A2021-06: Rate-dependent response of excavations and permanent underground structures

Johannes Tornborg | Skanska & Chalmers | BIG-webinarium 2024-05-17

Komplett redovisning samt referenser ges i avhandling: https://research.chalmers.se/en/publication/540291

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Outline

- Background
- Aim & Objectives
- Method
- Results
- Conclusions and recommendations

Background

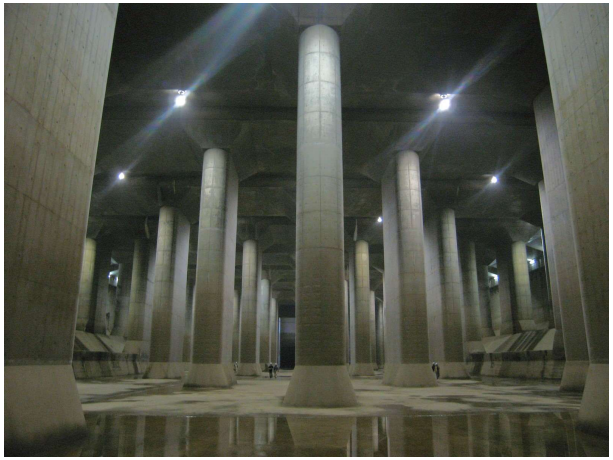
Increasing demand for underground space, e.g.:

- Sustainable transportation
- Storm water retention
- Energy storage
- Commercial & residential use

Calls for accurate predictions of earth pressures during the construction and serviceability stages



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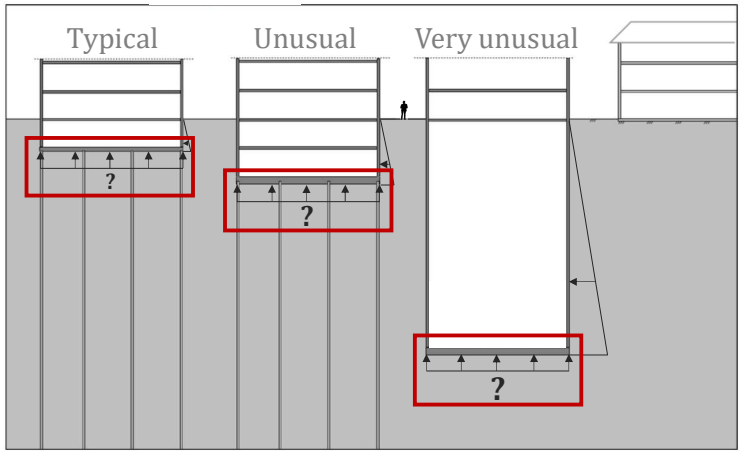


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Background

Earth pressures on underground structures

- Several systematic studies published on horizontal earth pressures, primarily on retaining structures during the construction stage
- In contrast, investigations into earth pressures below slabs or tunnels are scarce (especially in soft clays)
- A limited number of studies include the serviceability stage



A systematic approach is needed to quantify the evolution of earth pressures below the base of excavations and underground structures in deep excavations

Aim

The aim of this thesis is to investigate the temporal evolution of earth pressures acting on underground structures in deep excavations in soft clay by means of numerical analyses and field monitoring.

