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A model for the interpretation of the experimental drainage moisture characteristic

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ABSTRACT

A model for drainage is developed in terms of numbers rather than sizes of pores, recognising that some pores may be blocked or isolated during drainage. The total number of pores is evenly distributed between ten moisture potential steps. The proportion of each of the ten pore size groups that have drained by the end of each drainage step is presented as the *Ld* distribution.
The results of the model are discussed:

a) in the initial stages of drainage, before there is air continuity throughout the medium, the majority of larger pores are not detected;
b) at the stage where there is air continuity, most of the large pores belonging to the four largest groups drain and therefore the apparent number of middle sized pores (as determined by the moisture potential at which they are measured) is overestimated;
c) at the drier end of the moisture characteristic, isolation dominates and the majority of the three smallest groups are unable to drain.

An example of the procedure to amend the results for any particular experimental configuration is presented in the Appendix A to reproduce the experimental results reported in the literature and to derive the real pore size distribution. The qualification is that the model can only be used if precise drainage procedures and dimensions have been reported in the literature. The consequences for the calculation of the hydraulic conductivity from experimental moisture characteristics are considered.

1. Introduction

Childs and Collis-George (1950) presented a method for calculating the hydraulic conductivity of porous materials based on the drainage moisture characteristic. They erroneously assumed that the characteristic described the pore distribution of the sample under investigation. Their assumption had been unchallenged until recently (Collis-George, 2012). This challenge does not affect the current interpretation of the characteristic to describe accurately the mode and size of the pores emptying during drainage.

The use and development of the model presented herein differs from the approach of the many papers in the literature since then, e.g. Grant et al. (2010), Yang and Lu (2012), where the emphasis has been on procedures to predict the moisture characteristic from first principles rather than to reinterpret experimentally determined ones. Many of authors have used mathematical models to derive experimental relationship that rely on several parameters of questionable physical meaning as well as matching an experimentally determined value of the matric potential at a known moisture content (Hunt et al., 2013).

The misinterpretation of the experimentally determined moisture characteristic to describe pore-size distributions in particular the underestimation of the proportion of large pores has implications for the understanding of the habitat and culturing of microorganisms in porous media, including soils (Wallace, 1968), and for the movement and recovery of fluids in porous media.

This paper by contrast presents a relatively simple procedure to make a more accurate description of the real pore size distribution from experimentally determined moisture characteristics.

2. Assumptions in the development of the model

1) That the total volume of the media can be represented by a small unit e.g., a column with area of 100 pores and vertical side of 20 pores, that is replicated through the media and where each unit is surrounded by identical units.
2) That each unit contains exactly the same number of each pore group.
3) That the geometry of the porous medium be such that each pore has six neighbours, one above and one below and four in the same "layer". A "layer" need not be exactly planar but be an approximately horizontal surface that passes through the centres of the pores

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in that layer. It follows that each pore also has four neighbours in an approximately vertical plane.

4) That each layer has equal numbers of pores from each pore group.
5) That the pores are randomly distributed, i.e., there is no organised clustering of either larger or smaller pores and consequently a largest pore can be adjacent to a smallest pore.

3. Definition of *L* and *Ld*

For each moisture potential, corresponding to the end of a step, *j*, let the sum of the proportion of pores of a size potentially able to empty be *Lj*. At the start of the moisture characteristic, $Lj = 0$ and at the end $Lj = 1$. For a value of *Lj*, there is a corresponding matric potential Ψj. Not all of the pores composing *Lj* can drain at the value of Ψj; because some are blocked, Lj_b, some are isolated, Lj_i. The pores that have drained by Ψj equal the difference Ldj.

