System response of lime-cement columns

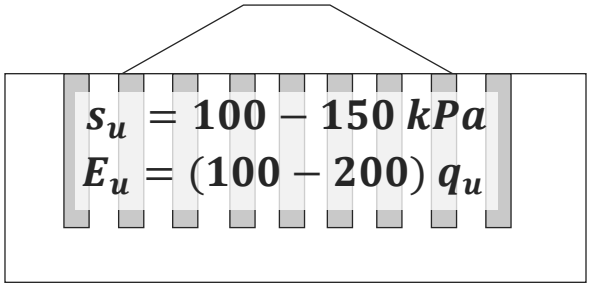
Minna Karstunen (based on work of **Sinem Bozkurt**, Urs Vogler & Ayman Abed)

FORMAS
VINNOVA
Sweden's Innovation Agency
NCC
Branschsamverkan i Grunden
TRAFIKVERKET
SWEDISH TRANSPORT ADMINISTRATION

Outline

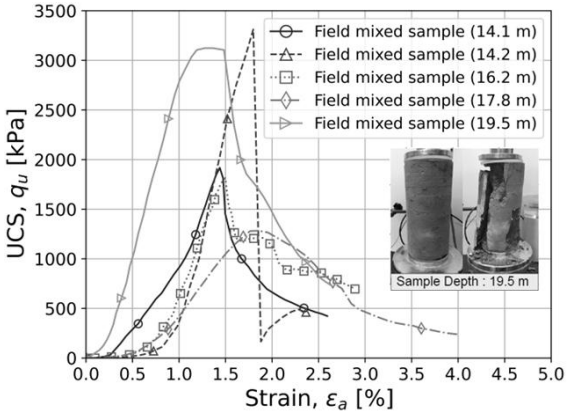
- Background & motivation
- Introduction to Volume Averaging Technique (VAT)
- VAT for embankments
- VAT for excavations
- Sensitivity analysis using VAT for embankments
- Conclusions

Background & Motivation



Trafikverket (2014)



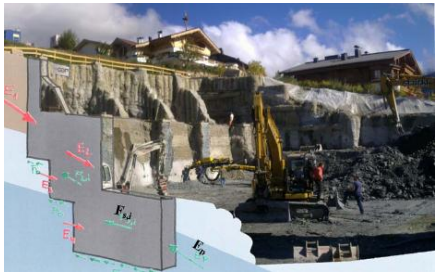




Bozkurt et al. (2023)



Topolnicki (2004)



Marte et al. (2017)

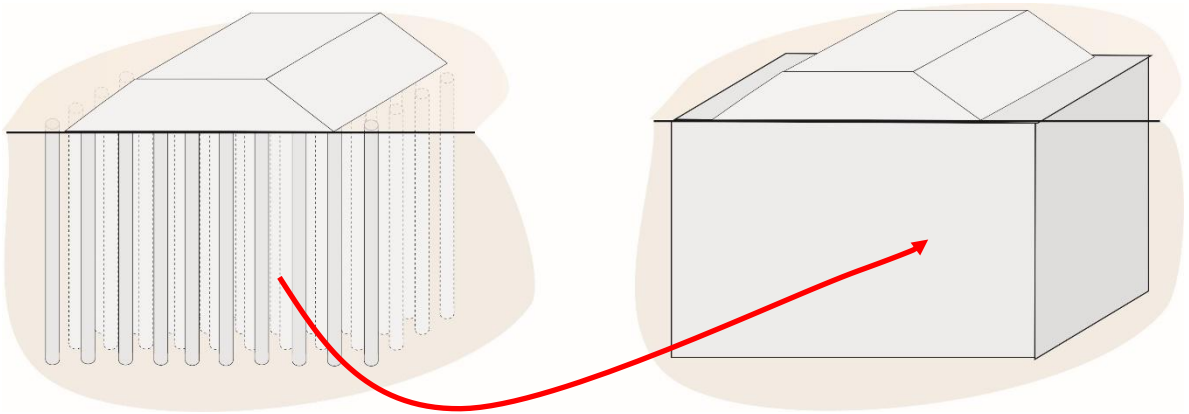
Design based on UCS strength, but in most applications key consideration is actually stiffness (settlements, horizontal movements and vibrations)

Aim and objectives

Investigating time-dependent stress-strain response of deep excavations and embankments stabilised with lime-cement (LC) columns in soft clays

- Validate VAT for embankments
- Identify the interaction mechanism between ***clay & column material***
- Derive a volume averaging technique ***(VAT)*** for excavations
- Inspecting the factors having the largest impact on ***the system response*** and associated anthropogenic greenhouse gas emissions

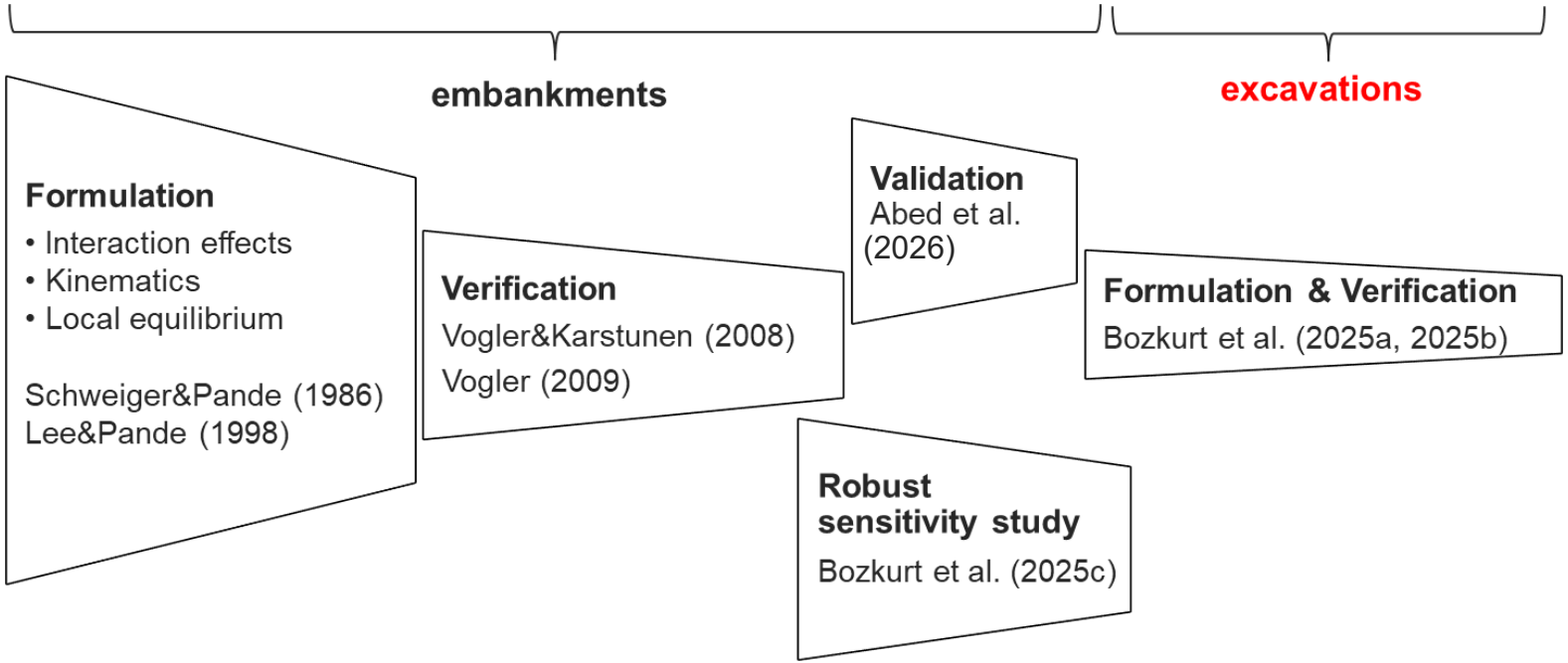
Volume Averaging Technique (VAT)



columns and soil (3D) composite system (2D plane strain)

