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CIVIL ENGINEERING

Evaluation of the effects of the hydraulic gradient variation on the permeability of a compacted soil

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ABSTRACT. The present study evaluated the influence of the hydraulic gradient on soil conductivity changes using data from permeability tests performed in a column percolation test system, in order to represent geoenvironmental engineering applications. A mature residual soil from gneiss, pedologically classified as Red-Yellow Latosol, with 67% of clay, 10% of silt, 23% of sand, 82% of liquid limit and 46% of plastic limit was used in the study. Soil specimens were compacted at the optimum compaction parameters determined at the Standard Proctor effort, i.e., w_{opt} =31.37% and γ_{dmax} =13.54 kN m^{-3}. After compaction, it was determined the permeability of specimens under the hydraulic gradients of 15, 66, 85 and 140. The results obtained support that: (i) at the 5% level, there is statistical significant variation in the permeability coefficient according to the hydraulic gradient used in the tests; (ii) from a geotechnical perspective, there is a slight tendency of increasing the permeability coefficient when increasing the hydraulic gradient, but of no significance for geotechnical practical applications.

Keywords: column percolation; environmental geotechnics; permeability coefficient.

Avaliação dos efeitos da variação do gradiente hidráulico na permeabilidade de um solo compactado

RESUMO. O presente trabalho teve por objetivo avaliar a influência do gradiente hidráulico empregado em ensaios de percolação em coluna na permeabilidade de um solo argiloso compactado, sob o prisma de aplicações em geotecnia ambiental. O solo empregado no estudo foi um residual maduro, pedologicamente classificado como Latossolo Vermelho-Amarelo, com 67% de argila, 10% de silte, 23% de areia, limite de liquidez de 82% e limite de plasticidade de 46%. Corpos de prova desse solo foram compactados nos parâmetros ótimos determinados na energia do ensaio Proctor Normal, com w_{ot} de 31,37% e γ_{dmax} de 13,54 kN m^{-3}. Após a compactação, esses corpos de prova foram utilizados em ensaios de permeabilidade, nos gradientes hidráulicos 15, 66, 85 e 140. Os resultados obtidos sustentam que (i) estatisticamente em nível de significância de 5%, observou-se variação significativa no coeficiente de permeabilidade em função do gradiente hidráulico utilizado nos ensaios; (ii) sob o prisma geotécnico, observou-se leve tendência de aumento no coeficiente de permeabilidade com o aumento do gradiente hidráulico, mas de pequena monta para fins práticos de engenharia.

Palavras-chave: percolação em coluna; geotecnia ambiental; coeficiente de permeabilidade.

Introduction

Among the laboratory tests for geoenvironmental applications, column percolation is commonly applied in the study of transport of contaminants in fine soils. In general, these tests are performed on laboratory equipment which employs relatively low hydraulic gradients and, in the case of the study of contaminants, requires long times for execution.

In relation to prior studies using column percolation tests, Yong (2001) adopted a hydraulic gradient of the order of 55, Morandini and Leite (2015) adopted a hydraulic gradient of the order of 50, based on recommendations of the standard ASTM D 4874 (American Society for Testing and Materials [ASTM], 1995) it could be used a hydraulic gradient of 24, and Rojas, Consoli, and Heineck (2007) worked with a maximum hydraulic gradient of approximately 92. Therefore, from the geotechnical perspective, there is need of characterizing the influence of the hydraulic gradient used in column percolation tests on soil structure.

In that tests the effective stresses at one end of the specimen are different from the other end as a function of the hydraulic gradient. That difference, can lead to reduce void ratio and permeability coefficient (k) due an increase in seepage forces. Besides that, the high hydraulic gradient may wash soil fine particle within the specimen, changing the measured value of k due to clogging or loss particles (Daniel, 1994). Considering the influence of the hydraulic gradient on the hydraulic responses of this material (Daniel, 1994; Shackelford & Glade, 1994; Ke & Takahashi, 2012; Steiakakis, Gamvroudis, Komodromos, & Repouskou, 2012; Al-Taie, Pusch, & Knutsson, 2014), this study addressed the influence of the hydraulic gradient on permeability of a compacted clayey soil. Permeability tests were conducted in a compacted clayey soil using different hydraulic gradients in a column percolation system.

