DISCUSSION

Hydraulic conductivity of a recent estuarine silty clay at Bothkennar

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The Paper contains good experimental data which help understanding of the hydraulic behaviour of soils and in obtaining the best parameters to characterize a given soil. I would like to present a general equation, given by the principle of natural proportionality, which can be applied to experimental permeabilities measured in the laboratory (Figs 6 and 9).

The natural equation provided by the principle of natural proportionality reads (Juárez-Badillo, 1983, 1992)

$$\frac{k}{k_1} = \left(\frac{V}{V_1}\right)^\kappa = \left(\frac{1+e}{1+e_1}\right)^\kappa \quad (3)$$

where k is the permeability, V is the total volume, e is the nominal void ratio in terms of the initial volume of solids, κ is a constant parameter—the coefficient of permeability, characteristic of the material and (k_1, e_1) is a known point. The known point may be the in situ point (k_0, e_0) .

When a soil is one-dimensionally compressed its permeability anisotropy increases so that

$$k_v = k_{v1} \left(\frac{1+e}{1+e_1}\right)^{\kappa_v} \quad (4)$$

$$k_h = k_{h1} \left(\frac{1+e}{1+e_1}\right)^{\kappa_h} \quad (5)$$

$$r_k = \frac{k_{h1}}{k_{v1}} \left(\frac{1+e}{1+e_1}\right)^{-(\kappa_v - \kappa_h)} \quad (6)$$

Equations (4)–(6) may alternatively be written as

$$k_v = k_{v0}'(1+e)^{\kappa_v} \quad (7)$$

$$k_h = k_{h0}'(1+e)^{\kappa_h} \quad (8)$$

$$r_k = \frac{k_{h0}'}{k_{v0}'} (1+e)^{-(\kappa_v - \kappa_h)} \quad (9)$$

where k_{h0}' and k_{v0}' are the permeabilities for the nominal (not the actual) void ratio $e_1 = 0$.

Equations (4)–(6) may also be written as

$$k_v = k_{ip} \left(\frac{1+e}{1+e_{ip}}\right)^{\kappa_v} \quad (10)$$

$$k_h = k_{ip} \left(\frac{1+e}{1+e_{ip}}\right)^{\kappa_h} \quad (11)$$

$$r_k = \left(\frac{1+e}{1+e_{ip}}\right)^{-(\kappa_v - \kappa_h)} \quad (12)$$

where k_{ip} is isotropic permeability for $e_1 = e_{ip}$ such that $r_k = 1$.

I believe that e_{ip} , k_{ip} , k_0' , together with κ_v and $\kappa_v - \kappa_h$, may be used to characterize the permeability of soils.

By applying equations (4)–(12) to the experimental data presented in Figs 6 and 9 the results in Table 3 were obtained. The last column is the in situ value of k_0 from the equations (4)–(12); it compares well with the values of k_0 in Table 1.

From 6 m to 15 m depth, κ_v varies from 5.5 to 7.6, κ_h from 5.2 to 6.6 and $\kappa_v - \kappa_h$ from 0.5 to 1.5. Negative values of $\kappa_v - \kappa_h$ are unrealistic for a given soil sample. Values of e_{ip} , k_{ip} and r_{k0} that appear as unrepresentative of the clay deposit are written in parenthesis. When duplicated, values of k_0' , κ and $\kappa_v - \kappa_h$ that appear representative are given in italics. It therefore appears that κ_v varies from 6.7 to 7.6. For the cases that are considered to be representative, the values of k_{v0}' vary from 0.26 to 0.82×10^{-12} m/s, e_{ip} varies from 4.3 to 5.2, k_{ip} varies from 0.91 to 3.6×10^{-7} m/s and the in situ permeability anisotropy r_{k0} varies from 1.8 to 3.1, i.e. the clay deposit is very uniform.

Table 3 also shows the parameters I have found (Juárez-Badillo, 1991) for other soils; additional data are given in Juárez-Badillo (1983).

