Drains in ZSoil v2026.

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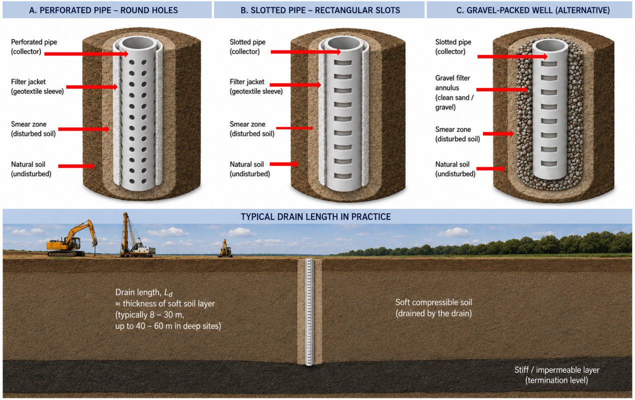
- Main goal: solving seepage/consolidation problems for soft soils, dewatering of slopes
- Consolidation: standard method (drains + adding external loading) / vacuum consolidation
- Straining of drains is neglected
- Partial saturation is handled
- Soil models for weak soils are usually needed (MCC, Cap, Soft Soil Creep (in v2027))

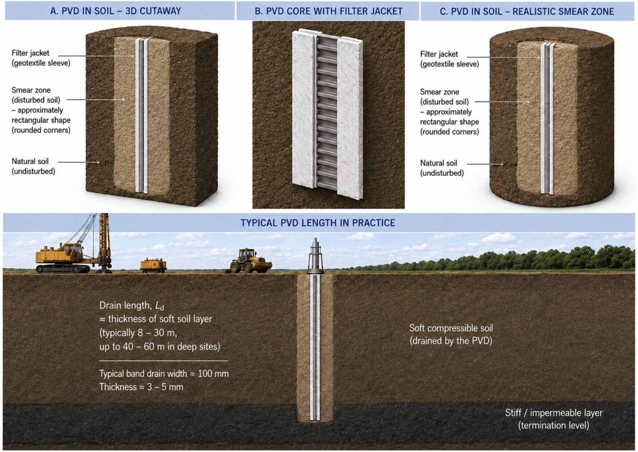
- High aspect ratio ($L \approx 10..40$m, $D \approx 10..30$cm)
- Complex fluid flow related to the composite drain construction (perforated pipe, filter pack, smear zone caused by the installation procedure)
- Conclusion: full 3D modeling is not possible in the practice and we need a simplified formulation
- Drain elements are reduced to 1D FE elements arbitrarily embedded in the background continuum 2D/3D mesh (this may introduce some kind of singularities and may yield severe mesh dependency)

Drain type: circular shape



- Three formulations are foreseen for circular drains
  1. With high level of complexity (perforated pipe (with holes/rect. slots)/filter pack and smear zone)
  2. With medium level of complexity (perforated pipe (with holes/rect. slots)/filter pack and smear zone but permeability of the pipe+filter is defined in a simplified manner)
  3. With low level complexity (perforated pipe and filter pack (treated together) and smear zone)

Drain type: PVD type



- One formulation is foreseen for PVD drains
  1. With low level complexity (core and filter jacket (treated together) and smear zone)

- Drain consists of a perforated pipe, a filter zone, a smear zone, and a **fictitious inner soil**
- The **fictitious inner soil** is represented as a **highly permeable porous medium** with a very large void ratio, providing a regularized Darcy-type approximation of the laminar water flow inside the pipe
- The axial hydraulic conductivity of the fictitious inner soil must be selected sufficiently large to make the hydraulic-head loss along the drain negligible in comparison with the radial hydraulic-head losses in the external soil, smear zone, filter, and perforated pipe wall
- At the same time, it should remain sufficiently limited to avoid the severe ill-conditioning that could result from using the full Hagen–Poiseuille conductance of the pipe
- The general fluid flow balance equation is expressed as

$$\underbrace{S\ \dot{u}_{k,k}}_{\text{cancel for the drain}} \quad + v^f_{k,k} - c\ \dot{p} = 0$$

- The primary unknown is the water pressure in each of the drain zones (i is the inner soil, f is the filter, s is the smear zone, o is the outer soil):

$$p_k(s,t), \quad k \in \{i, f, s, o\}$$

- **Inner zone**

$$\int w_i\left(-c_i(p_i)\dot{p}_i\right)A_i ds - \int k_i\left(\frac{1}{\gamma_w}p_i' + \mathrm{t}^T\mathrm{b}\right)w_i' A_i ds + \int w_i\beta_{if}(p_f - p_i)ds = 0$$

The cross section area is denoted here as A_i while in the Robin term the circumference is directly embedded in β_{if}.

