A STUDY ON THE DETERMINATION OF EFFECTIVE POROSITY OF POROUS MEDIA UNDER UNSATURATED CONDITIONS

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1. Introduction

Fluid flow and storage take place in the voids of soils and rocks. However, very small pore spaces and pore throats are not available for fluid flow. The porosity that is available for fluid flow is referred to as effective porosity (n_e). In unsaturated aquifers, effective porosity is an important parameter in the estimation of the storage capacity of underground dams and how much groundwater can be pumped out in order to refresh the stored groundwater. Effective porosity is an important parameter in the estimation of groundwater velocity, saturated hydraulic conductivity and contaminant transport modeling (Flint and Selker, 2003; Gehlin and Hellström, 2003; Suleiman and Ritchie, 2001; Timlin et al., 1999; Hudak, 1995; Helalia, 1993; Bair et al., 1991; Hall et al., 1991). Due to its importance, several methods have been developed to determine n_e but under saturated soil and rock conditions. These include mercury intrusion porosimetry, mixing models, tracer tests and field pumping tests (Andriani and Walsh, 2002; Kong and Li, 2001; Yeh et al., 2000; Stephens et al., 1998; Ii et al., 1996; Novakowski et al., 1996). Using the Frequency Domain Reflectometer (FDR) method, Nishigaki et al (2003) have carried out extensive tests on real-time determinations of n_e in saturated sand columns in the laboratory and have found the method to be very reliable. Under unsaturated conditions, however, methods for determining n_e are not well developed. Such methods are especially needed in studies on underground dam storage conditions which occur under unsaturated conditions in unconfined aquifers. This study proposes a constant flow rate injection method for determining the effective porosity of unsaturated river sand in the laboratory
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2. Mathematical formulation

Under constant flow rate conditions, the relationship between flux (q_o), permeation front, $L_{(t)}$ and effective porosity (ne), and is given by:

$$q_0 t = L_{(t)} n_e \tag{1}$$

where, q_0 = flux = $Q_{(t)}/A$ and where Q = flow rate, A is the cross-sectional area of flow. Therefore,

$$L_{(t)} = \frac{q_0 t}{n_e} \tag{2}$$

The slope, M_1, of graph $L_{(t)}$ - t (Fig 1) is given as:

$$M_1 = \frac{q_0}{n_e} \tag{3}$$

Therefore, $n_e = \dfrac{q_0}{M_1}$ (4)

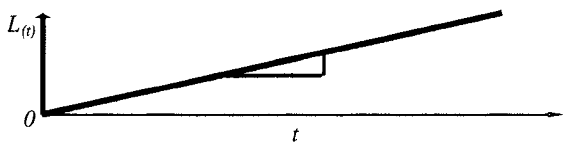

Figure 1. Progression of permeation front

From Darcy`s equation

$$v = -ki = -k\frac{\partial h}{\partial x} \tag{5}$$

where v = k = permeability coefficient and i = hydraulic gradient) and from the continuity equation $Q = vA$ (where Q = flow rate; v = flow velocity and A = flow section):

$$q_0 = -k\frac{\partial h}{\partial x} \tag{6}$$

The boundary conditions are:

$$x = 0: h = h_{0(t)};\ x = L_{(t)}:\ h = h_c \tag{7}$$

where, $h_{0(t)}$ = pressure head at time t and h_c = intial critical pressure head. Integrating Equation (6):

$$q_0\int_0^t \partial x = -k\int_0^t \partial h \tag{8}$$

$$h_{0(t)} = \frac{q_0}{k}L_{(t)} + h_c \tag{9}$$

and substituting (2) into (9):

$$h_{0(t)} = \frac{q_0}{k}\cdot\frac{q_0 t}{n_e} + h_c = \frac{q_0^2 t}{kn_e} + h_c \tag{10}$$

For h$_c$ = 0, $h_{0(t)} = \dfrac{q_0^2 t}{kn_e}$ (11)

The slope, M_2, of graph $h_{o(t)}$ - t (Fig 2) is given as:

$$M_2 = \frac{q_0^2}{k}\cdot\frac{1}{n_e} \tag{12}$$

Therefore, $k = \dfrac{q_0^2}{n_e}\cdot\dfrac{1}{M_2}$ (13)

3. Laboratory tests

To evaluate the validity of the above mathematical models, constant flow rate injection tests were carried out on River sand in horizontal columns in the laboratory. The normal porosity and degree of saturation of the River sand were 0.4 and 8 %, respectively. The particle size distribution of the River sand was as shown in Fig. 3. Three (3) levels of viscousity of injection fluid were used, viz: μ = 1, 44.9 and 88.8, respectively. Figure 4 shows the experimental set-up.