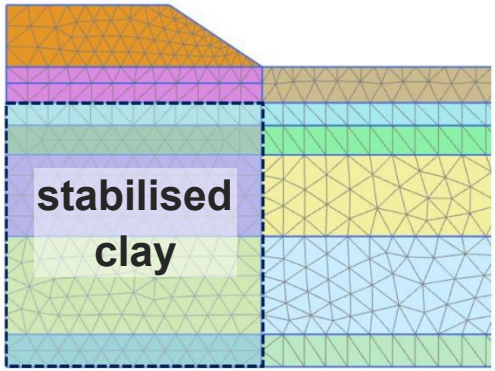
- **Colum/soil system response**
- **Use the known behaviour of constituents (soil and column)**
- **Computationally efficient/fast**

Volume Averaging Technique (VAT)

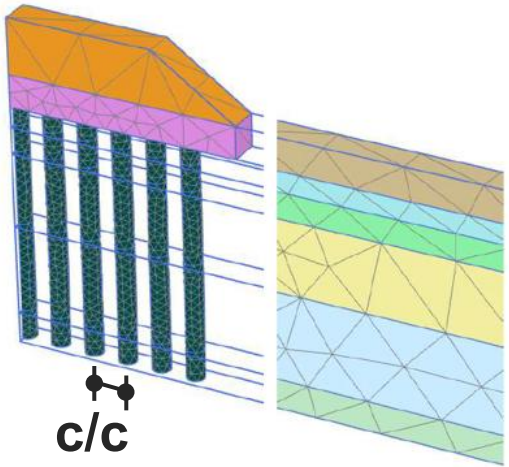


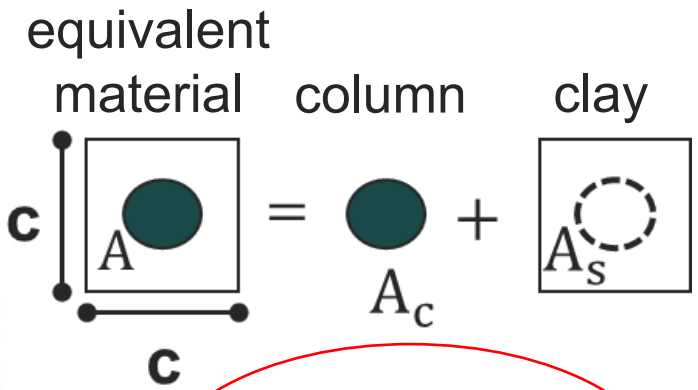
VAT for embankments

2D-VAT



3D





volume fraction: Ω

$$\Omega_{c,s} = \frac{A_{c,s}}{A}$$

$$\dot{\sigma}^{eq} = \Omega_s \dot{\sigma}^s + \Omega_c \dot{\sigma}^c$$

$$\dot{\varepsilon}^{eq} = \Omega_s \dot{\varepsilon}^s + \Omega_c \dot{\varepsilon}^c$$

Schweiger & Pande (1986)
Lee & Pande (1998)

Implementation (Vogler 2009)

PLAXIS2D

finite element code

stiffness matrix **D** $(f(\sigma', \kappa))$

previous stress state $\boldsymbol{\sigma}'^{n-1}$

strain increment $\dot{\boldsymbol{\varepsilon}}$

state variables

updated stress state $\boldsymbol{\sigma}'^{n}$

updated state variables

(for every integration point)