- In discretized form an extra term is added to handle seepage type BC on top of the drain

$$k_v(p_o - p_i)$$

- **Filter zone**

$$\underbrace{\int w_f\left(-c_f(p_f)\dot{p}_f\right)A_f ds}_{\text{canceled}} - \int k_f\left(\frac{1}{\gamma_w}p_f' + \mathrm{t}^T\mathrm{b}\right)w_f' A_f ds + \int w_f\beta_{fi}(p_i - p_f)ds + \int w_f\beta_{fs}(p_s - p_f)ds = 0$$

- **Smear zone**

$$\underbrace{\int w_s\left(-c_s(p_s)\dot{p}_s\right)A_s ds}_{\text{canceled}} - \int k_s\left(\frac{1}{\gamma_w}p_s' + \mathrm{t}^T\mathrm{b}\right)w_s' A_s ds + \int w_s\beta_{sf}(p_f - p_s)ds + \int w_s\beta_{so}(p_o - p_s)ds = 0$$

- **External soil zone**
here extra term is added to preserve consistency

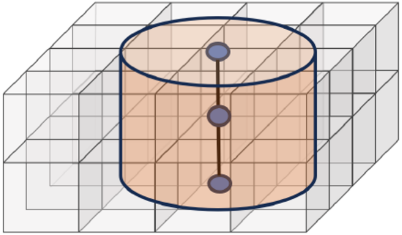
$$\int w_o\beta_{so}(p_s - p_o)ds$$

Flow between the inner fictitious soil and the outer boundary of the filter passes through two components connected in series:

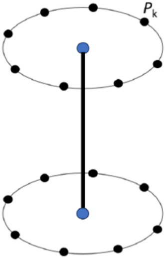
- the porous filter layer, governed by a linear Darcy-type relation,
- the perforated pipe wall, for which both viscous and inertial losses may contribute (this is the most complex part in fact)
- note that for series of components we can add resistances (inverses of conductances)

Nonlocal formulation for linking drains with background mesh

- The same idea that is used for heat exchangers is adopted here
- In the nonlocal formulation $\mathbf{p}_o = \sum_{i=1}^{\text{size}(\mathcal{S})} w_i^{\text{glo}} \mathbf{p}_{o,i}^{\mathcal{S}}$
- Two possible strategies for w_i^{glo} are possible



