Modeling coupled water and heat transport in a freezing soil using the modified HYDRUS-1D code.

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Liquid water & ice coexist in a frozen soil (Unfrozen water, θ_u)

Soil freezing model

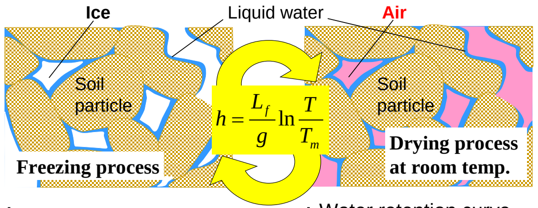
Water

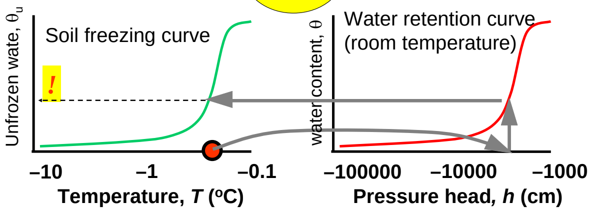
$$\frac{\partial\theta_{uw}(h)}{\partial t}+\frac{\rho_i}{\rho_w}\frac{\partial\theta_i(T)}{\partial t}=\frac{\partial}{\partial z}\left[K_{Lh}(h)\frac{\partial h}{\partial z}+K_{Lh}(h)+K_{LT}(h)\frac{\partial T}{\partial z}+K_{vh}(\theta)\frac{\partial h}{\partial z}+K_{vT}(\theta)\frac{\partial T}{\partial z}\right]$$

Heat

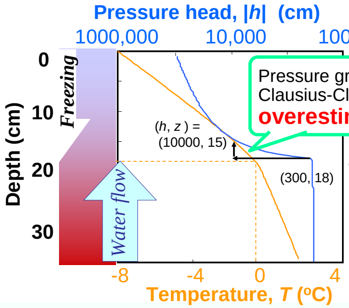
$$\frac{\partial C_pT}{\partial t}-L_f\rho_i\frac{\partial\theta_i}{\partial t}+L_0(T)\frac{\partial\theta_v(T)}{\partial t}=\frac{\partial}{\partial z}\left[\lambda(\theta)\frac{\partial T}{\partial z}\right]-C_{uw}\frac{\partial q_{uw}T}{\partial z}-C_v\frac{\partial q_vT}{\partial z}-L_0(T)\frac{\partial q_v}{\partial z}$$

Pressure of θ_u in frozen soil is related to temperature with the Clausius-Clapeyron equation (C-C eq.).





Calculating soil freezing using $K_f=K(\theta_u)$



Pressure gradient evaluated by Clausius-Clapeyron eq. **overestimates water flux, J_w!**

2 scenarios to reduce J_w

$$J_w=K_f\frac{dh}{dz}$$

Two possible scenarios for the reduce of J_w

Scenario 1: Reduce hydraulic conductivity of the frozen soil

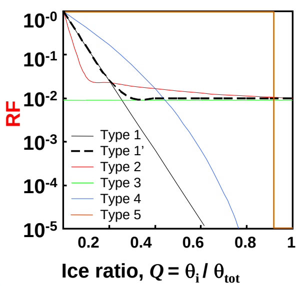
The reduction function, RF for *K*.

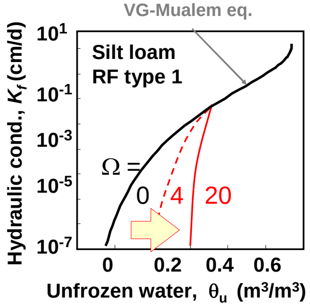
$$K_f=\mathrm{RF}\times K=10^{-Q\Omega}\times K$$

List of example formula for RF

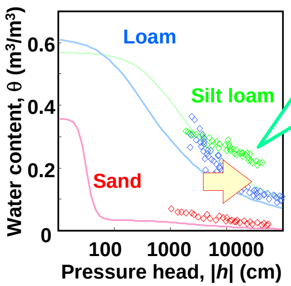
Type 1	$10^{-Q\Omega}$	Type 3	$10^{-\Omega}$
Type 1'	Cut off	Type 4	$(1-Q)^{\Omega}$
Type 2	$10^{-nQ^{\Omega}}$	Type 5	Step

K: hydraulic cond. at room temperature
K_f: hydraulic cond. of frozen soil
Q: Ice to total water ratio
Ω: impedance factor





Scenario 2: Modify h-T relationship (Clausius-Clapeyron eq.)