An important topic for future research is the variation of all of these parameters as a function of the mineralogy, size, form, structure and activity of the solid particles and of the quality of water.

The relationship between the parameter C_k used by the Authors and κ is

$$C_k = de/d \log k = 2.3k \, de/dk \quad (13)$$

Thus

$$\frac{1}{k} \frac{dk}{de} = \frac{2.3}{C_k} \quad (14)$$

and, as

$$\kappa = \frac{dk/k}{de/(1+e)} = \frac{1+e}{k} \frac{dk}{de} \quad (15)$$

Table 3. Characteristics of laboratory permeability tests

Depth: m	Test	e_0	k'_0 : 10^{-12} m/s	κ	$\kappa_v - \kappa_h$	e_{ip}	k_{ip} : 10^{-7} m/s	r_{k_0}	k_0 : 10^{-9} m/s
3	k_v oedometer	1.37	1.2	8.5	1.0	(0.25)	—	—	1.84
	k_h radial flow	1.65	1.5	7.5	—	—	—	—	2.24
6	k_v oedometer	1.97	0.82	6.7	1.5	5.1	1.5	2.9	1.21
	k_v triaxial (UL)	1.93	2.9	5.7	0.5	(16.7)	(380)	2.5	1.33
	k_h radial flow	1.84	12.2	5.2	—	—	—	—	2.78
9	k_v oedometer	2.20	0.25	7.0	1.0	(24)	(14,000)	(7.8)	0.86
	k_v triaxial (UL)	1.95	0.40	7.5	1.5	5.2	3.6	3.1	1.34
	k_h radial flow	1.74	6.2	6.0	—	—	—	—	2.62
12	k_v oedometer	1.89	0.34	7.5	1.0	4.3	0.91	1.8	0.97
	k_v triaxial (UL)	1.86	2.5	5.5	(-1.0)	—	—	—	0.81
	k_h radial flow	1.88	1.8	6.5	—	—	—	—	1.74
15	k_v oedometer	1.73	0.26	7.6	—	—	—	—	0.54
	k_h radial flow	1.60	1.5	6.6	1.0	4.8	1.6	2.2	0.82
	k_h radial flow	1.45	0.60	9.4	(-1.8)	—	—	—	2.73
Kaolin tested by		k_v	11.1	5.5	2	2.4	0.093		
Al-Tabba & Wood (1987)		k_h	128.3	3.5	—	—	—		
Mexico City clay		k_v	0.08	4.0	—	—	—		
Clay tested by Basak (1972)			—	—	4.5	—	—		
Sand statically		k_v	2.65×10^{-6}	10.4	2.4	0.815	1.31×10^{-3}		
compacted			m/s				m/s		
Chapuis <i>et al.</i> (1989)		k_h	11.1×10^{-6}	8.0	—	—	—		
			m/s						

then

$$\frac{1}{k} \frac{dk}{de} = \frac{\kappa}{1+e} \quad (16)$$

Comparing equations (14) and (16) gives

$$C_k = 2.3(1+e)/\kappa \quad (17)$$

Equation (17) is very similar to the relationship between the compressibility index C_c and the coefficient of compressibility γ (Juarez-Badillo, 1975)

$$C_c = 2.3\gamma(1+e) \quad (18)$$

The values of C_k and C_c decrease when the volume decreases and both tend to zero, as they should, when the volume tends to zero ($e = -1$).

By taking $e_0 = 2$ and $\kappa_v = 7$ with $\kappa_h = 6$, for this clay in the neighbourhood of e_0 , equation (17) gives

$$C_{kv} = \frac{2.3}{7} (1+2) = 0.9857 = 0.5e_0 \quad (19)$$

$$C_{kh} = \frac{2.3}{6} (1+2) = 1.15 = 0.58e_0 \quad (20)$$

Equation (19) agrees with the equation quoted by the Authors. For large compressive strains, the variation of C_k may be taken into account by

equation (17), i.e. C_k is directly proportional to $1+e$.

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