Material and methods

Material

A clayey soil geotechnically classified as mature residual gneiss soil and pedologically as Red-Yellow Latosol of expressive occurrence in the brazilian territory and, especially, in the Zona da Mata of the state of Minas Gerais was used thoroughly in this study.

Disturbed soil samples were collected from a slope on the right bank of the highway connecting the municipalities of Viçosa and Paula Cândido, at the coordinates 20º 45' 35" S; 42º 52' 28" W, in the Campus of the Federal University of Viçosa, Brazil. These soil samples were air-dried, broken up, passed through a nominal 2 mm sieve and stored for use in geotechnical tests, in compliance with NBR 6457 (*Associação Brasileira de Normas Técnicas* [ABNT], 1986a).

Methods

Geotechnical characterization and soil compaction laboratory tests

The geotechnical characterization tests included: (i) particle-size distribution (ABNT, 1984a); (ii) specific gravity of soil solids (ABNT, 1984d); (iii) liquid limit (ABNT, 1984b); and (iv) plastic limit (ABNT, 1984c).

The compaction tests were carried out at the Standard Proctor effort (600 kN m^{-1} m^{-3}) according to ABNT (1986b), with limits for acceptance of specimens relative to maximum dry unit weight (γ_{dmax}) of ± 0.30 kN m^{-3} and to optimum water content (w_{opt}) of ± 0.5%. Specimens were compacted in PVC cylinders (100 mm diameter and 120 mm height) with four repetitions for each hydraulic gradient to be tested so that they could be used directly in the permeability laboratory tests.

Permeability laboratory tests

Permeability tests were conducted with hydraulic gradients of 15, 66, 85 and 140, with four repetitions for each hydraulic gradient using the column percolation device, Figure 1a, implemented at the Civil Engineering Laboratory from the Federal University of Viçosa, Brazil.

In permeability test, the compacted specimens in PVC cylinders (Figure 1b) were sealed at the top and bottom in order to allow water flow upward, measuring the percolated volume at the top of the specimen. In the production of the hydraulic gradients 15, 66, 85 and 140, pressures of 1.8, 7.92, 10.2 and 16.8 m of water column (mH_2O), respectively, were applied by a compressed air system on the storage interfaces (Figure 1c). After assembling each soil specimen in the column percolation system, it was started the water flow in order to saturate its voids and to measure its permeability coefficient.

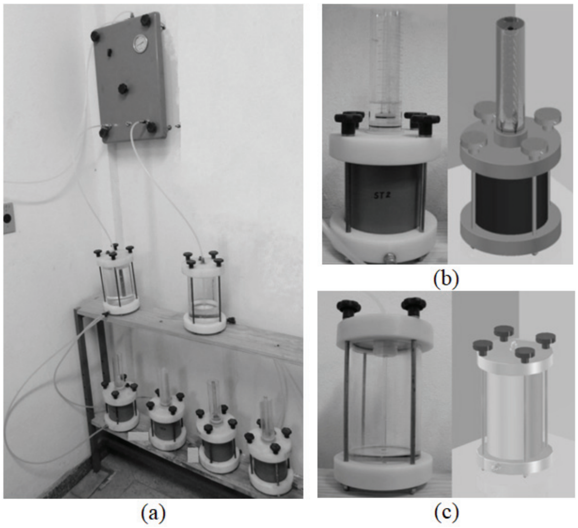

Figure 1. (a) Percolation column testing system: (b) permeameter set; and (c) storage reservoir (interface).

The permeability tests were carried out in a room with the temperature of 21 ± 1°C, using Darcy´s Law to determine the permeability coefficient from daily readings (Head, 1982). In order to obtain more readings of the volume percolated through the specimens after stabilization of the water flow, the permeability tests were carried out during a longer time than the usual procedure. The flow was allowed to complete a percolated volume equal to more than one volume of pores in tests that took from 2 to 5 months.

