The author’s idea about the stresses applied on the REV faces is fully granted. Matric suction is a pore scale pressure and should be multiplied by a parameter representing physical characteristics of the soil, soil sample preparation method, and stress state (Ajdari et al. 2008; Khalili et al. 2008) to be upscaled to the macro scale, and therefore, capable of coupling with the net stress.

The discussers wish to extend this evaluation to the physical effects of matric suction on the unsaturated soil behavior. Matric suction plays two different roles in the soil behavior. Initially, the increase in matric suction will increase the effective stress, resulting in a behavior comparable to the fully saturated soils. In this respect, yielding and increase in shear strength are two important phenomena. Besides, hardening of the soil is due to the plastic work performed by the effective stress on the REV. Therefore, these incidents could be successfully modeled similar to saturated soils by employing a single effective stress (Khalili and Khabbaz 1998; Fazeli et al. 2008).

Surpassing the air entry value, the plastic energy of matric suction is consumed to desorb water from the soil media. While the mechanical behavior of unsaturated soil appears fully elastic in the effective stress-specific volume space; this plastic work can be detected in the hysteresis loop of soil water characteristic curve. The amount of this plastic work per unit volume of soil water can be determined by subtracting the area below the wetting cycle of the soil water characteristic curve from the area below its drying cycle. Therefore, the reason for the observed hardening and movement of the normal consolidation line is the plastic work performed by matric suction on the soil water, even though, the moisture content is not the main parameter of interest during modeling of mechanical behavior of unsaturated soils. Thus, employing the matric suction as a second state variable is unavoidable. In other words, to capture these two diverse incidents in a single elastic-plastic framework, we are forced to employ matric suction in two dependent state variables, such that one of them plays the role of a hardening parameter while the other is an important part of the stress state variable. Obviously, if suction hardening is negligible in a soil (Bagherieh et al. 2008), using the matric suction as a separate parameter besides the effective stress is not necessary.

References


Discussion of “Is Matric Suction a Stress Variable?” by Ning Lu

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The writer appreciates the recognition of the distinction between matric suction and stress variables by the discussants. The implications raised by such a distinction in modeling the plastic and hardening behavior of unsaturated soil are thoughtful and logical, and provide possible pathways to modeling the mechanical behavior of unsaturated soil. The writer would like to further clarify one important issue raised by the discussants: the relationship between matric suction and effective stress in unsaturated soil.

The discussants point out that “the increase in matric suction will increase the effective stress, resulting in a behavior comparable to the fully saturated soils.” This is an inaccurate statement as the effective stress in unsaturated soil, in general, is not a monotonic function of matric suction (Lu and Likos 2004, 2006). Depending on the type of soil and the prevailing matric suction, the effective stress can either increase or decrease as matric suction increases. The effective stress in soil can be unified for all types of soils under all degrees of saturation by the following form (Lu and Likos 2004, 2006)

\[ \sigma' = (\sigma - u_a) - \sigma^* \]  \hspace{1cm} (1a)

where \( u_a \) = pore air pressure; \( \sigma \) = total stress; \( \sigma^* \) = generalized effective stress; and \( \sigma^* \) is defined as the suction stress characteristic curve of the soil with a general functional form of (Lu and Likos 2004; Lu and Godt 2008)

\[ \sigma^* = -(u_a - u_w) \quad u_a - u_w \leq 0 \]  \hspace{1cm} (1b)

\[ \sigma^* = -\frac{(u_a - u_w)}{(1 + \alpha (u_a - u_w))^n} \quad u_a - u_w \geq 0 \]  \hspace{1cm} (1c)

where \( u_a \) = pore water pressure and \( n \) and \( \alpha \) are empirical fitting parameters of soil properties, with \( \alpha \) being correlated to the inverse of air-entry pressure for water-saturated soil, and \( n \) being

Closure to “Is Matric Suction a Stress Variable?” by Ning Lu

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The writer appreciates the recognition of the distinction between matric suction and stress variables by the discussants. The implications raised by such a distinction in modeling the plastic and hardening behavior of unsaturated soil are thoughtful and logical, and provide possible pathways to modeling the mechanical behavior of unsaturated soil. The writer would like to further clarify one important issue raised by the discussants: the relationship between matric suction and effective stress in unsaturated soil.

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where the pore-size distribution parameter. The parameters $n$ and $\alpha$ are identical to those defined in the widely used soil-water retention model by van Genuchten (1980)

$$S_e = \frac{S - S_r}{1 - S_r} = \left[ \frac{1}{1 + \left(\alpha (u_a - u_w)\right)^n} \right]^{1-1/n} \quad (2)$$

where $S_e$ = equivalent degree of saturation and $S_r$ = residual saturation. The nonmonotonic feature of the suction stress defined in Eqs. (1b) and (1c) for hypothetical sand, silt, and clay is illustrated in Fig. 1. The soil-water retention curves of the three soils described by van Genuchten Eq. (2) are shown in Fig. 1(a), whereas the corresponding scaling function (suction stress characteristic curves) described by Eqs. (1b) and (1c) are shown in Fig. 1(b). For the hypothetical sand, the air-entry pressure is about $\sim 1$ kPa and the sand reaches its residual state when matric suction is greater than $\sim 100$ kPa. The resulting suction stress has a minimum value of $\sim 1.6$ kPa at matric suction of 5 kPa. As matric suction increases, suction stress for this soil increases drastically after the minimum point and becomes zero when matric suction is greater than $\sim 110$ kPa. For the silt, the air-entry pressure is at $\sim 10$ kPa and the soil can retain a substantial amount of water, up to 1,000 kPa of matric suction. The corresponding suction stress reaches its minimum value of $\sim 12$ kPa at the matric suction of $\sim 20$ kPa. Suction stress increases as matric suction increases and is sustained at several kPa for a wide range of matric suction values (illustrated here only up to 500 kPa). In contrast, the clay has an air-entry pressure of several tens of kPa and can retain substantial amount of water for matric suctions of several hundreds of MPa. The corresponding suction stress varies monotonically as matric suction increases. For this clay, suction stress can decrease to $\sim 110$ kPa, resulting in an increase in effective stress of equal amount.

In summary, although matric suction has the units of stress, it is not a stress quantity per se (Lu 2008). Suction stress, on the other hand, is a stress variable. The relationship between matric suction and suction stress is nonmonotonic for sandy and silty soils and monotonic for clayey soil, yet can be unified by the concept of suction stress conceived by Lu and Likos (2006). Suction stress defined in Eqs. (1a)–(1c) and illustrated in Fig. 1 provides a simple unified scaling function that converts matric suction to effective stress in variably saturated soil. Suction stress can describe the nonmonotonic characteristics of effective stress in sandy and silty soils and the monotonic characteristics of effective stress in clayey soils with one closed-form equation for their mechanical behavior, thus unifying the description of state of stress in all types of soils.

References