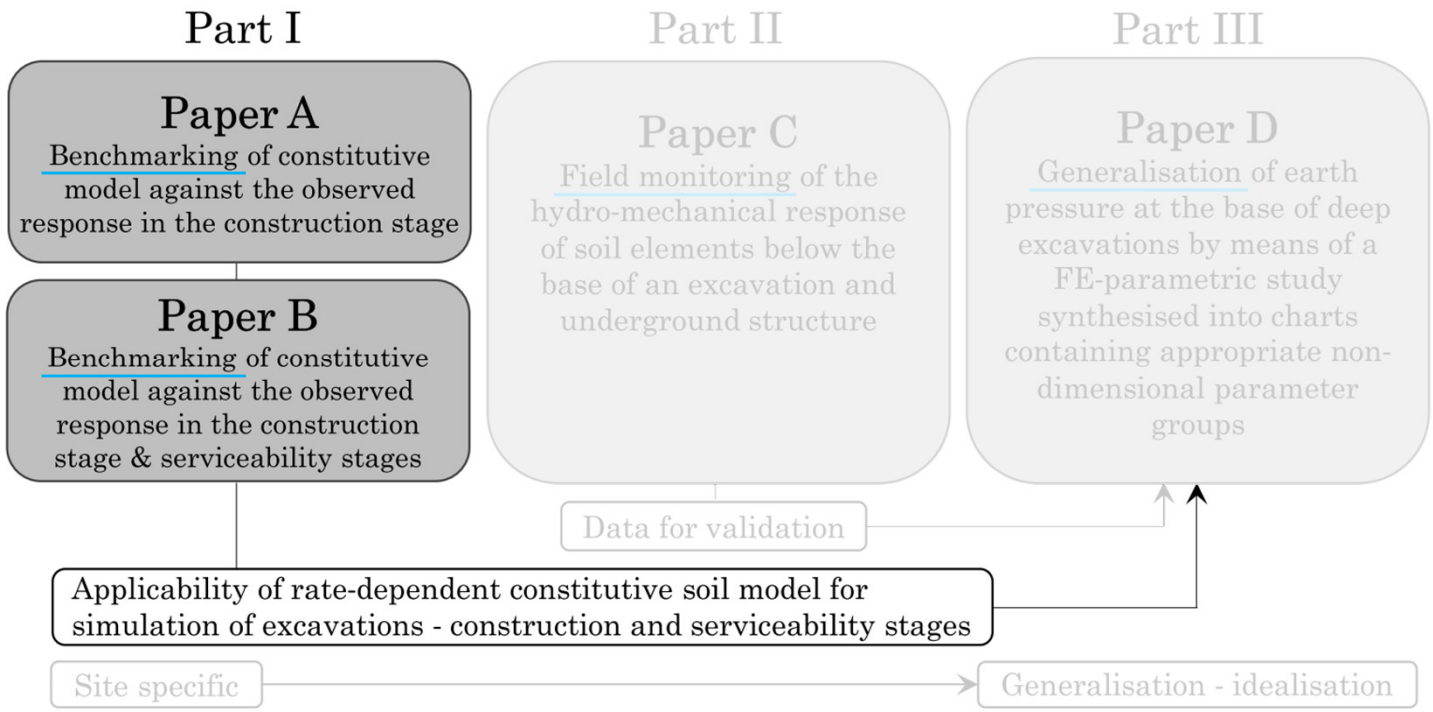
Objectives

i) Benchmark a rate-dependent constitutive model against case studies of deep excavations in soft clay

ii) Monitor the hydro-mechanical response of soil elements below the base of an underground structure in soft clay

iii) Generalise the evolution of earth pressures below the base of underground structures in soft clay by performing a parametric study

Methodology



Från Tornborg (2024b)

Part 1: Benchmarking of Creep-SClay1S

Paper A

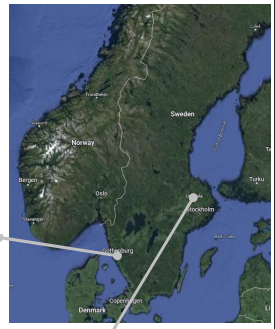
Tornborg, J., Karlsson, M., Kullingsjö, A., & Karstunen, M. (2021).

Modelling the construction and long-term response of Göta Tunnel.

Computers and Geotechnics, *134*, 104027, 1–19.

https://doi.org/10.1016/j.compgeo.2021.104027





Tornborg et al. (2021)

Paper B

Tornborg, J., Karlsson, M., & Karstunen, M. (2023).

Permanent Sheet Pile Wall in Soft Sensitive Clay.

Journal of Geotechnical and Geoenvironmental Engineering, 149(6), 1–13.

