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The paper under discussion presents an effective stress-based methodology that provides valuable insight into the earthquake-induced free-field ground settlement of partially saturated soil layers containing occluded air bubbles. However, there are challenges with the theoretical background, formulation, and validation of the methodology that are raised in this discussion to help guide the proper use of this methodology in practice.

First, in order to evaluate the impact of partial saturation on seismic settlement, the authors utilized the effective stress equation of Lu et al. (2010):

$$\sigma' = \sigma - u_a + S_e(u_a - u_w) \quad (1)$$

where σ'= effective stress, σ = total stress, u_a = pore air pressure, u_w = pore water pressure, $(\sigma - u_a)$ = net normal stress, $(u_a - u_w)$ = matric suction, S_e = the effective degree of saturation defined using the soil water retention curve (SWRC) model of van Genuchten (1980), and $S_e(u_a - u_w)$= suction stress. The use of Equation (1) to calculate the effective stress in partially saturated soils without considering the state of saturation in soils may lead to several challenges, especially in the case of soils with high degrees of saturation and occluded air bubbles. To demonstrate the effect of state of saturation on the effective stress, three soil elements are shown in Figure 1. Although each of the soil elements has the same degree of saturation, each has a different magnitude of matric suction. These three cases may be reached by: (a) draining an initially saturated soil by lowering the water table, which causes the pore water pressure to decrease while the pore air pressure remains equal to atmospheric pressure; (b) wetting an initially partially saturated soil by raising the water table, so that pressure in occluded air bubbles is nearly equal to the water pressure at a given depth; or (c) artificially introducing gas bubbles into a saturated soil below the water table, which may cause formation of pressurized gas bubbles inside the pore space. In the paper under discussion, the authors reported peak suction stress values of 0.97 kPa and 2.83 kPa for Hostun sand and Ottawa sand, respectively, using the estimated SWRC model parameters obtained from the primary drainage curve (i.e. case (a)). However, these values may not be reached in partially saturated sand layers containing occluded air bubbles for which the proposed methodology is developed (i.e. case (c)). Terzaghi's effective stress principle (i.e., $\sigma' = \sigma - u_w$) for fully saturated soils is also valid for the case (b) (Finno et al. 2017). Depending on the degree of saturation and soil type, case (c) may result in the development of matric suction and interparticle stresses (Mousavi and Ghayoomi 2018; Mousavi and Ghayoomi 2019; Mousavi et al. 2019).

The proposed seismic settlement methodology was validated using seismic data from air-injected partially saturated soil layers. In this desaturation approach, injected air does not enter the saturated soil until the air pressure reaches the sum of hydrostatic pressure at the injection point and air entry value of the soil (Zeybek and Madabushi 2017). Therefore, the injected air may fill the pore space with a pressure higher than hydrostatic water pressure resulting in development of suction. However, the suction stress at this state may not result in a significant change in the effective stress. This can be explained by reviewing the impact of suction stress on effective stress in Equation 1. Although the elevated air pressure results in increase in suction stress, it also decreases the net normal stress. Assuming the suction stress is completely exerted on soil grains (i.e., $S_e = 1$), the effective stress in a partially saturated soil with occluded air bubbles will be the same as in a saturated soil. It is important to emphasize that the matric suction and the degree of saturation both play important roles in the effective stress state in partially saturated soils. Only considering the degree of saturation as the governing factor may not be appropriate. Specifically, for soil layers containing occluded air bubbles and high degrees of saturation, this assumption may result in an overestimation of the stiffness of the soil layer and an inaccurate prediction of its response to earthquake shaking. Although this error may not be significant for sands, the error may be higher for soils containing fines.

Second, another challenge with the theoretical basis of the model is the equation used to estimate the volumetric strains due to compression of air voids. The proposed equation for the compression of air voids is obtained by using Boyle-Charles law:

$$u_{a0} V_{a0} = (u¿¿a0 + \Delta u)(V¿¿a0 + \Delta V_a)¿¿$$

(2)

where u_{a0} and V_{a0} are the absolute initial pressure and initial volume of pore air, respectively, and Δu_a and ΔV_a are the air pore and volume change due to compression of pore air. If it is assumed that the pore water and occluded air bubbles have nearly equal pressures, the proposed equation for the compression of air voids can be obtained from Equation (3) by substituting the absolute water pressure, p_0, for the absolute air pressure:

$$\varepsilon_{v-comp(part)} = \frac{\Delta u}{p_0 + \Delta u}(1 - S_r)\frac{e}{1+e} \leq \frac{\sigma'_{v0}}{p_0 + \sigma'_{v0}}(1 - S_r)\frac{e}{1+e} \quad (3)$$