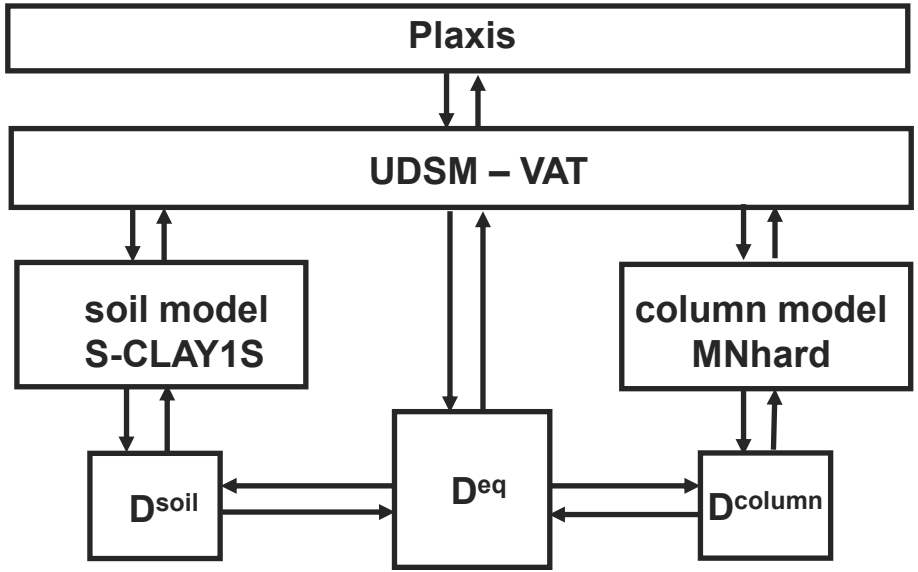
UDSM

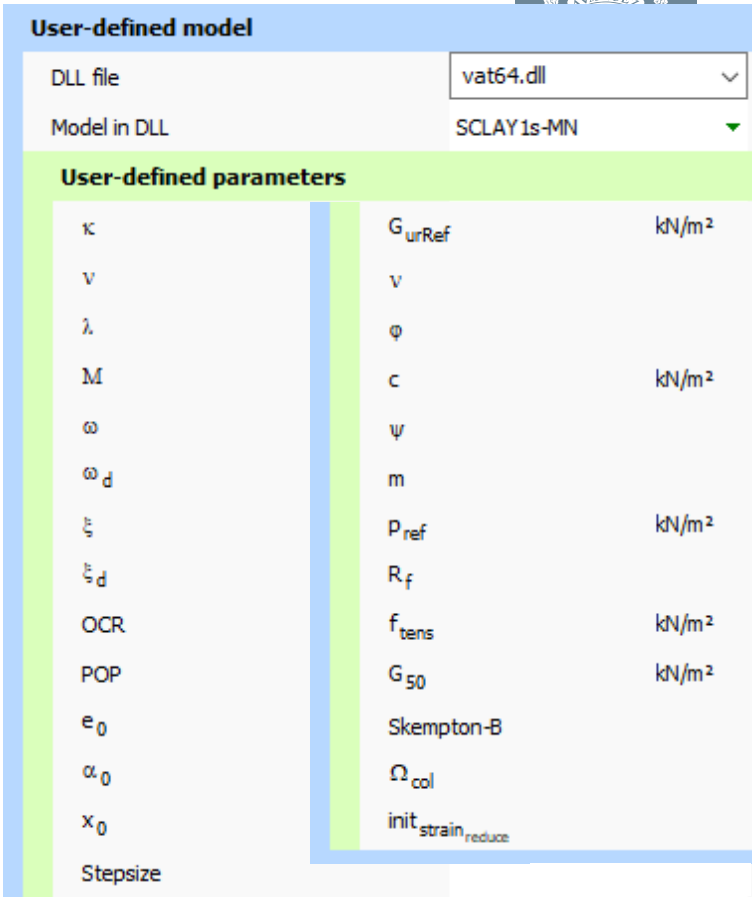
VAT subroutines

- S-CLAY1S
- MNhard
- Averaged material

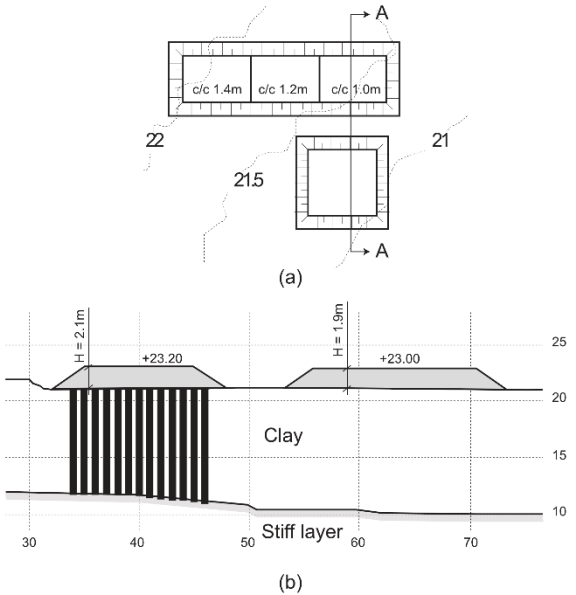
User defined soil model (UDSM)

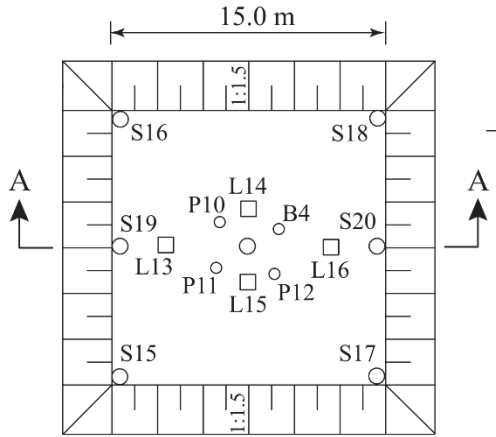
Volume **A**veraging **T**echnique (**VAT**)