4. Procedures

1) To construct a unit, each layer is randomly filled with the numbers 9 to 0 in equal proportions, where 9 refers to the largest pores. This implies nothing about the matric potential associated with each size group, nor of the distribution of pores in the medium. The pore size distribution can be of any pattern, e.g., log normal, so that the range of pore sizes in any group will vary according to the original distribution. The only stipulation is that the largest ten pores are in group 9, the next largest ten pores are in group 8, etc., so that the smallest tenth are in group 0. For a column with 100 pores per layer, ten of each size group are randomly placed in each layer. The difference between placing all the 9s before starting to place the 8s as distinct from placing one of each size and then repeating the sequence 10 times is found to be minor. Units composed of columns 20 layers thick and with either 100 or 400 pores per layer were used. Since the porous body is made up of identical columns side by side, a pore on a vertical face of the column is adjacent to a pore with the same properties as one on the far side of the column. As would be expected, examination of the columns shows chains and clusters of both the larger pores (9 to 6) and of the smaller pores (4 to 0). Clustering in which larger pores, say 9 and 8, cannot be adjacent to smaller pores 1 and 0 can be built into the construction of a column with the consequence that Ld is slightly larger for the first three steps but has minimal effect on the major conclusions.
2) The pre-drainage programme:
    a. Initially all pores are coded “neutral” (included in the code is the original size);
    b. The pores in the layer adjacent to the drain are coded “full” if they are undrained (the start of the first step all pores are full of water);
    c. The pores in the layer above the layer adjacent next to the drain are coded “full” if they are “neutral” pores and are in contact with a full pore in the layer beneath. Each layer is then repeatedly searched for “neutral” pores adjacent to “full” pores and in their turn converted into “full” pores. This is repeated layer by layer to the top-most layer. Hence a “full” pore is one that has water continuity to the drain.
    d. Any “neutral” pores left after this search are not in contact with the drain although full of water and are reclassified as “isolated” pores and take no part in subsequent drainage steps;
3) The drainage programme
    a. Starting with the largest pores, 9. All size 9 pores in the top layer that are “full” are emptied and coded as “empty” pores. The layers beneath are repeatedly searched for size 9 pores and when found to be in contact with an “empty” pore in any of the adjacent pores they are turned into “empty” pores. (end of drainage step 1):
    b. All remaining pores full of water in all layers are coded as “neutral”. Then pre-drainage programme c is repeatedly applied to identify all pores in all layers that are in contact with the drain as “full”. This is followed by sub-step d to identify “isolated” pores.

Drainage Step 2 now starts. All size 8 pores in the top layer are emptied. The layers beneath are successively searched for “full” pores of sizes 9 and 8 in contact with “empty” pores, and are converted into “empty” pores (End of Drainage Step 2).

Pre-drainage programmes c and d are now carried out in preparation for Drainage Step 3, which involves pores of sizes 9, 8 and 7.

The process is repeated with increasing numbers of pore sizes at each succeeding drainage step.

The drainage programme requires repeated searching of each layer to ensure that each pore is correctly labeled at the end of each drainage step. This meets the requirements that for a pore to drain there is both continuity of air from the upper layers and continuity of water-filled pores to the drain.

5. Results

40 columns each 20 layers thick were constructed using random procedure 1) and then drained using procedure 2). 20 columns had 100 pores per layer and 20 had 400 pores per layer. For every drainage step, the means of the number and the size of the drained pores for the two sets, each of 20 columns, are indistinguishable in terms of their standard deviations. Detailed examination of the results of the 40 columns shows that the depth of penetration of drained pores before breakthrough is never greater than six layers. These two results imply that columns of area 100 pores and 20 layers depth are more than adequate for the description of pore drainage. The means are presented in Fig. 1 as proportions of the total number of drained pores in each column, L_{dj}, relative to the initial number of pores, L_j. Breakthrough comes before the end of drainage Step 4 and would occur regardless of the number of layers. Its position is indicated roughly in Fig. 1. Indicated on the figure is the region ($L = 0$ to < 0.4) where blocking of large pores by undrained small pores is the dominant process and also the region ($L = 0.7$ to 1) and where most small pores are isolated by drained larger pores and where simultaneous water continuity is limiting.

Step 0 in Fig. 1 effectively starts at the end of consolidation and of the partial drainage of the open half pores on the external surface of the sample.

The composition of the drained water in terms of the proportions of each pore group size at the end of each step is summarised in Table 1.

The percentages with their standard deviations are derived from the analysis of the 40 random columns. In view of the smallness of the standard deviations, analysis of additional columns will not substantially alter the conclusions.

6. Modification of L_d

The L_d results above are for columns 20 layers thick. L_d is adjusted when a) the number of layers is different, and b) when the geometry is not that of a flat disc, and c) when consolidation has occurred so that drainage through the sides as well as the original air interface can occur. Because during steps 4 to 7, there is both water and air continuities, no adjustment of L_d is needed in this interval for any geometry.

The thicker the sample in terms of layers of pore relative to 20 layers, the greater the reduction in L_d for all steps other than 4 to 7. An estimate of the number of layers can be obtained from the thickness of the sample relative to the average diameter of the aggregates.

(For intraporosities of 36%, the layer spacing is ~ .875.D_m, whereas for tetrahedral layer spacing is 0.75. D_m, and for cubical is 1.D_m). When D_m is not experimentally available an approximate mean diameter, D_m, is obtained from the relation: $D_m.\tau_m = 1.04 \pm 0.03$ where τ_m is the matric potential at the middle of the experimental drained moisture range. (Both τ_m and D_m are in cm.) This relation was obtained from 12