Compaction front controls soil liquefaction dynamics of drained saturated grain layers, as evident by theory, numerical simulations and lab experiments

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Is soil liquefaction an undrained phenomena?

Soil liquefaction is traditionally considered as an **undrained** phenomenon. In the undrained mechanism, the pore pressure rise is due to a small **change** in the soil's **pore volume**. Considering rapid earthquake shaking, this process is considered "effectively undrained".

Here we present a mechanism for pressurization (up to lithostatoc values) of the pore's fluid under **drained** conditions, which means that fluid can flow out of the soil layer during earthquake shaking. Drained pressurization is governed by the **rate of compaction**, rather than the volumetric strain itself. We present theory and simulation results for the pressurization, including spatial and temporal evolution via a "compaction front model".

Theory – rate of compaction of a drained layer is coupled to the fluid flow

$$u_{sy} = \frac{\kappa}{\eta}\frac{\partial P'}{\partial y} \propto \frac{\partial \phi}{\partial t}$$

permeability

Vertical gradient of pore fluid pressure

Vertical velocity of solid grain

Fluid viscosity

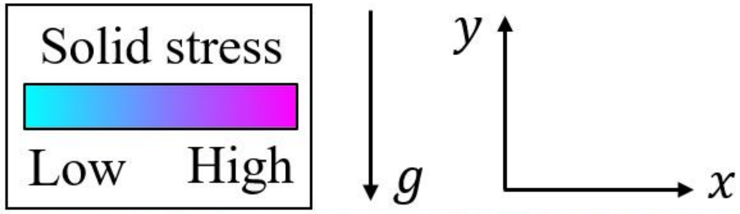
Rate of compaction

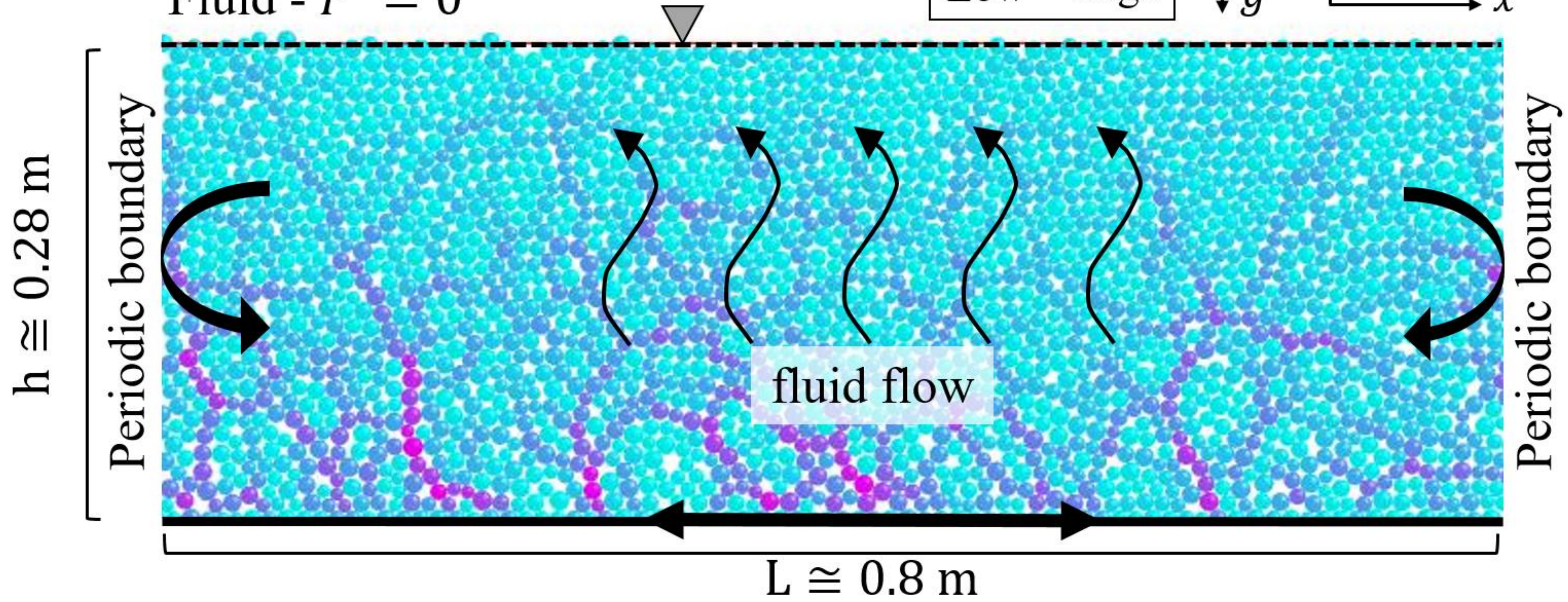
Numerical Setup: DEM + fluid solver

Top boundary condition:

Solid - $\sigma_0 = 0$

Fluid - $P' = 0$



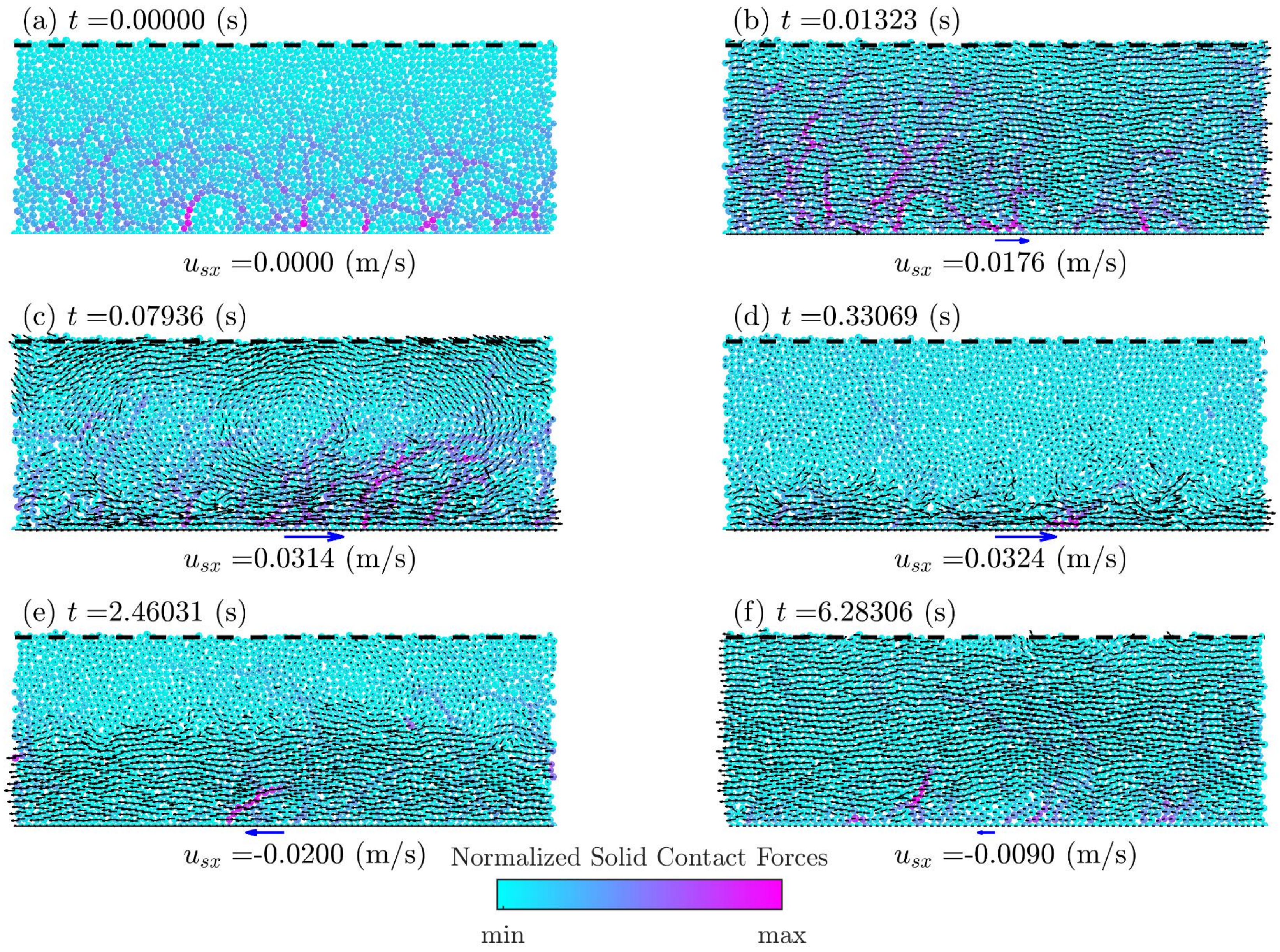


Bottom boundary condition:

Solid – Cyclically sheared ($\Delta X = A\sin(\omega t)$; $\Delta Y = 0$)

Fluid – No flow ($\partial P'/\partial y = 0$)

Snapshots from high horizontal acceleration simulation (peak=25% of g)



Layer at rest

Solid-like, shear wave travels upward

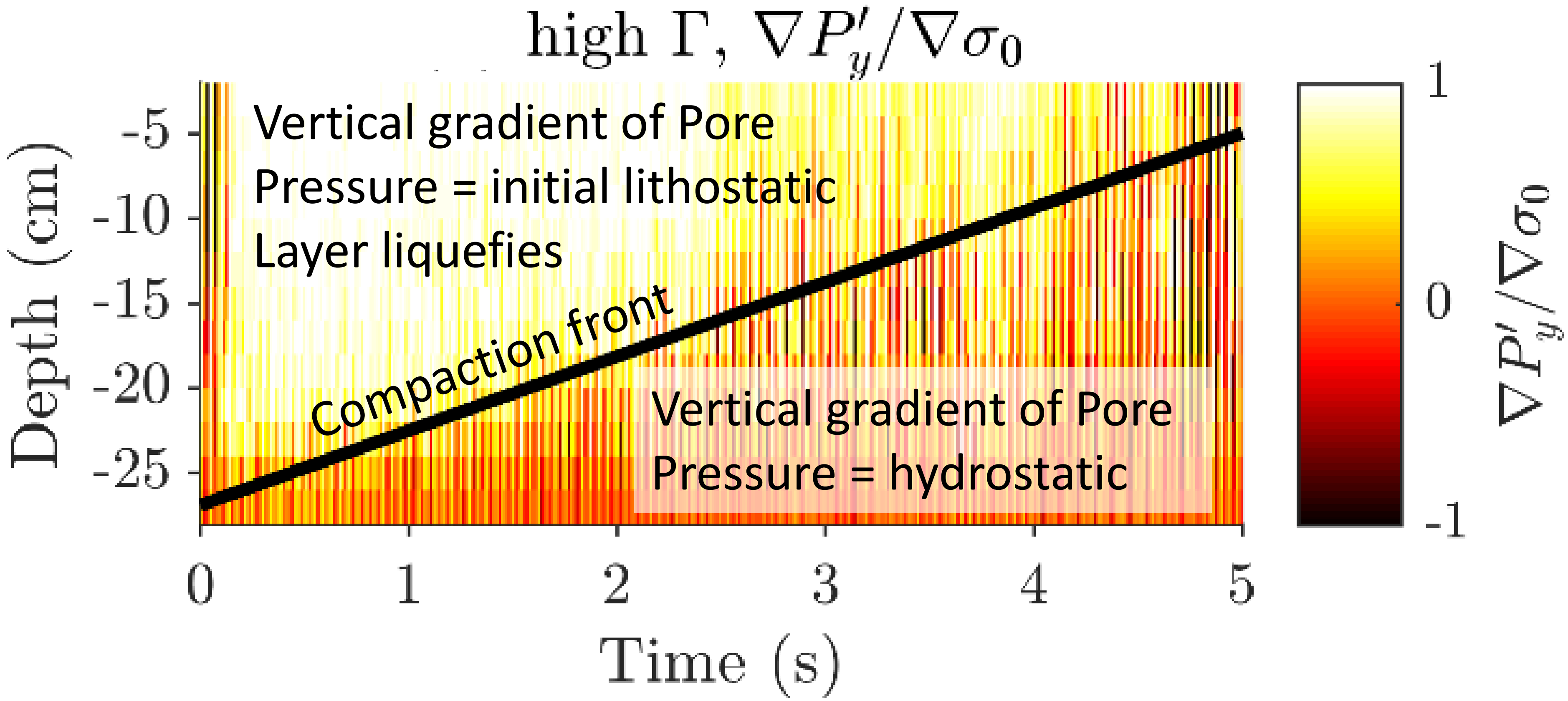
Solid-like, granular vortices

The upper part is fluid-like. Shear localized at the bottom

The thickness of the shear zone increase

Solid-like again

Pore pressure during high horizontal acceleration simulation (peak=25% of g)