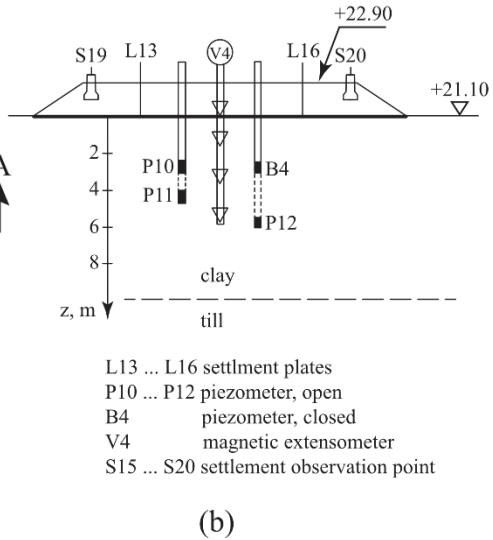




Application: Paimio test embankments

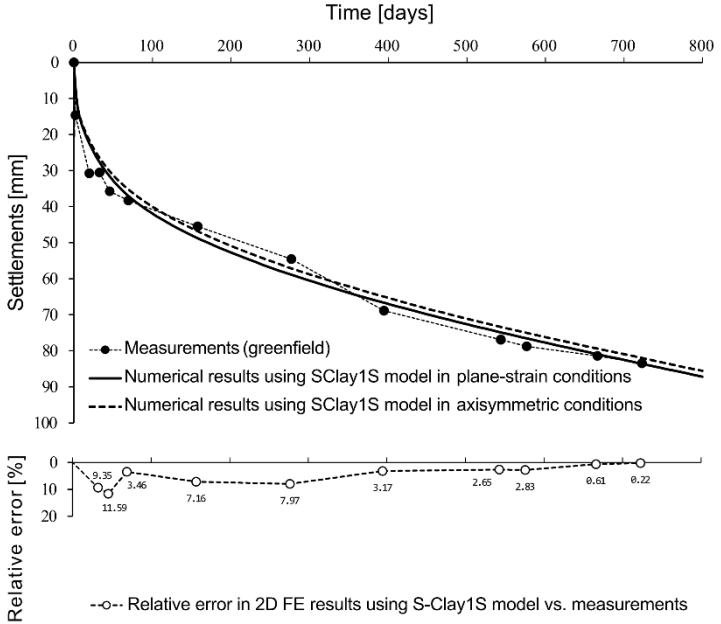


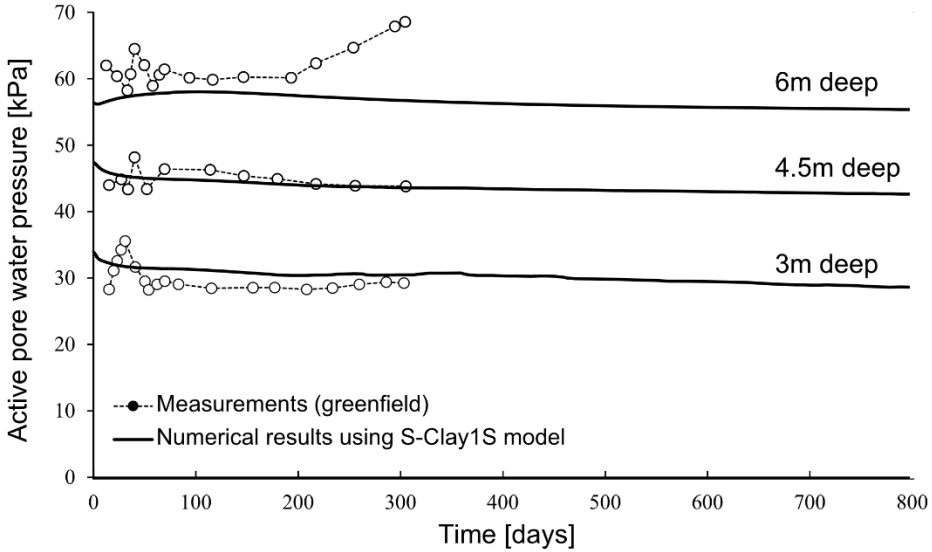




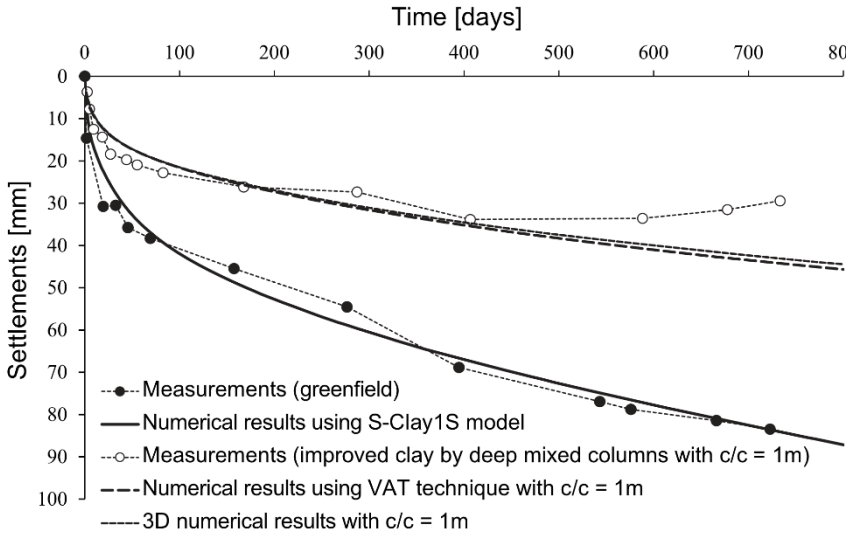
Abed et al. (2025)

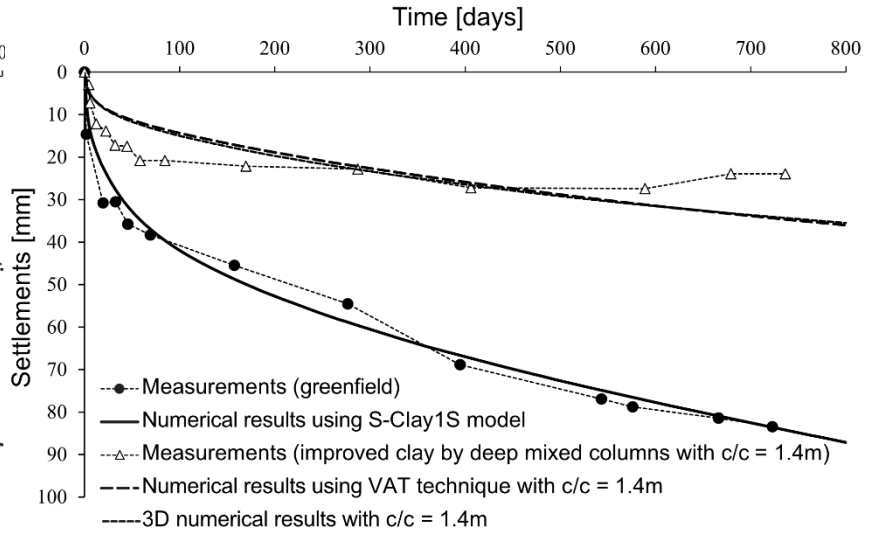
Application: Paimio test embankments



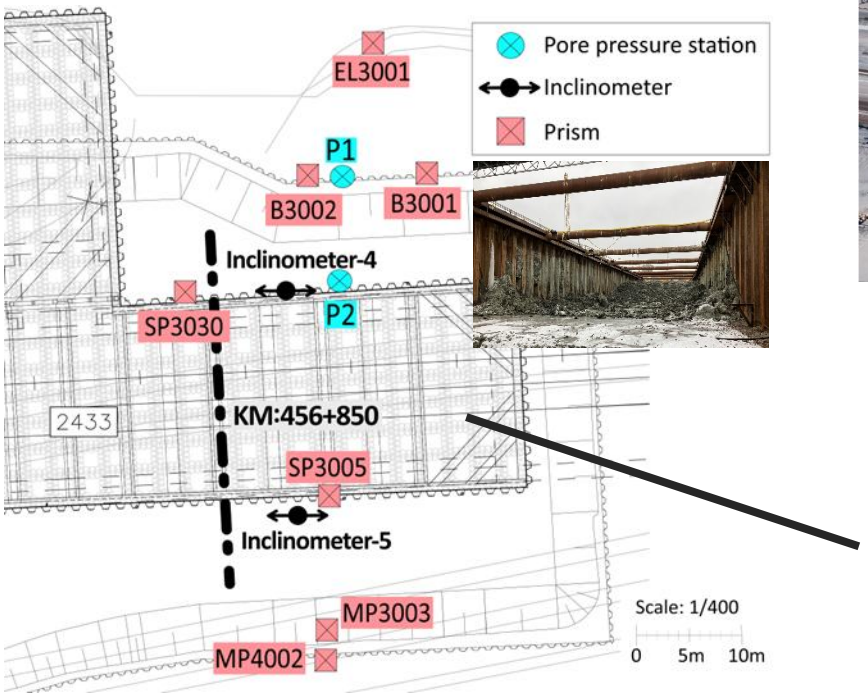


Application: Paimio test embankments

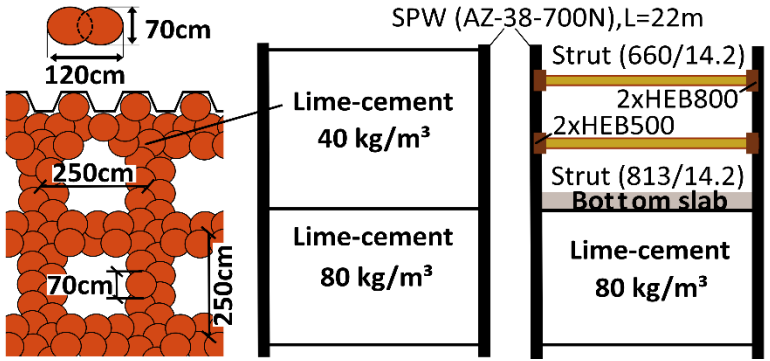




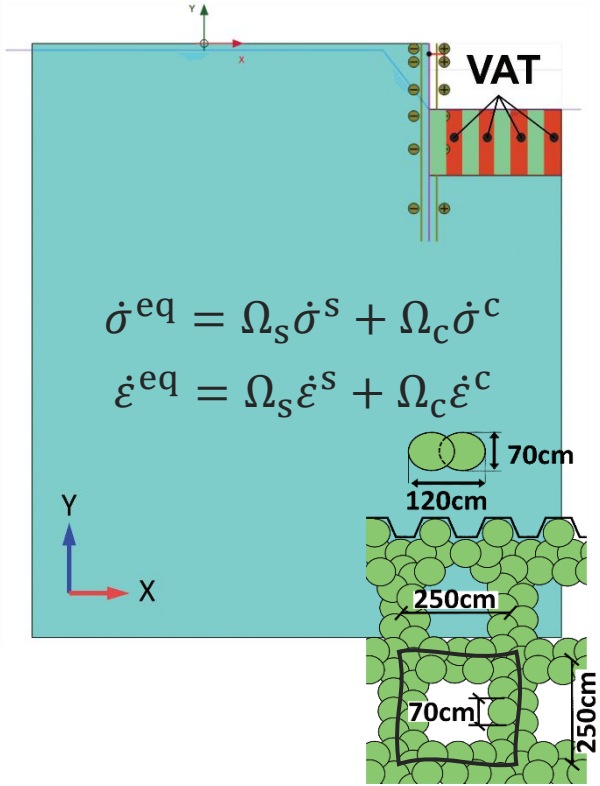
Gothenburg central station







VAT for excavations



$$\Omega_c \times \underset{A_c}{\boxed{\dot{\varepsilon}^c, \dot{\sigma}^c}} + \Omega_s \times \underset{A_s}{\boxed{\dot{\varepsilon}^s, \dot{\sigma}^s}} = \underset{A}{\boxed{\dot{\varepsilon}^{eq}, \dot{\sigma}^{eq}}}$$