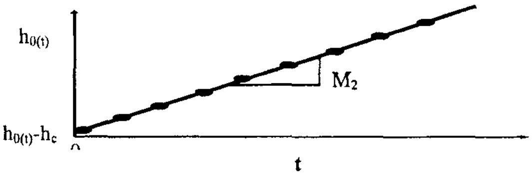

Figure 2. Variation of pressure head with time

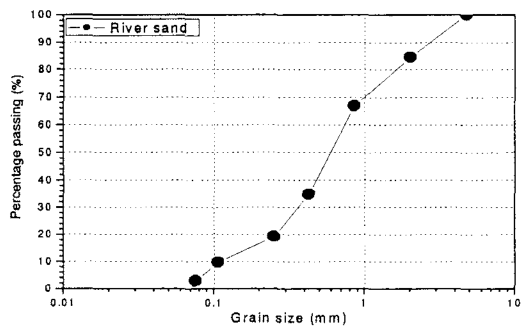

Figure 3. Particle size distribution of River sand

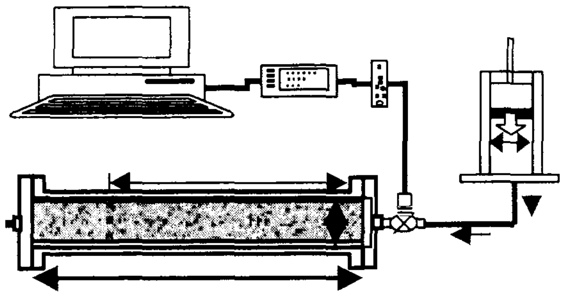

Figure 4. Experimental set-up

4. Results and Discussion

Table 1 shows the summary of the results obtained from the laboratory tests. The average effective porosity (n_e) ranged from 0.24 to 0.31, with increasing viscousity. These were 60-93 % of the normal porosity. In similar tests at constant injection pressure, the corresponding effective porosities were 0.19 and 0.26. Nishigaki et al (2003) obtained effective porosity values of 0.27–0.34 in a comparative study using the Frequency Domain Reflectometer systems.

Table 1 Laboratory results

Test	μ (mPa · s)	Q (cm^3/s)	A (cm^2)	q_0 (cm/s)	M_1	M_2	n_e	k (cm/s)	n_e/n	Av. n_e
1-1	1	2.68	21.24	0.126	0.54	2.17	0.23	3.13E-2	0.59	0.24
1-2	1	2.68	21.24	0.126	0.51	1.84	0.25	3.50E-2	0.62	
1-3	1	2.68	21.24	0.126	0.51	1.96	0.25	3.25E-2	0.62	
2-1	44.9	2.66	21.24	0.125	0.44	32.19	0.29	1.69E-3	0.72	0.29
2-2	44.9	2.66	21.24	0.125	0.43	36.52	0.29	1.46E-3	0.73	
3-1	88.8	2.65	21.24	0.125	0.59	86.40	0.21	8.56E-4	0.53	0.31
3-2	88.8	2.65	21.24	0.125	0.34	83.73	0.37	5.03E-4	0.92	
3-3	88.8	2.65	21.24	0.125	0.36	89.89	0.35	4.98E-4	0.87	

5. Conclusion

In this paper, we have proposed a new method of constant flow rate injection for determining the effective porosity of a porous media under unsaturated conditions in the laboratory. For River sand, with porosity (n) of 0.4 and 8 % saturation, the average n_e varied from 0.24 to 0.31, with increasing viscuosity. These results compared favourably with those obtained by other workers. Further research work on the proposed method is on-going.

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