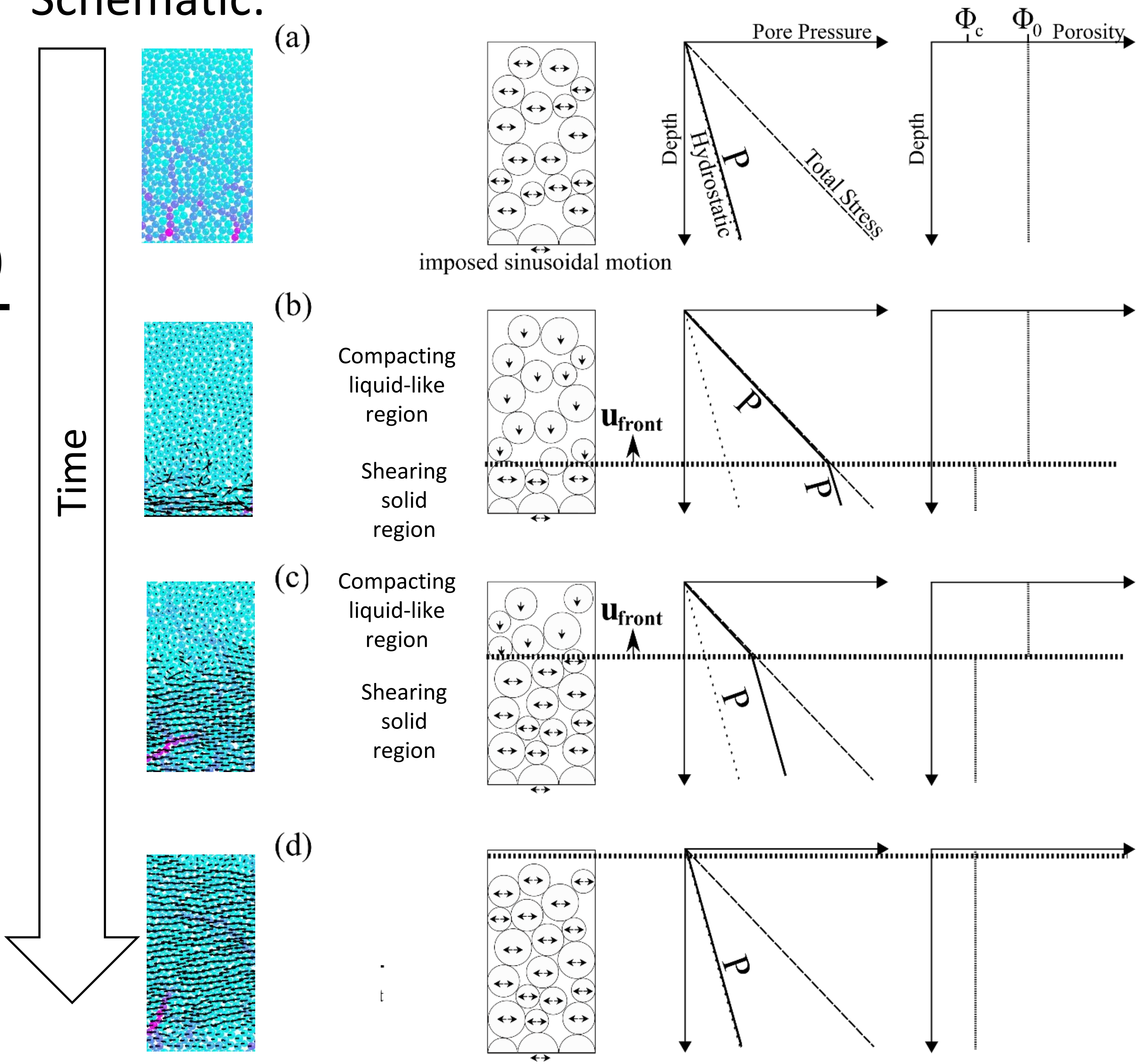
Compaction front controls the pressure profile

Initial porosity

$$u_{front} = \frac{\phi_0 - 1}{\phi_0 - \phi_c} \frac{\kappa}{\eta} \frac{\partial \sigma_0}{\partial y}$$