column clay stabilised clay

column fraction : $\Omega_c = \frac{A_c}{A}$

clay fraction : $\Omega_s = 1 - \Omega_c$

Equivalent stiffness matrix

$$\mathbf{D^{eq}} = \Omega_s \mathbf{D^s S_1^s} + \Omega_c \mathbf{D^c S_1^c}$$

$$\mathbf{S_1^{s,c}} = \mathrm{f}\left(\Omega_s/\Omega_c, \mathbf{D^s}, \mathbf{D^c}\right)$$

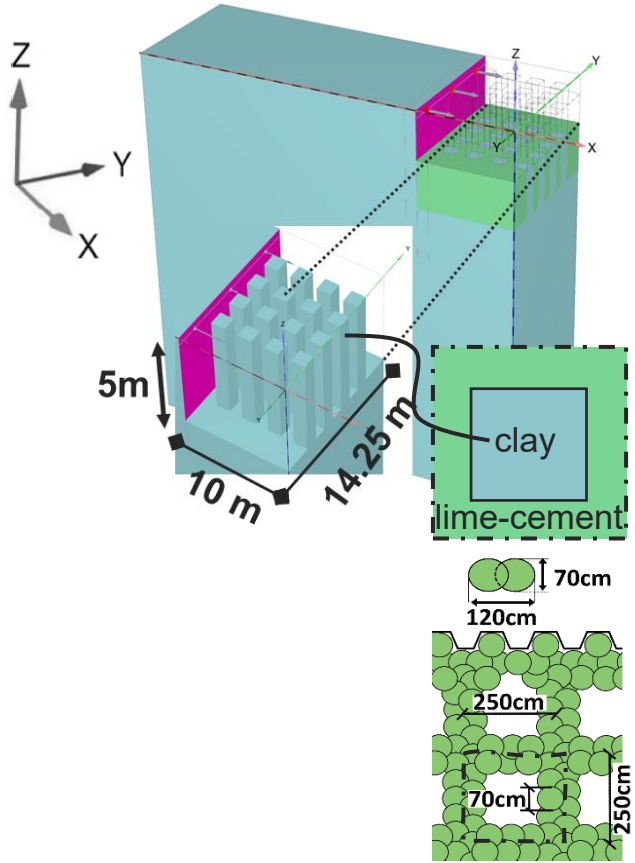
Kinematic constraints:

$$\Delta\varepsilon_{xx}^{eq} = \Delta\varepsilon_{xx}^{c} = \Delta\varepsilon_{xx}^{s}$$
$$\Delta\varepsilon_{zz}^{eq} = \Delta\varepsilon_{yy}^{c} = \Delta\varepsilon_{yy}^{s}$$
$$\Delta\gamma_{zx}^{eq} = \Delta\gamma_{zx}^{c} = \Delta\gamma_{zx}^{s}$$

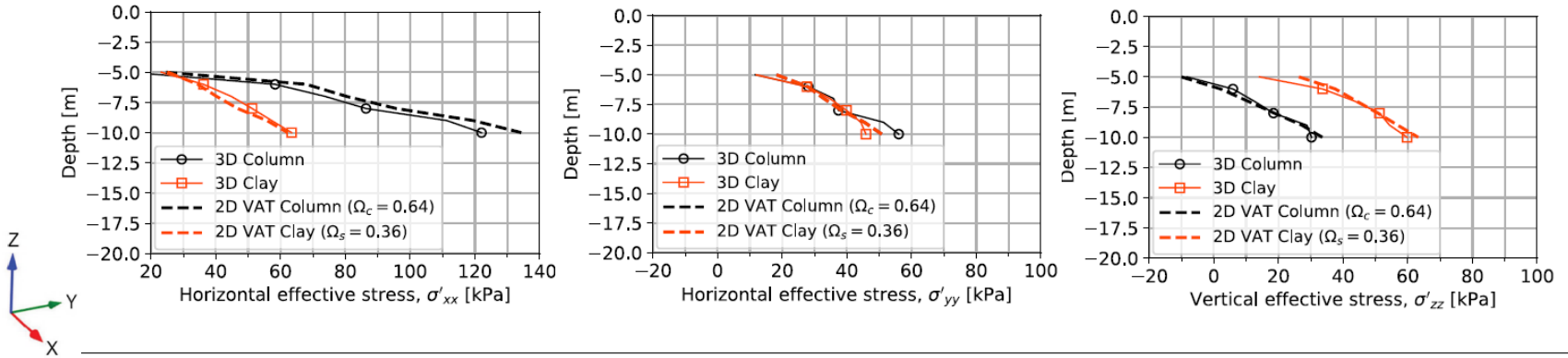
Local equilibrium:

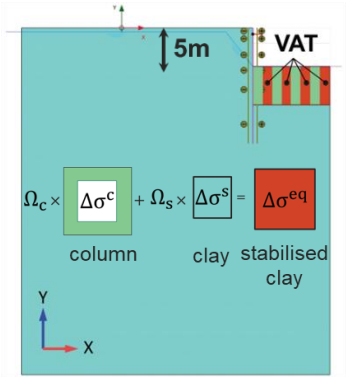
$$\Delta\sigma_{yy}^{eq} = \Delta\sigma_{yy}^{c} = \Delta\sigma_{yy}^{s}$$
$$\Delta\tau_{xy}^{eq} = \Delta\tau_{xy}^{c} = \Delta\tau_{xy}^{s}$$
$$\Delta\tau_{yz}^{eq} = \Delta\tau_{yz}^{c} = \Delta\tau_{yz}^{s}$$

