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with an increase of turbulence characteristics. Both Figs. 17 and 18 show a similar trend if compared with the studies of Ko and Graf (15,16) for circular cylinders.

Accordingly, the drag coefficient of the cube can be evaluated for turbulent flow provided the turbulence characteristics can be determined.

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Perturbation Analysis of Two-Phase Infiltration*

Discussion by Charles B. England,[5] Chin L. Yen,[6] A.M. ASCE, and Robert M. Dixon[7]

The dynamics of flow and compression of displaced air during water infiltration into soils has been considered too complex to model, or its importance in the field has been deemed negligible. The authors not only have presented a computationally-efficient method for solving the equations describing the process, but they also have demonstrated the effects entrapped air can have on the infiltration rate curve and the saturation profile in stable homogeneous porous media.

By considering air flow and compressibility the authors' analysis for two-phase infiltration is more realistic physically than the traditional unsaturated flow equation; however, as in traditional theory, assumptions of porous media homogeneity and stability are made. Both of these assumptions are seldom satisfied in actual soils and thus can lead to unrealistic conclusions concerning the interaction and relative importance of gravity, capillarity, and soil air in the infiltration process.

Soils, as they occur in nature, usually contain macroporosity (in addition to the microporosity commonly used to test traditional theory) that greatly

*September, 1972, by Alain Noblanc and Hubert J. Morel-Seytoux (Proc. Paper 9186).

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influences soil air and water movement during infiltration (14). Surface-connected macroporosity readily vents displaced soil air through the soil surface at pressure differences one order of magnitude lower than those given in Fig. 8; however, infiltration is still greatly reduced since these air vents would otherwise be contributing greatly to infiltration. Thus, very low soil air pressures can greatly reduce infiltration by restricting the gravitational flow of water into the surface-connected macroporosity (13).

A saturated soil surface is highly unstable, often more nearly behaving as a suspension or fluid than as a stble, porous layer. Therefore, in soils containing surface-disconnected macroporosity the saturated soil surface is ruptured by much less soil air pressure than that required (according to capillary theory) to force air through a stable microporous surface. Air bubbling through this rupture erodes a relatively stable conical crater or a surface connection for the macroporosity. After the soil air pressure is reduced enough, this crater conveys free surface water into the underlying macroporosity, thereby causing a marked increase in infiltration. Although this increase would be in general agreement with those shown in Fig. 6, the physical basis is very different.

In soils having surface-connected macroporosity an increase in infiltration also can probably be demonstrated; however, this increase would be caused by air counterflow only in the terminal ends of a few open macropores rather than the uniform counterflow as envisioned by the authors.

Soil surface roughness or microrelief (another form of soil heterogeneity) interacts with soil macroporosity to affect profoundly the counterflow of free water and soil air through the soil surface. A smooth surface favors balance between the opposing hydrostatic and pneumatic forces, whereas a rough surface creates imbalance.

The authors' statement that the total velocity, V, is only a function of time appears to be a rough approximation. For two-phase flow of air and water, the equation of mass conservation for the air-phase can be written as

$$\Phi \frac{\partial[\rho_a(1-S)]}{\partial t} = \frac{\partial(\rho_a V_a)}{\partial v} \qquad (31)$$

Combining Eqs. 10 and 31 yields

$$\frac{\partial V}{\partial z} = -\left[\Phi(1-S)\frac{\partial \rho_a}{\partial t} + V_a \frac{\partial \rho_a}{\partial z}\right] \qquad (32)$$

Now, one can see that only if the right-hand side of Eq. 32 vanishes, then $V = V(t)$. The authors' results presented in this paper (Fig. 8) and elsewhere (5) indicate that variations of air pressure, with respect to both space and time, are of significant magnitude. Therefore, the adverse effect that this approximation has on the computed results may not be negligible. Also, in arriving at Eq. 19, a term, "$\epsilon E(S)(\partial^2 S/\partial z^2)$", has been dropped. This term may be negligibly small in comparison with the term, "$\epsilon E'(s)(\partial S/\partial z)$", at low p_c values. However, this is not necessarily true at medium p_c values because the p_c' value [consequently, $E'(S)$] is small (see Fig. 2).

In the treatment of air-phase, the fact that air can be gradually absorbed by water has not been taken into account. There is evidence (15) that air absorption by water is quite significant if the soil surface is ponded for a few days. The

absorption of air certainly reduces air counterflow. Had this been taken into consideration, the difference between the hydraulic conductivity and the computed asymptotic infiltration rate should not be as large as those shown by the authors.

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Discussion by Willem F. Brutsaert[8]

The authors clearly demonstrate the merits of a two-phase flow approach to certain infiltration problems. Based on the analytical treatment of one-dimensional infiltration the authors made the following statement in the abstract: "It is recommended that the traditional unsaturated flow equation be abandoned in favor of the two-phase flow approach." The writer feels that this statement needs modification. The authors should make it clear that their statement holds only in the case of one-dimensional infiltration with a water table boundary condition. Obviously, the one-dimensional approach with water table condition does not permit the sideways escape of air from the column resulting into resistance to flow of air with compression of the air phase. Neglecting the resistance to flow of air and recognizing the large differences in viscosity between air and water is the basic assumption of the Richards one phase flow approach. Experiments, summarized, e.g., in Braester, et al. (16), have shown that whenever this assumption is not violated (permitting free flow of air) good agreement is obtained with theory. In general, infiltration is at least a two-dimensional flow phenomenon with little resistance to flow of air in some instances and therefore, the Richards approach is a valid approximation.

The recommendation of the authors to abandon the Richards approach seems to be based mostly on the fact that they have computed infiltration rates always below the value of hydraulic conductivity at residual air saturation. Soil scientists and some hydrologists, on the other hand, have indicated that the infiltration rate asymptotically approaches the value of hydraulic conductivity at residual air saturation. Physically, this infiltration rate limit does not exist and depending upon the ponding conditions (depth of water ponded) infiltration rates either below or above this limiting value can be obtained. Mathematically, this phenomenon can be modelled with the Richards equation by selecting its proper form (17,18). The Richards equation in three dimensions for homogeneous isotropic media can be written in one of two forms: the moisture content form

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