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Experimental and numerical study on thermal conductivity of partially saturated unconsolidated sands

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A class of problems in heat flow applications requires an understanding of how water saturation affects thermal conductivity in the shallow subsurface. We conducted a series of experiments using a sand box to evaluate thermal conductivity (TC) of partially saturated unconsolidated sands under varying water saturation (Sw). We first saturated sands fully with water and varied water saturation by drainage through the bottom of the sand box. Five water-content sensors were integrated vertically into the sand box to monitor water saturation changes and a needle probe was embedded to measure thermal conductivity of partially saturated sands. The experimental result showed that thermal conductivity decreases from 2.5 W/mK for fully saturated sands to 0.7 W/mK when water saturation is 5%. We found that the decreasing trend is quite non-linear: highly sensitive at very high and low water saturations. However, the boundary effects on the top and the bottom of the sand box seemed to be responsible for this high nonlinearity. We also found that the determination of water saturation is quite important: the saturation by averaging values from all five sensors and that from the sensor at the center position, showed quite different trends in the TC-Sw domain. In parallel, we conducted a pore-scale numerical modeling, which consists of the steady-state two-phase Lattice-Boltzmann simulator and FEM thermal conduction simulator on digital pore geometry of sand aggregation. The simulation results showed a monotonous decreasing trend, and are reasonably well matched with experimental data when using average water saturations. We concluded that thermal conductivity would decrease smoothly as water saturation decreases if we can exclude boundary effects. However, in dynamic conditions, i.e. imbibition or drainage, the thermal conductivity might show hysteresis, which can be investigated with pore-scale numerical modeling with unsteady-state two-phase flow simulators in our future work.