If the pore space is occupied by pressurized air, as in the case of soils desaturated by air injection, the assumption that the pore water and occluded air bubbles have nearly equal pressures and consequently Equation (3) may not be valid. In addition, according to the Boyle-Charles law, the proposed equation [i.e., Equation (3)] is only valid for an ideal gas in a closed system. Although it could be assumed that gas bubbles in pore fluid behave like an ideal gas, Equation (3) may only be applicable to partially saturated soils with occluded gas bubbles under fully undrained conditions. Thus, the use of Equation (3) is in contrast with the authors' initial argument that sand layers in free-field condition are not likely to experience a fully undrained condition and that partial drainage is likely to occur (i.e., Adamidis and Madabhushi 2018).

Third, the authors utilized the experimental results of Ghayoomi et al. (2011) to validate their proposed methodology. However, these results may not be appropriate for validation of the proposed methodology for partially saturated soils containing occluded gas bubbles. The steady-state infiltration method used to control the partially saturated conditions in the experiments of Ghayoomi et al. (2011, 2013) led to degrees of saturation below 0.8. The degrees of saturation considered by Ghayoomi et al. (2011, 2013) corresponded to suctions above the air entry value and is likely that the air voids were inter-connected. Accordingly, further experimental testing may be necessary to fully validate the proposed methodology.

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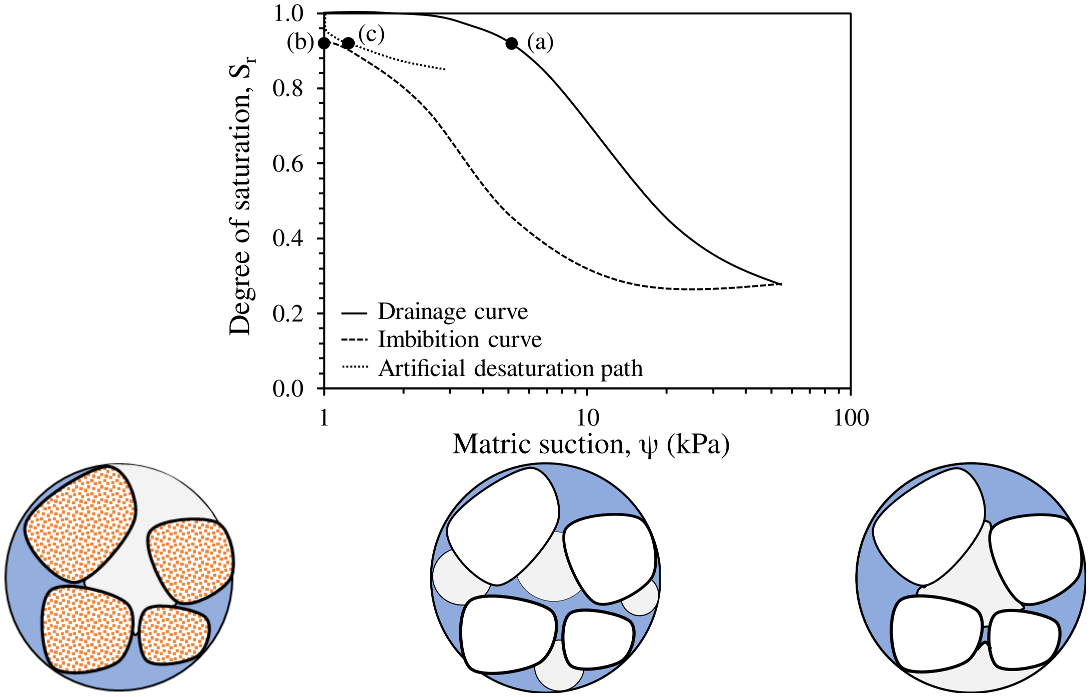

(a): Point of air entry on primary drainage curve $u_w < 0$, $u_a \approx 0$, $u_a - u_w > 0$, positive interparticle stress

(b): Occluded air at zero matric suction $u_a \approx u_w$, No interparticle stress

(c): Occluded air at positive suction on desaturation curve, $u_a > u_w > 0$, $u_a - u_w > 0$, positive interparticle stress

FIG. 1. Generic hysteretic soil-water-retention curve showing different cases having the same degree of saturation.