, VL}$ (m/s) | Hydraulic Anisotropy |
|----------|---------------------|---------------------|----------------------|
| 1        | 5.17E-10            | 2.20E-09            | 4.26                 |
| 2        | 1.92E-09            | 1.12E-08            | 5.83                 |
| 3        | 9.85E-09            | 8.92E-08            | 9.06                 |

The SWCCs of specimens 1, 2 and 3 are shown in Figures 4, 5 and 6, respectively. It can be seen that all SWCCs have a unimodal shape although their grain-size distribution curves are gap-graded distributions. These results are in agreement with investigations by Satyanaga et al. (2013) where soil having a bimodal grain-distribution curve can produce a unimodal SWCC, depending on the initial condition (dry density and water content) of the soil. Specimen 1 has a higher air-entry value (40 kPa) as compared to specimen 2 (20 kPa) and specimen 3 (4 kPa). This is attributed to the higher percentage of silt content within specimen 1 as compared to specimens 2 and 3.
attributed to the higher percentage of fines content within specimen 1 as compared to those of specimens 2 and 3. For a given specimen, the SWCCs obtained from laboratory data are comparable regardless of HL or VL orientations. These results are in line with the study by Priono et al. (2016) where SWCC is a scalar variable and it is not dependent on the direction of soil layering.

Permeability functions of specimens 1, 2 and 3 are presented in Figures 7, 8 and 9, respectively. For a given specimen, VL orientation gave a higher coefficient of permeability as compared to that of HL orientation. The hydraulic anisotropy measured in the unsaturated condition showed similarity with those observed in the saturated condition as reflected in Table 3. Different initial conditions and different shapes of permeability functions observed in specimens 1, 2 and 3 are found to yield similar hydraulic anisotropy in the unsaturated and saturated conditions. Figures 7 to 9 also indicated that the hydraulic anisotropy values are relatively constant throughout application of matric suction and are similar to the value measured during the saturated condition for each specimen. These results are in agreement with the results from Priono et al. (2016, 2017) and Ursino et al. (2000).
4 DISCUSSIONS

Statistical analyses were carried out to investigate the relationship between soil properties and hydraulic anisotropy of three different compacted soil mixtures. Figure 10 shows the effect fine particles on hydraulic anisotropy. Figure 11 indicates the effect of dry density on hydraulic anisotropy.

It can be seen from Figure 10 that hydraulic anisotropy ratio of soil decreases nonlinearly with the increase in fines content of the soil. This may be attributed to the higher presence of macro-pores in the soil particle arrangement, contributing to the organized packing or “ordering” of soil particles within the soil with a lower percentage of fines content. As a result, the permeability in perpendicular direction is much lower than the permeability in parallel direction, thereby increasing the hydraulic anisotropy ratio of soil with a lower percentage of fines content.

Figure 11 demonstrates that hydraulic anisotropy ratio of soil increases nonlinearly with the increase in dry density of the soil. This could be due to the fact that the soil with a higher dry density is associated with a lower percentage of fines content (see Table 2), resulting in the higher percentage of macro pores as compared to the percentage of micro pores. Hence, the soil particles are packed in a more organized arrangement and it is much easier for water to flow in parallel direction than in perpendicular direction within the soil with a higher dry density.

10 CONCLUSIONS

The conclusions of this study are as follows:

1. Soil with a higher percentage of fines has a lower hydraulic anisotropy as compared to soil with a lower percentage of fines.

2. Soil with a higher dry density has a higher hydraulic anisotropy as compared to soil with a lower dry density.

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REFERENCES

1) ASTM D2487-11. 2011. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

2) ASTM D422-63e2. 2007. Standard test method for particle-size analysis of soils. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

3) ASTM D4318-10e1. 2010. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.
4) ASTM D5084-10. 2010. Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

5) ASTM D698-12e1. 2012. Standard test methods for laboratory compaction characteristics of soil using standard effort. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

6) ASTM D7664-10. 2010. Standard test methods for measurement of hydraulic conductivity of unsaturated soils. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

7) Bear, J. and Cheng, A.H.D. (2010) Modeling Groundwater Flow and Contaminant Transport (Theory and Applications of Transport in Porous Media), Springer.

8) Goh, S.G., Rahardjo, H., Leong, E.C. 2010. Shear strength equations for unsaturated soil under drying and wetting. Journal of Geotechnical and Geoenvironmental Engineering, 136(4):594-606.

9) Krisdani, H., Rahardjo, H., Leong, E. C. 2006. Experimental study of 1-D capillary barrier model using geosynthetic material as the coarse-grained layer. Unsaturated Soils 2006 (Geotechnical Special Publications 147), ASCE, Reston, VA, 1682–1694.

10) Ong, B.H., 1999. Shear strength and volume change of unsaturated residual soil. M.Eng. thesis, Nanyang Technological University, Singapore.

11) Priono, H. Rahardjo, K. Chatterjea, and E.C. Leong (2017) “Laboratory Investigation on Hydraulic Anisotropy Behavior of Unsaturated Soil”, Canadian Geotechnical Journal, Vol. 54, No. 7, pp. 1034-1046.

12) Priono, H. Rahardjo, K. Chatterjea, E.C. Leong, and J.Y. Wang (2016), “Effect of Hydraulic Anisotropy on Soil-Water Characteristic Curve”, Soils and Foundations, Japanese Geotechnical Society, Vol. 56, Issue 2, Pages 228–239.

13) Rahardjo, H., Satyanaga, A. and Leong, E.C. (2012a), “Unsaturated Soil Mechanics for Slope Stabilization”, Southeast Asian Geotechnical Journal, Vol. 43, No.1, pp. 48-58.

14) Rahardjo, H., Santos, V.A., Leong, E.C., Ng, Y.S., Hua, C.J. 2012b. Performance of an Instrumented Slope covered by a capillary barrier system. Journal of Geotechnical and Geoenvironmental Engineering, 138 (41).

15) Tami, D., Rahardjo, H., Leong, E.C., Fredlund, D. G. 2004. Design and laboratory verification of a physical model of sloping capillary barrier. Canadian Geotechnical Journal, 41(5):814–830.

16) Ursino, N., Roth, K., Gimmi, T., and Fluhner, H. 2000. Upscaling of anisotropy in unsaturated Miller-similar porous media. Water Resources Research, 36(2): 421–430.