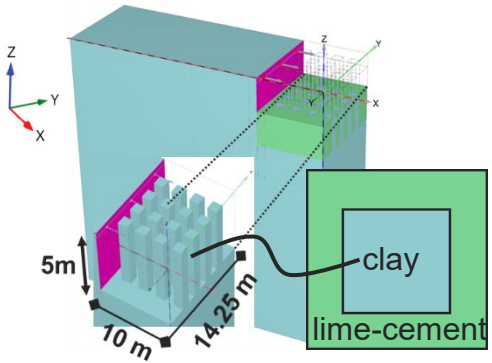
$\mathbf{D^{eq}}$



Verification of VAT for excavations





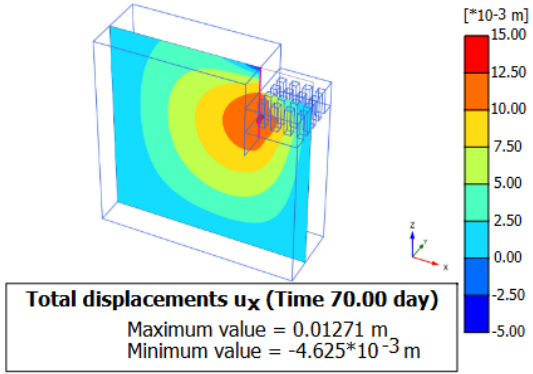


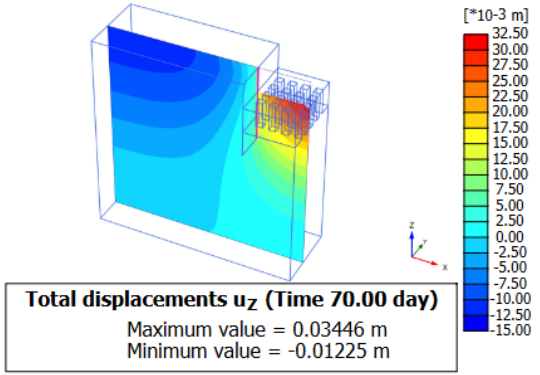
fully coupled consolidation analyses

70 days

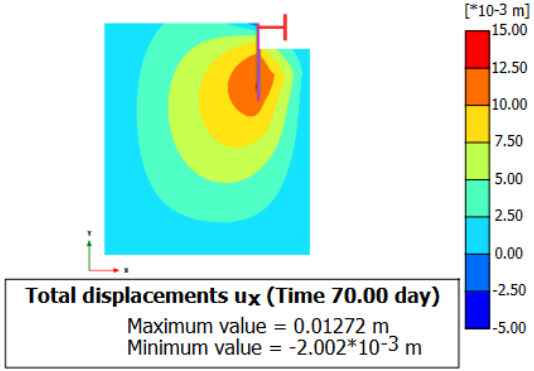
Comparison of 2D and 3D

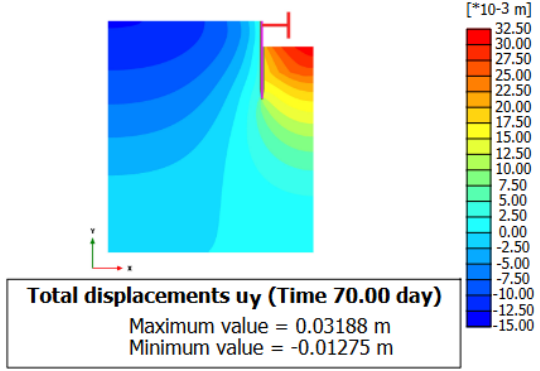
3D



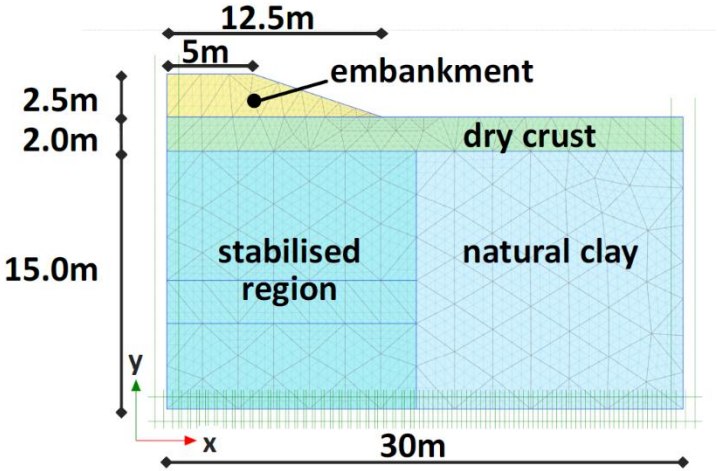


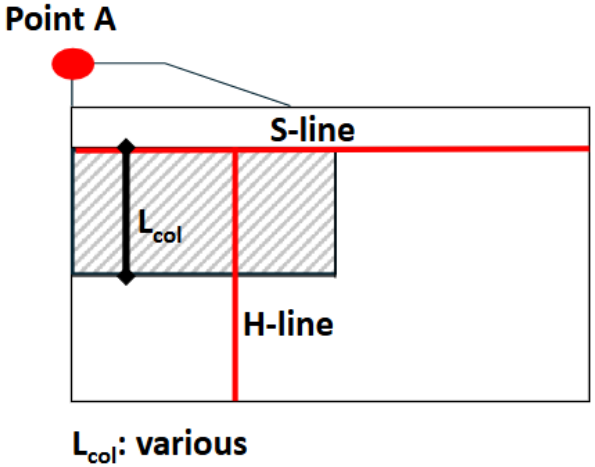
2D-VAT





Sensitivity analyses (DOE)





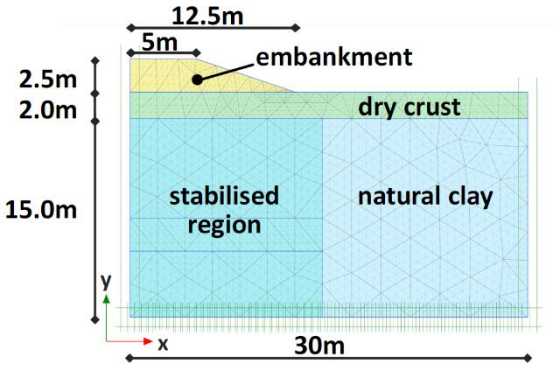
- 2D-VAT and DOE, fully coupled analyses
- fractional factorial design: a range of 5%

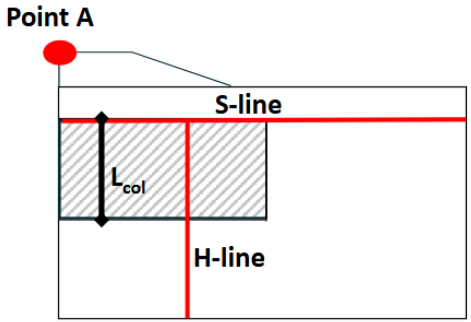
Bozkurt et al. (2025)

- soft clay: S-CLAY1S model
- columns: MNhard model
- various column lengths and spacings

