J. Jpn. Soc. Soil Phys.
土壌の物理性
No. 152, p.3 ∼ 6 (2022)

What perspective will best lead soil physics into the future?

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Because so many issues facing humanity (food security, fresh water, nutrient management, energy reserves, climate change, recycling and decay, etc.) are connected to soil preservation and health (Janzen et al., 2011), these authors argue that fundamental understanding of soil is necessary: "The place to start is knowing soil." But knowing soil physics is critical to knowing soil. In the context of a network model of soil and percolation properties of networks, one can learn how to predict the water balance (cycle) from optimizing the productivity of the plants (Hunt et al., 2021a) along a climate gradient. In order to optimize plant productivity, one must be able to relate it to how plant growth and soil depth depend on the fundamental hydrologic fluxes. The result then links climate change, water, food, nutrients, and energy, five of the eight issues presented, as well as ecosystem adaptation.

Unfortunately, the soil physics curriculum does not contain the physics required to understand these developments. Relatedly, soil physicists face an identity crisis (Hunt et al., 2013a), requiring a paradigm shift (Hunt et al., 2021b). The curriculum in place, based on a simple mental picture, is unsuited to the medium we study. Soils are not continua, but physical networks, while capillary bundle models breed misconceptions. Soil networks underpin the biological networks that operate over them (Hunt and Manzoni, 2016). That soils are not homogeneous was emphasized by Nielsen et al. (1973), but the unsuitability of capillary bundles was already noted by Fatt (1956). Whatever connectivity/tortuosity corrections get pasted on to capillary bundles, they are unrelated to the properties of any natural network. Abandoning these two concepts presents the greatest intellectual challenge to the discipline.

Are soils really heterogeneous? Evaluations are typically based on appearance. However, heterogeneity itself needs to be assessed within a network model, in which the network links represent the difficulty of movement of water from one pore to the next. With typical ranges of pore sizes covering a couple orders of magnitude, Poiseuille's law generates 6, or even 8, orders of magnitude (a factor of one hundred million) of local hydraulic resistance values, which is large heterogeneity. Tortuosity and connectivity become network properties; heterogeneity in local flow/transport coefficients is balanced by finding much longer connected paths that avoid the blockages.

To proceed, we must first replace continuum models by network models (thereby eliminating any need for capillary bundles); the fundamental soil physics quantities and any scale-dependence they may exhibit, must then be obtained directly from the networks. Then we need to be aware of the limitations of our available tools. According to user's manuals (e.g., Hunt and Sahimi, 2017), stochastic methods (perturbation theory) can address only small heterogeneity, the effective-medium approximation can handle small to moderate heterogeneity, and percolation theory (PT) can be adapted to all ranges of heterogeneity, but is exact in the limit of large heterogeneity. Given that PT has a consistent and systematic treatment of the variation in local geometry together with quantitative descriptions of the scale dependence of properties like tortuosity and connectivity, it offers what we need. Further, the salient point of applying PT to heterogeneous materials is that it quantifies the tendency of water to follow paths of least resistance.

What do we gain from PT applied to network models? Its fundamental advantage is that it transforms a disorganized study into a science. How it does so, is outlined in part:

- It clarifies that average values of flow (or conduction) properties have a relationship with observed (effective) quantities only in specific two-dimensional (2D) cases; but in 2D, a grain-supported medium permits no flow,
- It eliminates internal contradictions in formulae (Hunt, 2004a), e.g., between the treatment of pore-size effects and connectivity. These contradictions render the van Genuchten (1980)[1] (vG) and related formulations unscientific

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[1] By using the capillary bundle model with its averaging, vG effectively assumes a residual moisture content of zero, but in its connectivity/tortuosity correction, it makes this parameter adjustable.

(with such internal contradictions, flexibility is maximized, but predictability is sacrificed and the impossible is allowed),

- It unifies interpretations of, e.g., residual water across properties,
- It unites understanding of properties,
- It places the theory of connectivity/tortuosity on solid footing and allows simultaneous assessment of the effects of geometry (pore size/shape/roughness) and topology (connectivity/tortuosity) on each property individually,
- It makes actual predictions possible,
- It reduces uncertainty in inverse modeling and in interpretation of measurement,
- By clarifying differences between heterogeneous media and homogeneous media, the distinctions between living and non-living media become clearer as well,
- It can change the perspective of a field as being too complex for solution, to one which offers soluble problems, if addressed logically.