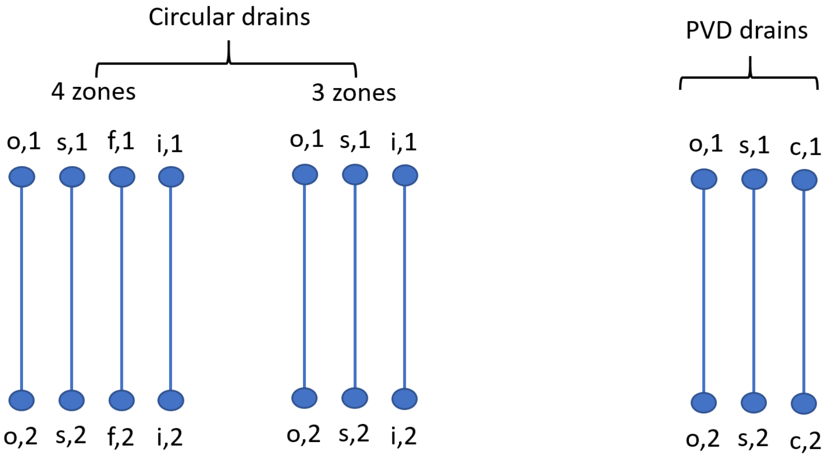
local version



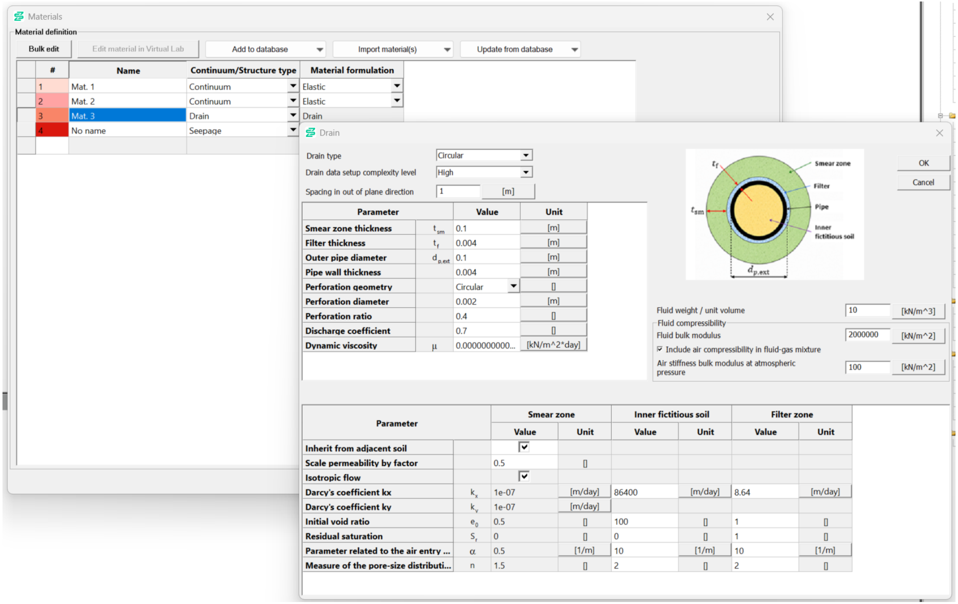
nonlocal version

A. Truty. Nonlocal FEM modeling of piles as beam elements embedded within 3D continuum. https://doi.org/10.1016/j.engstruct.2022.115460, Engineering Structures, Vol. 277, 2023

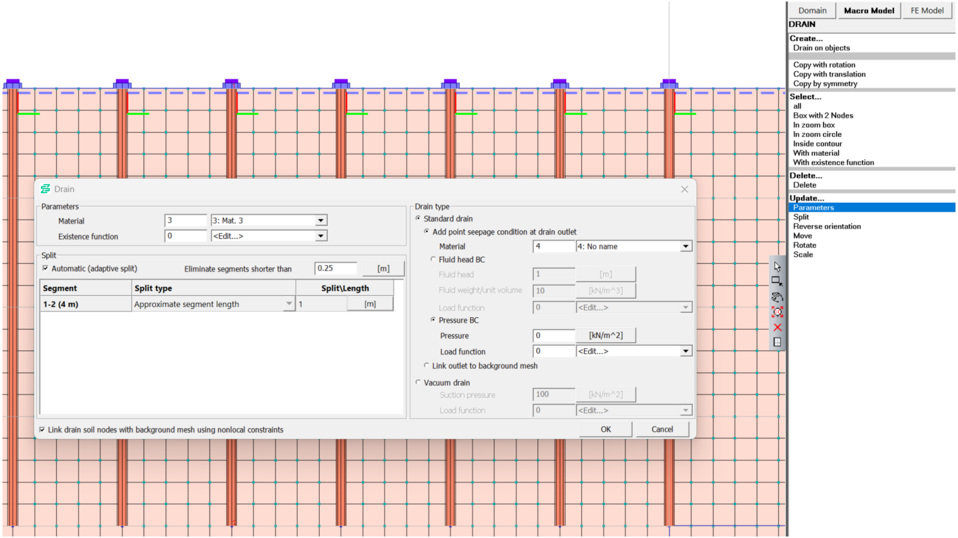
Drain finite element classes



Material GUI



Preprocessing GUI and associated BC



Permeability dependence on void ratio according to Taylor

- Taylor's empirical law assumes a linear relation between void ratio and logarithm of hydraulic conductivity:

$$e = e_0 + C_k \log_{10}\left(\frac{k}{k_0}\right).$$

- Equivalent exponential form used in computations:

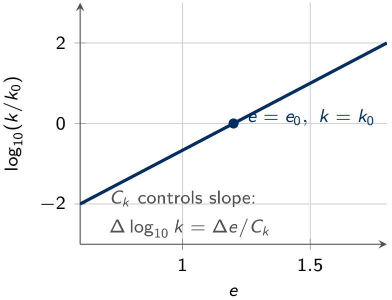
$$k(e) = k_0\, 10^{(e-e_0)/C_k}$$

where k_0 is measured at $e = e_0$ and C_k is the *hydraulic-conductivity change index*.

- Sensitivity needed for Newton linearization:

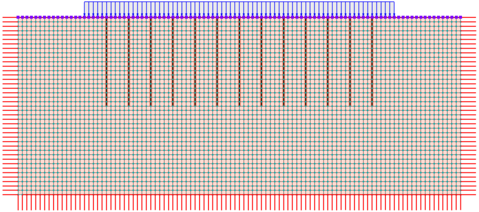
$$\frac{\partial k}{\partial e} = \frac{\ln 10}{C_k}\, k(e), \qquad \delta k = \frac{\ln 10}{C_k}\, k\, \delta e.$$

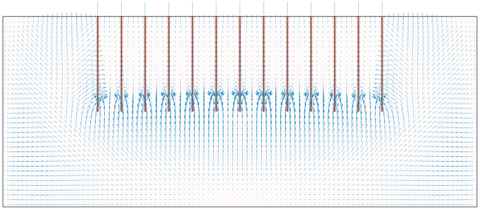
log-linear Taylor law

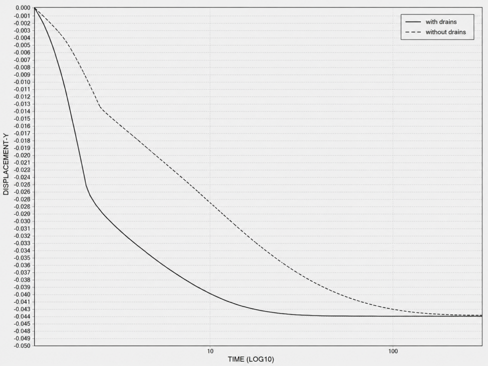


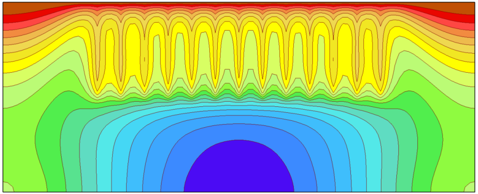
Compression decreases e, hence k drops exponentially. Use the law only within the calibrated void-ratio range.

Example (2D) of subsoil consolidation









- Mohr–Coulomb yield condition in principal effective stresses:

$$F_{\mathrm{MC}} = \sigma_1' - K_p \sigma_3' - f_c = 0, \qquad K_p = \frac{1 + \sin\varphi'}{1 - \sin\varphi'}, \qquad f_c = \frac{2c' \cos\varphi'}{1 - \sin\varphi'}.$$

- Equivalent pressure associated with the current stress state:

$$p_{\mathrm{eq}} = p' + \frac{\tilde{q}^{\,2}}{M^{*2}\,(p' + c' \operatorname{ctg}\varphi')}, \qquad \tilde{q}^{\,2} = M^{*2}\left(p' + c' \operatorname{ctg}\varphi'\right)\left(p_{\mathrm{eq}} - p'\right).$$

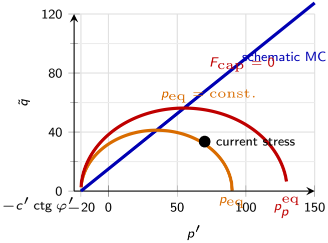
- Brinkgreve relation for the cap-shape parameter:

$$M^* = 3\sqrt{\frac{\left(1 - K_0^{NC}\right)^2}{\left(1 + 2K_0^{NC}\right)^2} + \frac{\left(1 - K_0^{NC}\right)(1 - 2\nu_{ur})(\lambda^* - \kappa^*)}{\left(1 + 2K_0^{NC}\right)(1 - 2\nu_{ur})\,\lambda^* - \left(1 - K_0^{NC}\right)(1 + \nu_{ur})\,\kappa^*}}.$$