https://doi.org/10.1061/JGGEFK.GTENG-10955



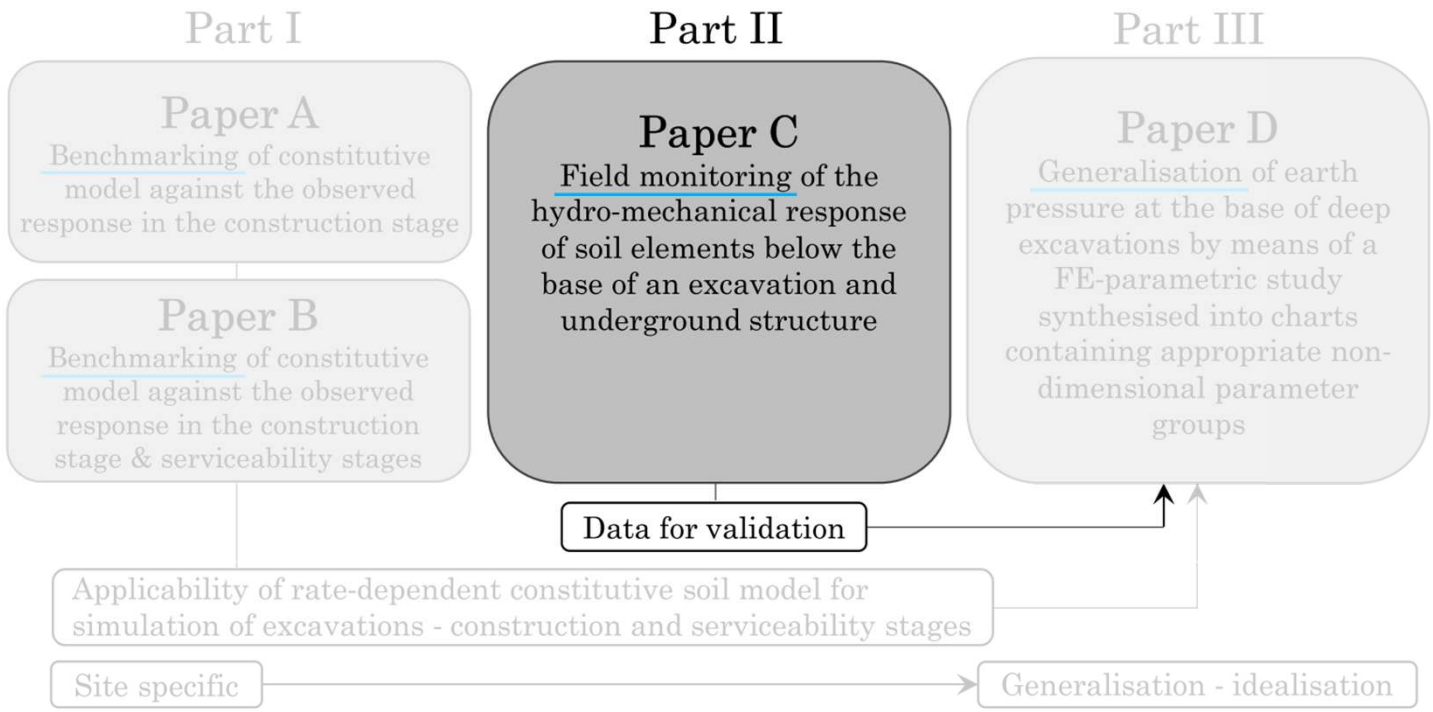
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Part 1: Main conclusions

- The Creep-SClay1S model can be used to compute the temporal evolution of earth pressures acting on underground structures in soft clay with sufficient accuracy.
- Rate-dependency enables to simulate the construction and serviceability stages using a single unified parameter set.
- Neither case provides any data on the evolution of earth pressures below the base of the excavation or underground structure.






Part I
Paper A
Benchmarking of constitutive model against the observed response in the construction stage
Paper B
Benchmarking of constitutive model against the observed response in the construction stage & serviceability stages
Part II
Paper C
Field monitoring of the hydro-mechanical response of soil elements below the base of an excavation and underground structure
Part III
Paper D
Generalisation of earth pressure at the base of deep excavations by means of a FE-parametric study synthesised into charts containing appropriate non-dimensional parameter groups
Data for validation
Applicability of rate-dependent constitutive soil model for simulation of excavations - construction and serviceability stages
Site specific
Generalisation - idealisation
Tornborg (2024b)

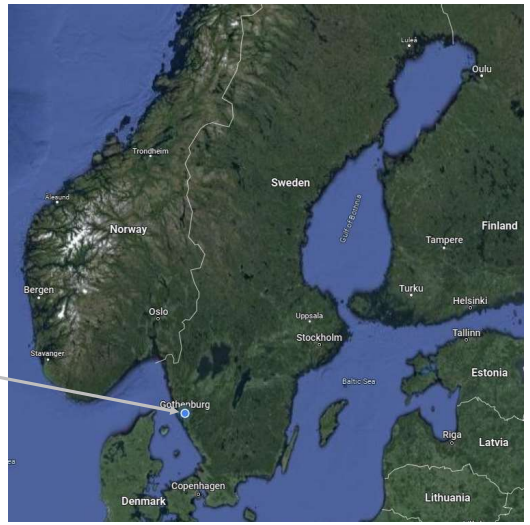
Paper C

Tornborg, J., Karlsson, M., & Dijkstra, J. (2024).