A few further specific examples for which PT has generated predictive understanding:

- Prediction of hysteresis in pressure saturation curves using particle-size information and an inference of the critical moisture content for percolation (Hunt, 2004b),
- Understanding (Hunt et al., 2013b) of the nearly universal behavior expressed across saturation dependences of air permeability, electrical conductivity, and solute and gas diffusion, since these reflect the universal connectivity and tortuosity properties of connected paths through random networks near the percolation threshold (for either wetting or nonwetting component),
- Understanding of how experimental uncertainties (dissolution of ions, contact resistances, etc.) can obscure such universality (Ewing and Hunt, 2006),
- Predicting entire solute arrival time distributions accurately with no adjustable parameters (Ghanbarian-Alavijeh et al., 2012),
- Predicting soil depth from decades to 150 Myr (Hunt et al., 2021c) as a function of the infiltration flux, time, and parent material. This advance effectively gives functional form to Jenny's soil formation factors for the first time (multiple examples),
- Developing a model which explains both the spatial variability and the time dependence from minutes to 100 kyr of vegetation growth (Hunt et al., 2020; Hunt et al., 2021c).

I believe that it is not the models themselves, but the adaptation of soil physics thought to their lack of success, which is the most serious problem facing our field. In this way, soil physics seems to me to foster a culture of followers at the expense of critical thinking. For the chief recommendation of the continuum models and constitutive relations used is that everybody uses them (see, e.g., the vG model above), and the chief criticisms, that they lack physical basis (treatment of connectivity issues) and do not work, are downplayed by the argument that no models work, or that the subject is too complicated to address. With such a foundation, a discipline will not thrive.

In an effort to increase its relevance, soil physics has allied itself with hydrology. But both disciplines eschew theory: "different men know, or think they know, different things. [the picture] becomes more distorted with increasing dependence on theory." (Cline, 1961, "The changing model of soil") "In physics, it is possible to distinguish between a successful theory and an unsuccessful one. Hydrology is different; every perspective is equally valid." (Frontiers in Hydrology 2022 conference attendee, 6/22/2022). Denial of the fundamental physical nature of flow and transport in porous media is unhelpful. Falsifiable predictions can be made. But bases for derivations of soil physics include: 1) maximizing flexibility, 2) maximizing ease of computation in a continuum model. These are not strategies that ensure reliable means of relating a model to observation. And the less said about the situation in hydrology, the better; model results are typically irreproducible (Hutton et al., 2016)!

Understanding the limitations of continuum models is furthered by examining when they work best. Of course, continuum models for heterogeneous systems perform optimally when discretized at the pore-scale. However, these are the network equations considered.

The dwindling research support for fundamental soil physics in recent decades may be related to the above difficulties. Soil physics has maintained a strong footprint in applied problems, but success in advancing understanding with its traditional playbook has been rare. It has frequently been asserted that, as the 20th Century was the century of physics, the 21st Century will be the century of biology. In particular, biological networks in soils and the critical zone are now a dominant (emergent) topic. But the network approach to soil physics is highly productive in linking soils with biology.

Why did soil physicists not adopt percolation techniques, when chemical and petroleum engineers like Muhammad Sahimi (1993) have been able to exclaim that there is scarcely a problem in porous media which is not based on PT? Michael Pollak (obituary in Physics Today, Castro-Neto et al., 2019) applied PT techniques in 1971 to find the connected conducting paths through amorphous semiconductors with the lowest cumulative resistance and thus their electrical conductivity. It is not surprising then that soil physicists like Nielsen did not adopt a method of calculating effective properties of disordered media, which was first employed in the physics literature only two years before the seminal paper. My personal history explains why I made the connection. Michael Pollak was my dissertation advisor in physics. In the 1990's I began a transition from physics to soil physics, working with Zbigniew Kabala on stochastic subsurface hydrology (SSH). While I understood that SSH is a perturbative theory, I knew that PT takes into account heterogeneity to infinite order, with results that are exact near the percolation threshold, or, equivalently, in the limit of large heterogeneity, since in that case, dominant flow paths are always near the percolation threshold. This history is consistent with Wilford Gardner's (2009) assessment that advances in soil physics will come from those who obtained graduate degrees in physics.

Before closing, it should be mentioned that an entire range of problems, such as nonlinear processes in the unsaturated zone, may be better served by using network models on account of the sensitivity to small changes in initial conditions and model parameters. Chaotic signals tend to be hidden in continuum approximations. Understanding how long a deterministic chaotic model may inform predictions will also require the higher degree of accuracy conferred by use of difference, rather than differential, equations. As noted by Sivapalan (2005), hydrology lacks a central theory. I do not foresee such development in the near future, but any model change which can improve treatments of both nonlinearity and chaos as well as heterogeneity, as would be accomplished here, has as good a chance as any to bring us further on such a path.

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