— Observed VG eq.
◇ Freezing experiment (frozen soil) (θ_u:TDR, *h*: *T* & C-Ceq.)

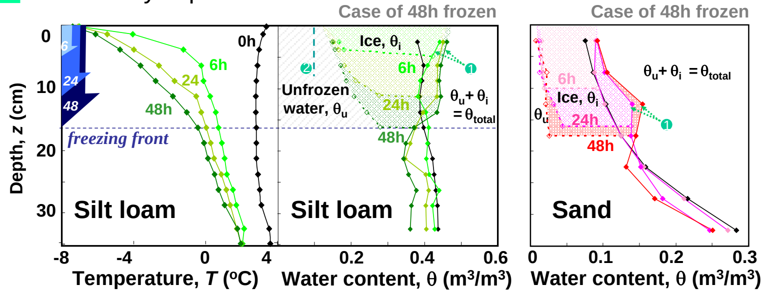
During soil freezing,
Freezing exp. θ_u > Observed VG eq. θ_u
(due to the ice formation time)

Apparent *h* would be given as

$$h=\mathrm{RF}\frac{L_f}{g}\ln\frac{T}{T_m}$$

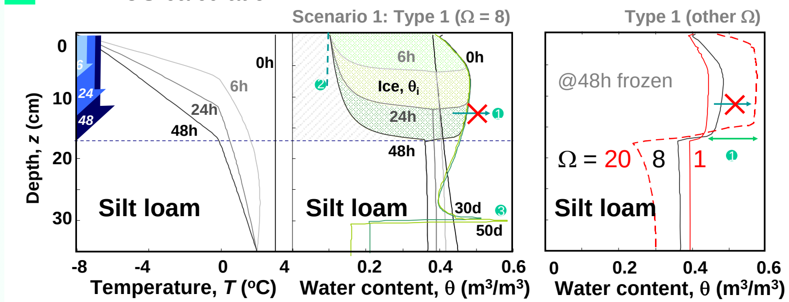
ex. RF = const.
$=\theta_{total}/\theta_s$

Laboratory experiment

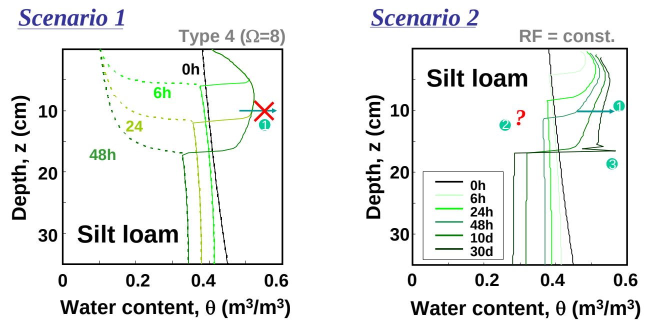


- *h*, *T*, θ_u, θ_{total}–profiles were measured for 3 freezing soils with various θ_{init}.
- ❶ θ_{total} in frozen regions of silt loam and sand increased with time (ice kept growing).

HYDRUS calculation



- ❶ Ω could change the θ_{total}, but could not describe the ice growth in frozen regions.
- ❷ θ_u was slightly underestimated compared to laboratory experiments.
- ❸ A sharp peak was observed at the freezing front at long-time, due to the underestimation of K_f.



- ○ Formula type of RF is **not sensitive** to J_w in frozen regions (Scenario 1).
- ❶❸ Modified C-C eq. improved the ice growth in frozen regions (Scenario 2).
- ❷ θ_u was overestimated and the soil froze only shallow depth (Scenario 2).

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