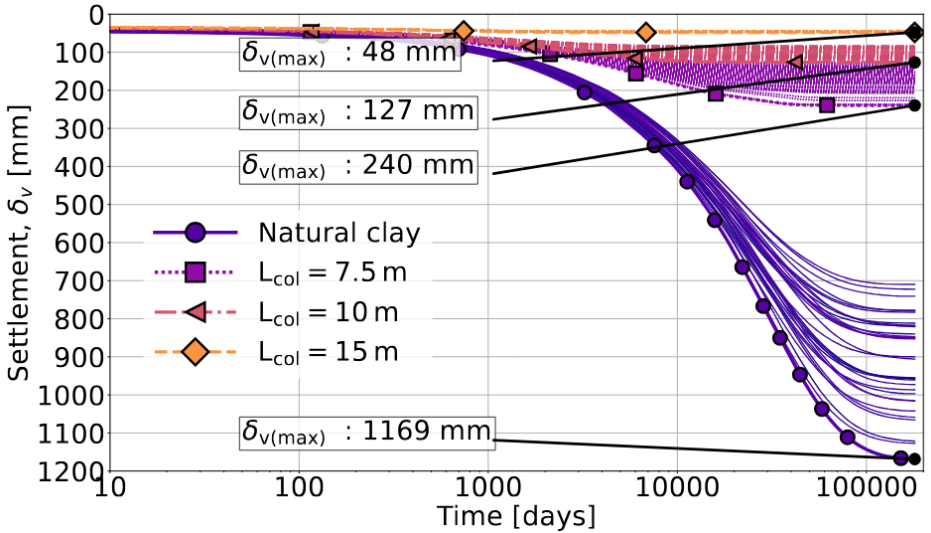
Sensitivity analyses (DOE)