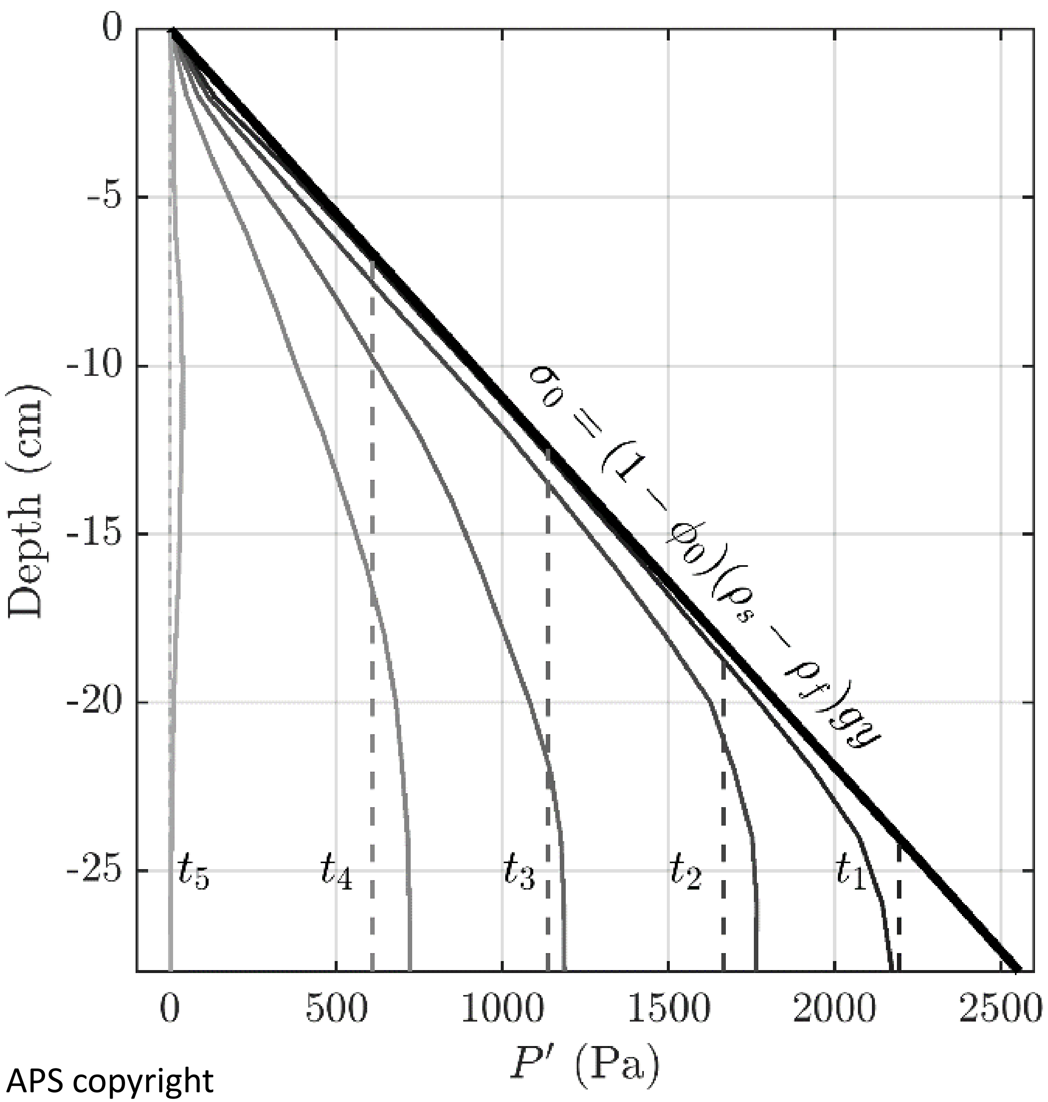
Critical porosity

Schematic:



Compaction front controls the pressure profile

$$P'(y,t) = \begin{cases} \sigma_0(y) & y \geq y_{front} \\ \sigma_0(y_{front}) & y < y_{front} \end{cases}$$



Dashed lines depict the theoretical profile from the compaction front model.

Solid lines depict the profiles from simulations

The bold solid line depicts the initial lithostatic stress

Pressure presented as the deviation from hydrostatic value.

Conclusions

- Under drained conditions, the pore pressure can rise to lithostatic values, i.e., the layer can liquefy. This in contrast to the regular view of liquefaction as an undrained phenomenon.
- The compaction front model allows predicting the pressure profile inside a compacting-liquified layer, spatially and temporally.
- This drained end-member should be considered as a mechanism for soil liquefaction, alongside the undrained end-member.
- We analyze field cases to apply this model and will be happy to receive suggestions for compatible documented events.

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