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Reply

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1. Introduction

We are delighted by the interest manifested by *Kirby and Smiles*, [this issue] and we welcome the opportunity they provide us to clarify the two main points of their comment.

2. Theoretical Issues

Kirby and Smiles [this issue] acknowledged that dual-energy synchrotron X-ray measurement is a powerful procedure for quickly and accurately measuring the bulk density and water content profiles but objected to the formulation of our (7a), (7b), and (8) [*Garnier et al*., 1998]. It is clear that in the work of *Garnier et al*. [1998] we can calculate the fluxes $q_{s/o}$ and $q_{w/o}$ with (9) and that $D_{w/s}$ in (8) can be rewritten using (6) and (7) in terms of these fluxes as

$$D_{w/s} = \frac{q_{s/o}\dfrac{\theta_w}{\theta_s} - q_{w/o}}{\dfrac{\partial \theta_w}{\partial z}}, \tag{1}$$

which is exactly like (5) of *Kirby and Smiles* [this issue], correcting a misprint in the sign. That is, our use of $D_{s/o}$ and $D_{w/o}$ was just an intermediate step which has no impact on the result. Thus their worry about our use of (7), even if justified, does not affect our results on $D_{w/s}$.

Kirby and Smiles [this issue] also state that our results are "quite inconsistent with the form that this equation must take [see, e.g., *Philip*, 1968, equation (9)]." The "inconsistency" with (9) of *Philip* [1968] is that the latter includes a "drift velocity" due to the flux of water at the base of the column. In fact, *Philip* [1968, p. 249] explicitly states that "the work deals specifically with the case where the solution exchange with the paste column is possible only through its base." In our experiment, on the contrary, the exchange is through the top of the column only, and, consequently, there is no need to account for a drift velocity. Had *Philip* [1968] considered a situation similar to ours, his equation would have been perfectly consistent with our (7). Hence the counterargument of *Kirby and Smiles* [this issue] does not prove that (7) is incorrect. Clearly, the similarity of *Philip* [1968] and our solution should have been made in the paper, and we are grateful for the opportunity to do so.

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3. Physical Constraints

Kirby and Smiles [this issue] implied that we were not aware of the physical constraints on our samples. The opposite is true, but their comment is understandable because a number of experimental details about possible wall friction effects were omitted in the interest of brevity. Wall friction was minimized by rounding off the corners with a smooth but hard sealant and by lubricating the walls with an oil. Moreover, to minimize friction, unlike the experiment of *Smiles and Colombera* [1975], no overburden pressure (except for the 2 cm ponded water) was applied. We could check that our attempts to minimize wall friction were successful by looking closer at our experimental results: (1) the surface of the soil remained flat and did not bulge, which could have indicated substantial friction, and (2) the swelling curves for all depths were identical [*Garnier et al*., 1998, Figure 5]. These experimental observations indicate that it is likely that the wall friction is negligible. Finally, the method of using ring sections that can be separated during swelling as suggested by *Kirby and Smiles* [this issue] is not feasible for measurement with X rays because the attenuation of the walls need to remain constant during the experiment.

It is dubious whether the results obtained by *Lal et al*. [1970] and *Bridge et al*. [1970] can be applied. Their soils were greatly different from ours, their infiltration rates were faster than ours, and the bulk density changes were likely much different. So it is not obvious that their results are transferable to our experimental situation, especially since our results indicate a minimal effect of the wall.

We appreciate the effort of *Kirby and Smiles* [this issue] in carrying out a simple experiment to test the validity of our experimental results. Similar to *Smiles and Colombera* [1975] and *Kirby and Smiles* [this issue], in our experimental results [*Garnier et al*., 1998, Figure 3] a linear part in the cumulative infiltration and soil heave can be distinguished until a characteristic time (15 min for the bentonite and 81 min for the vertisol). As shown by *Kirby and Smiles* [this issue], the wall friction is minimal during the time when the square root of time relationship is valid. Certainly, during this initial period the decrease in diffusivity with time can be associated with a decrease of interaggregate pore space due to the swelling of these aggregates, but even later in the experiments when the part of the decrease in swelling can be attributed in part to the constraints imposed by the wall, the flow of water certainly remained one-dimensional.

Finally, the Cornell High Energy Synchrotron Source is a National Science Foundation supported facility and can be used by all scientists. We would be delighted to cooperate with Kirby and Smiles on a new set of experiments to obtain a better understanding of swelling and wall friction. Data could be taken with dual-energy synchrotron radiation so that changes in bulk density could be examined at different locations (near and farther from the wall) for soil samples in containers with different dimensions.

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