- SSC isotache creep law, cap evolution and flow direction:

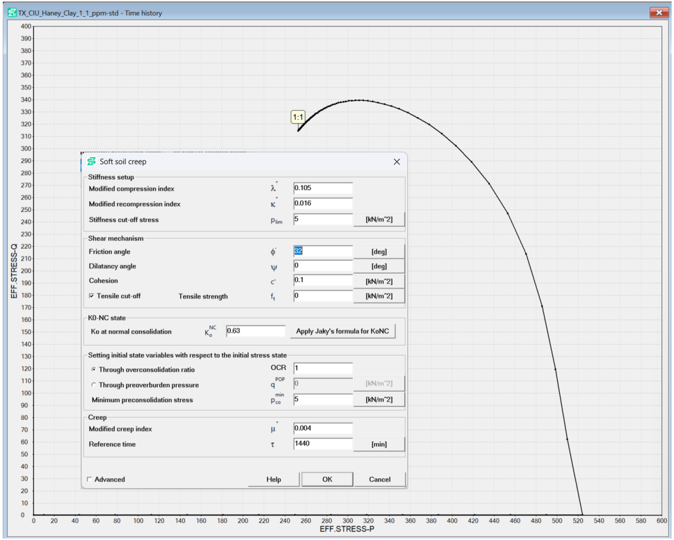
$$\dot{\varepsilon}_v^{\mathrm{c}} = \frac{\mu^*}{\tau}\left(\frac{p_{\mathrm{eq}}}{p_p^{\mathrm{eq}}}\right)^{\frac{\lambda^* - \kappa^*}{\mu^*}}, \qquad \dot{p}_p^{\mathrm{eq}} = \frac{p_p^{\mathrm{eq}}}{\lambda^* - \kappa^*}\,\dot{\varepsilon}_v^{\mathrm{c}},$$

$$p_p^{\mathrm{eq}} = p_{p0}^{\mathrm{eq}} \exp\left(\frac{\varepsilon_v^{\mathrm{c}}}{\lambda^* - \kappa^*}\right), \qquad \boldsymbol{n}_c \parallel \frac{\partial p_{\mathrm{eq}}}{\partial \boldsymbol{\sigma}'}.$$

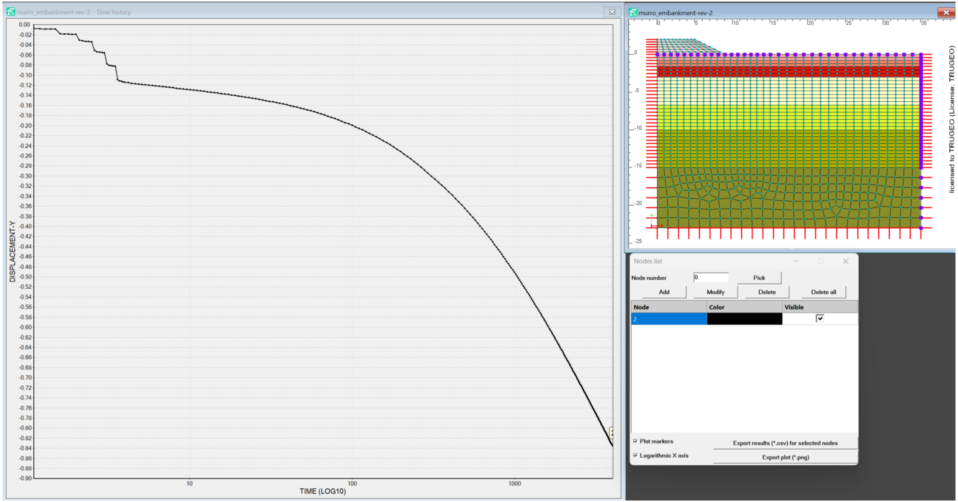


Schematic geometry in the p'-$\tilde{q}$ plane.

SSC model: undrained test



SSC model: simulation of settlements of embankment on organic subsoil



Thank you for your attention