Revisiting Axis Translation for Unsaturated Soil Testing

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Hilf's (1956) axis translation (AT) (also called pressure plates) is arguably the most widely used technique for controlling matric suction in laboratory unsaturated soil testing. Two assumptions are inherently involved in the AT: cavitation is not important in soil water retention (SWR), and matric suction ψ_m controlling a soil's water content is defined as the difference between pore air pressure u_a and pore water pressure u_w, i.e. [Fig. 1(a)]

$$\psi_m(w) = u_a - u_w(w) \tag{1}$$

A more general definition should include both capillarity and adsorption (Lu and Zhang 2019) [see Fig. 1(b) for illustration]

$$\psi_m(w) = u_a - u_w(x, w) - \psi_{ads}(x) \tag{2}$$

where x = statistical distance to a particle surface; and $\psi_{ads}(w)$ = soil sorptive potential (SSP) including electrical double layer, van der Waals, and hydration (Lu and Zhang 2019).

In nature, pore air pressure is controlled by the atmospheric pressure with a mean of 101.3 kPa at sea level. Pore water pressure can be higher or lower than pore air pressure, but cannot be lower than the cavitation pressure of water. The cavitation (saturated vapor) pressure at 25°C (298.2 K) is 3.2 kPa. Thus, capillary pressure $(= -\psi_m = u_w - u_a)$ reaches its cavitation pressure under a natural condition of $(u_w - u_a)_c = 3.2 - 101.3 = -98.1$ kPa. The negative sign indicates a value lower than the atmospheric pressure. Capillary pressure in soil with a water surface tension T_s (=72 mN/m at 25°C) and the interface radius r is governed by the Young–Laplace equation [Fig. 1(a)]

$$u_w - u_a = -2T_s/r \tag{3}$$

Therefore, the largest pore radius for cavitation pressure is: $r_c = -2T_s/(u_w - u_a)_c = \sim 10^{-6}$ m. As such, without the SSP, capillary water cannot exist in pores $< \sim 10^{-6}$ m. All capillary water down to $\sim 10^{-9}$ m (the size of water molecule) would be cavitated if there is no SSP.

In the lab, the practical upper limit of the AT is $u_a = 1{,}500$ kPa, which by Eq. (3) is equivalent to a capillary radius of $\sim 10^{-7}$ m. Thus the AT will prevent cavitation for capillary water in pores with sizes from $\sim 10^{-6}$ to 10^{-7} m, i.e., from μm to sub-μm.

Since all three components of SSP always elevate pore water pressure with a magnitude inversely proportional to distance from particle surface, soil water is less likely to cavitate. Van der Waals and hydration potentials generally only affect pore water pressure within a distance <10 water molecules or 3.0×10^{-8} m (e.g., Lu and Zhang 2019), so their effect on pressure increase has little impact on cavitation radius under the AT [Fig. 1(c), lightly shaded area]. Electrical double layer, however, can affect a distance of 10^{-7} m (e.g., Lu and Zhang 2019), depending on the thickness of the double layer that is strongly affected by pore water salinity and particle surface electrical potential. As such, it could elevate pore pressure at the same scale with the cavitation radius by the AT, suppressing the cavitation.

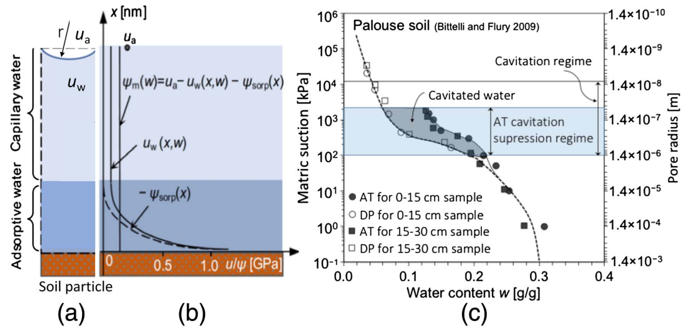

Fig. 1. (a) Capillary and adsorptive water in soil; (b) distributions of soil water pressure, SSP, and matric suction; and (c) SWR data under the AT for matric suction <1,500 kPa and DP for matric suction >100 kPa in Palouse soil (assuming specific gravity of 2.65).

Experimental SWR data by the AT and dew point (DP) (measuring matric potential through vapor pressure) for a silty (Palouse) soil [Fig. 1(c)] (Bittelli and Flury 2009) show significant and increasing discrepancies in the soil water content for matric suction >100 kPa, implying suppression of cavitation by the AT and a significant role of cavitation in soil water drainage in soils with pore sizes $<10^{-6}$ m in nature.

Implications

The AT can only control capillary pressure [Eq. (1)], and not matric suction in general [Eq. (2)]. Contrary to capillary water, sorptive water does not need a curved air–water interface [Eq. (3)] and can only be controlled through vapor pressure. For soil with dominant pore sizes $>10^{-5}$ m such as sand, AT has little effect on SWR. For silty soil, pore size is on the order of 10^{-5}–10^{-7} m, so cavitation can provide a significant mechanism for soil water drainage [Fig. 1(c), dark shaded area]. For soil with pore sizes dominated by $<10^{-6}$ m such as clay, AT can suppress cavitation for pore size $>10^{-7}$ m and has little effect for pore sizes smaller than 10^{-7} m. However, the SSP can be significant in clay with pore sizes $<10^{-7}$ m and low in salinity, elevating pore water pressure and suppressing cavitation.

These findings call for further research in assessing the role of cavitation in soil water drainage, the validity of the AT, and an imperative need for developing new and reliable methods of controlling matric suction <1,500 kPa for silty and clayey soils.

References

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