Statistical analysis

A completely randomized design was used in the statistical analysis, data obtained in the permeability tests were subjected to Analysis of Variance - ANOVA (Bussab & Moretin, 2004), and mean values of the permeability coefficient determined for each hydraulic gradient were compared using Tukey's test at 5% probability.

Results and discussion

Table 1 lists the results of geotechnical characterization of the soil, encompassing the liquid limit (LL), the plastic limit (PL), the plasticity index (PI), the specific gravity of soil solids (γ_s), and the particle diameter (ϕ) distribution. The optimum compaction parameters (w_{opt}: optimum moisture, γ_{dmax}: maximum apparent specific dry weight) are referred to the Standard Proctor effort.

Table 1. Results of geotechnical characterization and compaction of the LVA soil sample.

Geotechnical parameter	Value
Grain-size distribution (ABNT, 1995) (%): Clay ($\phi \leq 0.002$ mm)	67
Silt ($0.002 < \phi \leq 0.06$ mm)	10
Sand ($0.06 < \phi \leq 2$ mm)	23
γ_s (kN m^{-3})	27.27
LL (%)	82
PL (%)	46
PI (%)	36
w_{opt} (%)	31.37
γ_{dmax} (kN m^{-3})	13.54

The Figure 2 introduces the results of the four repetitions of the permeability tests for the hydraulic gradients 15, 66, 85 and 140, showing the number of daily readings after the stabilization of the water flow in the specimens versus the coefficient of permeability (k). On the other hand, Table 2 presents the results of the means and standard deviations of the four repetitions of the permeability tests conducted on the LVA in each of the hydraulic gradients 15, 66, 85 and 140, and Table 3 introduces the results of the comparison among the means of the permeability coefficients related to applied hydraulic gradients using the analysis of variance.

Discussion

Table 2 presents the means and standard deviations of the values of the permeability coefficients determined for each hydraulic gradient tested and the overall mean of all the results. On the other hand, the relationships between the permeability coefficients and the hydraulic gradients analyzed are shown in Figure 2, considering the results of four repetitions per hydraulic gradient analyzed, while the results of the statistical analysis are in Table 3.

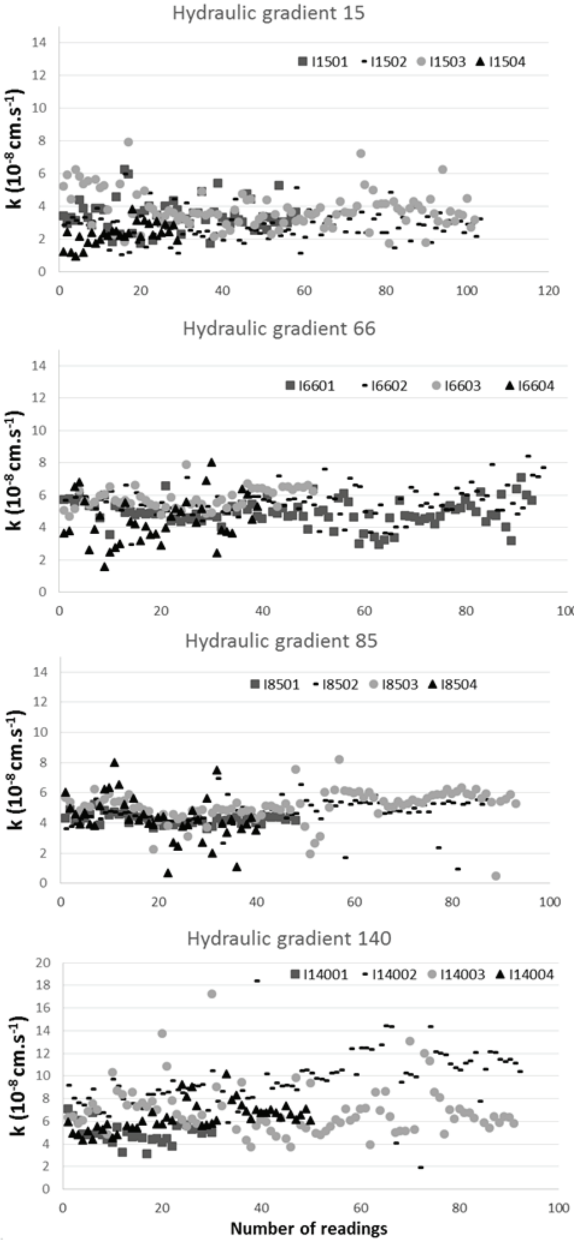

Figure 2. Results of the permeability tests for the hydraulic gradients 15, 66, 85 and 140: coefficient of permeability (k) versus number of daily readings.