range of factors: 5%



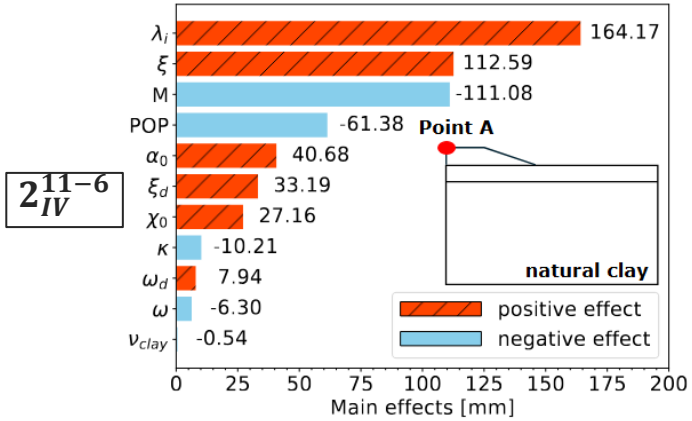


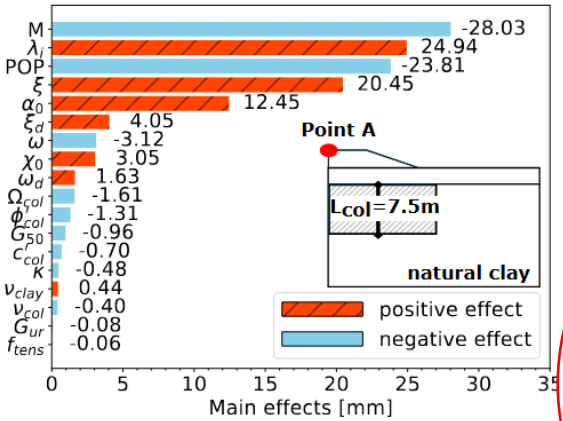
L_{col}: various

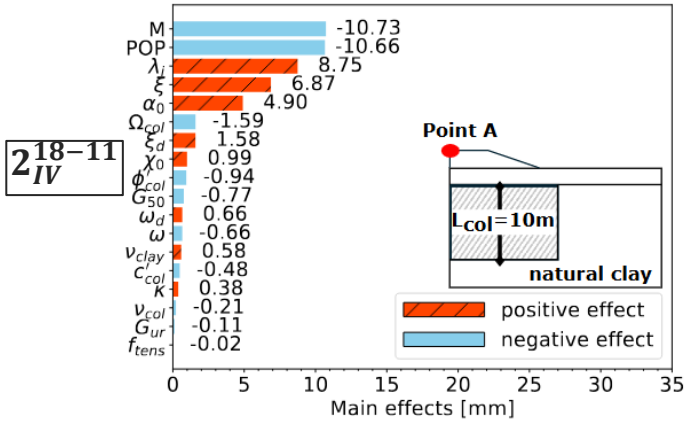


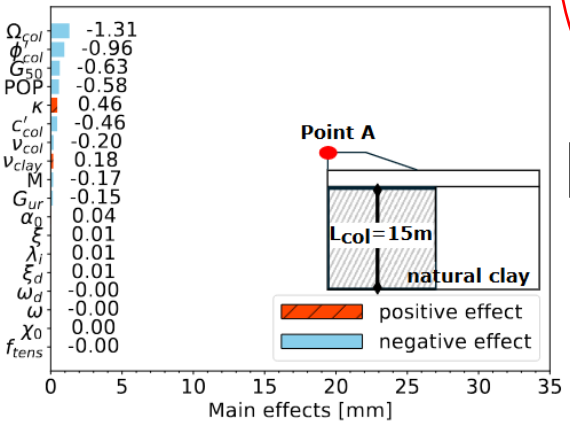
S-line

Influential factors









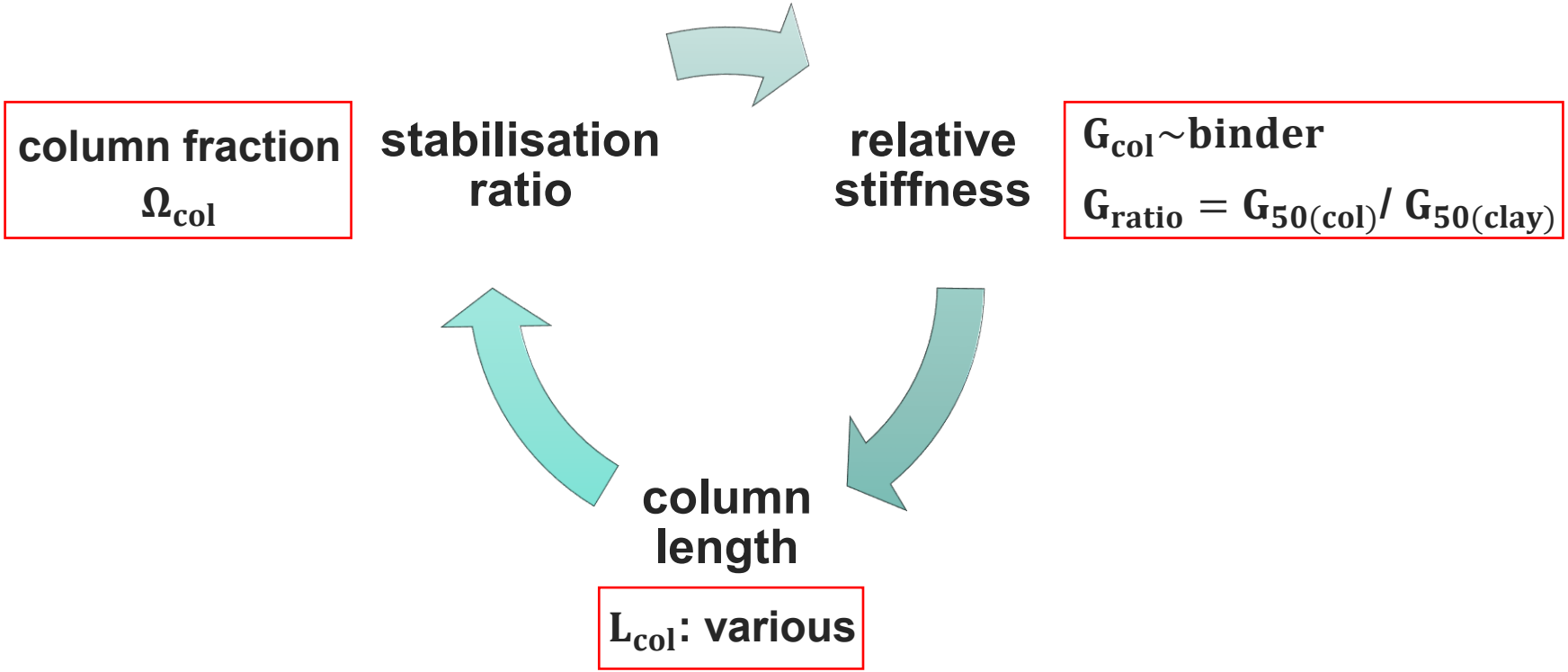
2_{IV}^{18-1}

2_{IV}^{18-1}

- End-bearing columns: **Columns govern!** Ω_{col}, G_{50}
- Floating colums: **Soft clay governs!** ***M***, λ_i, **POP**, ξ, α_0

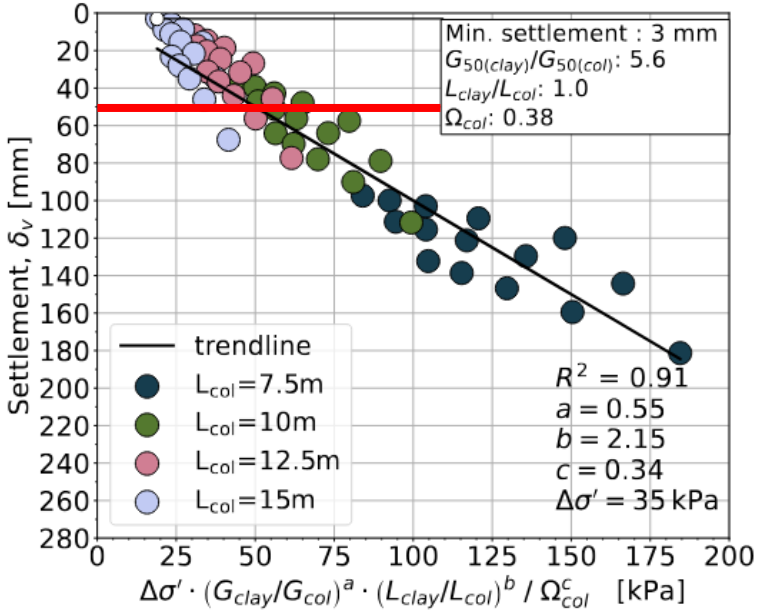
range of factors: 5%

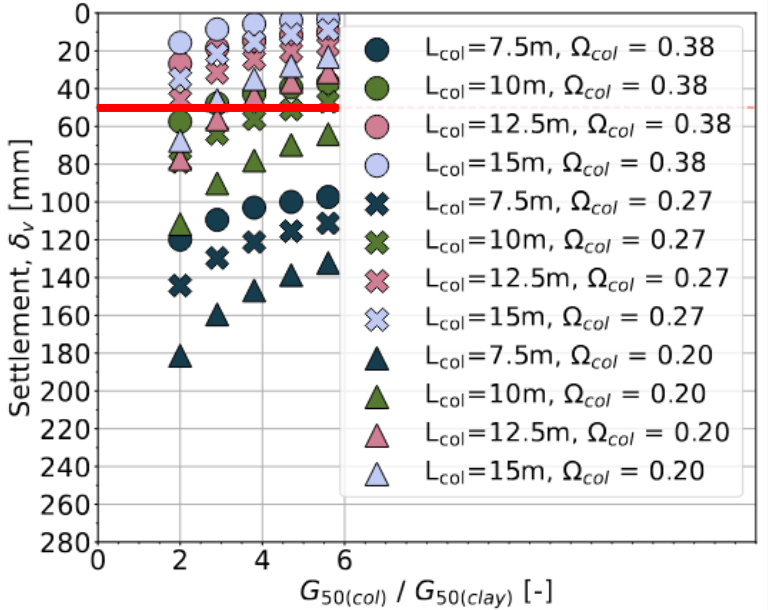
How weak can the columns be?



Linking stiffness, length, and stabilisation ratio

Limit settlement: 50mm



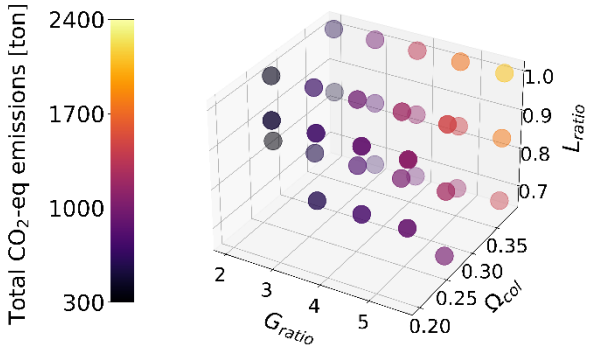


Material use related GHE

Combination	Component	Proportion (%)	Quantity (ton)	CO_2-eq emissions factor (kg CO_2-eq/ton)	Total CO_2-eq emissions (ton CO_2-eq)
Upper boundary	QL	50	921	1450[a]	1335
G_{ratio}=5.6 (110 kg/m^3)[b]	OPC	50	921	870[a]	801
L_{col} = 15 m Ω_{col} = 0.38	**Total**	**100**	**1842**	**1842**	**2136**
Lower boundary	QL	50	144	1450[a]	208
G_{ratio}=2.0 (30 kg/m^3)[b]	OPC	50	144	870[a]	125
L_{col} = 12.5 m Ω_{col} = 0.27	**Total**	**100**	**288**	**2320**	**334**

[a] CO_2-eq emissions factors are based on Klimatkalkyl version 7.0 by Trafikverket (Swedish Transport Administration).

[b] Binder contents corresponding to target stiffness moduli are estimated based on Paniagua et al. (2021).



$$\mathbf{G_{ratio} = G_{50(col)}/G_{50(clay)}}$$

column fraction: $\mathbf{\Omega_{col}}$

Conclusions

- For most geotechnical problems on deep mixed columns, serviceability limit controls the design.
- Volume Averaging Technique (VAT) enables mapping of a periodically arranged column system to 2D, yet modelling separately the individual constituent (clay and columns).
- VAT formulations were developed for two cases: embankments and excavations, and verified against 3D simulations.
- VAT can significantly save computational time, yet yields similar results to those of 3D analysis.
- The systematic approach, using the VAT in combination with factorial design, can be used to perform efficiently sensitivity analyses and/or data-driven procedures in a plane strain analysis.

Key references for VAT

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- Vogler, U., & Karstunen, M. (2008). Application of volume averaging technique in numerical modelling of deep mixing. In M. Karstunen & M. Leoni (Eds.), Geotechnics of Soft Soils: Focus on Ground Improvement: *Proceedings of the 2nd International Workshop on Geotechnics of soft soils, Glasgow, Scotland, 3 – 5 September 2008* (1st ed., pp. 189–195). CRC Press. https://doi.org/10.1201/9780203883334
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