Analyzing the results from Figure 2 and Table 3, it is observed that the means and respective standard deviations of the permeability coefficients are in the range of 2.3 x 10^{-8} and 0.65 x 10^{-8} cm s^{-1} (fourth repetition of the gradient 15) to 9.49 x 10^{-8} and 2.49 x 10^{-8} cm s^{-1} (second repetition of the gradient 140), with overall mean varying from 3.08x10^{-8} (gradient 15) to 6.95 x 10^{-8} cm s^{-1} (gradient 140). On the other hand, gradient 140 shows greater variability among all.

Table 2. Permeability coefficients and standard deviations of the permeability tests using the hydraulic gradients 15, 66, 85 and 140.

Repetition	Hydraulic gradient	Permeability coefficient (x 10^{-8} cm s^{-1})			
		15	66	85	140
1	Number of readings	58	93	48	30
	Mean	3.45	4.93	4.25	4.99
	Standard deviation	0.94	0.79	0.31	0.91
2	Number of readings	103	95	88	92
	Mean	2.79	5.57	4.70	9.49
	Standard deviation	0.86	0.96	0.87	2.49
3	Number of readings	102	50	93	91
	Mean	3.80	5.82	5.14	6.95
	Standard deviation	1.12	0.63	1.06	2.24
4	Number of readings	29	39	40	50
	Mean	2.30	4.32	4.33	6.39
	Standard deviation	0.65	1.57	1.49	1.26
	Overall mean	3.08	5.16	4.61	6.95

Table 3. Analysis of variance (ANOVA): comparison of the mean values of the permeability coefficient determined for each hydraulic gradient.

SV[1]	DF[2]	SS[3]	MS[4]	F[5]
Treatments	3	3.06×10^{-15}	1.02×10^{-15}	8,89*
Residual	12	1.38×10^{-15}	1.15×10^{-16}	
Total	15	4.44×10^{-15}		

*significant at level of 0.05; [1]Source of the variation; [2]The degrees of freedom in the source; [3]The sum of squares due to the source; [4]The mean sum of squares due to the source and [5]The F-statistic.

Based on the results in Table 2, from the geotechnical perspective, there is the tendency of increasing the permeability coefficient when increasing the hydraulic gradient. Complementary, according to Table 3, results of the statistical study support occurrence of contrast among the mean values of the treatments at the 5% probability level, which indicates the influence of the hydraulic gradient on the permeability coefficient.

However, for the geotechnical engineering practical purpose, the variations observed in the permeability coefficient are small, especially when considering the overall means presented in Table 2, which ratio varies from 1 (hydraulic gradient 15) to 2.26 (hydraulic gradient 140), and all results with the same exponent (10^{-8}).

Thus, like Daniel (1994), for this soil, can be allowed higher hydraulic gradients, necessary for testing involving chemicals or leachate, where a minimum number of pore volumes of flow are required and where the only practical way of achieving this in a realistic time is to use elevated hydraulic gradient.

Conclusion

The results obtained here indicate a tendency of increasing the permeability coefficient (k) when increasing the applied hydraulic gradient, which was statistically confirmed at the 5% probability level. Nevertheless, for practical engineering purposes, this variation can be considered of minor significance since all the results are in the same exponent, i.e. 10^{-8}, with overall mean values of the permeability coefficient varying from $3.08\ 10^{-8}$ cm s^{-1}, for the hydraulic gradient 15, to 6.95×10^{-8} cm s^{-1}, for the hydraulic gradient 140.

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