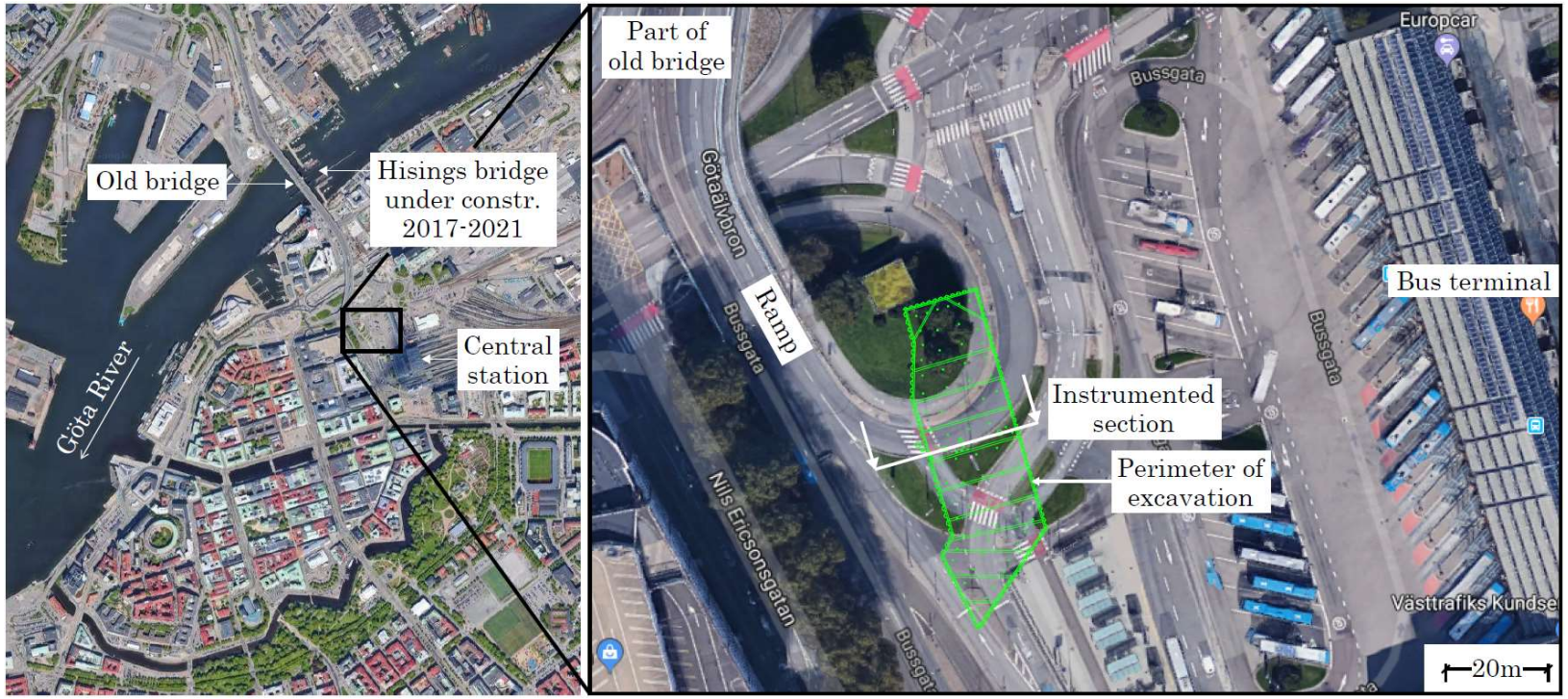
Temporal effective stress response of soil elements below the base of an excavation in sensitive clay.

Canadian Geotechnical Journal. In print.

https://doi.org/10.1139/cgj-2023-0355

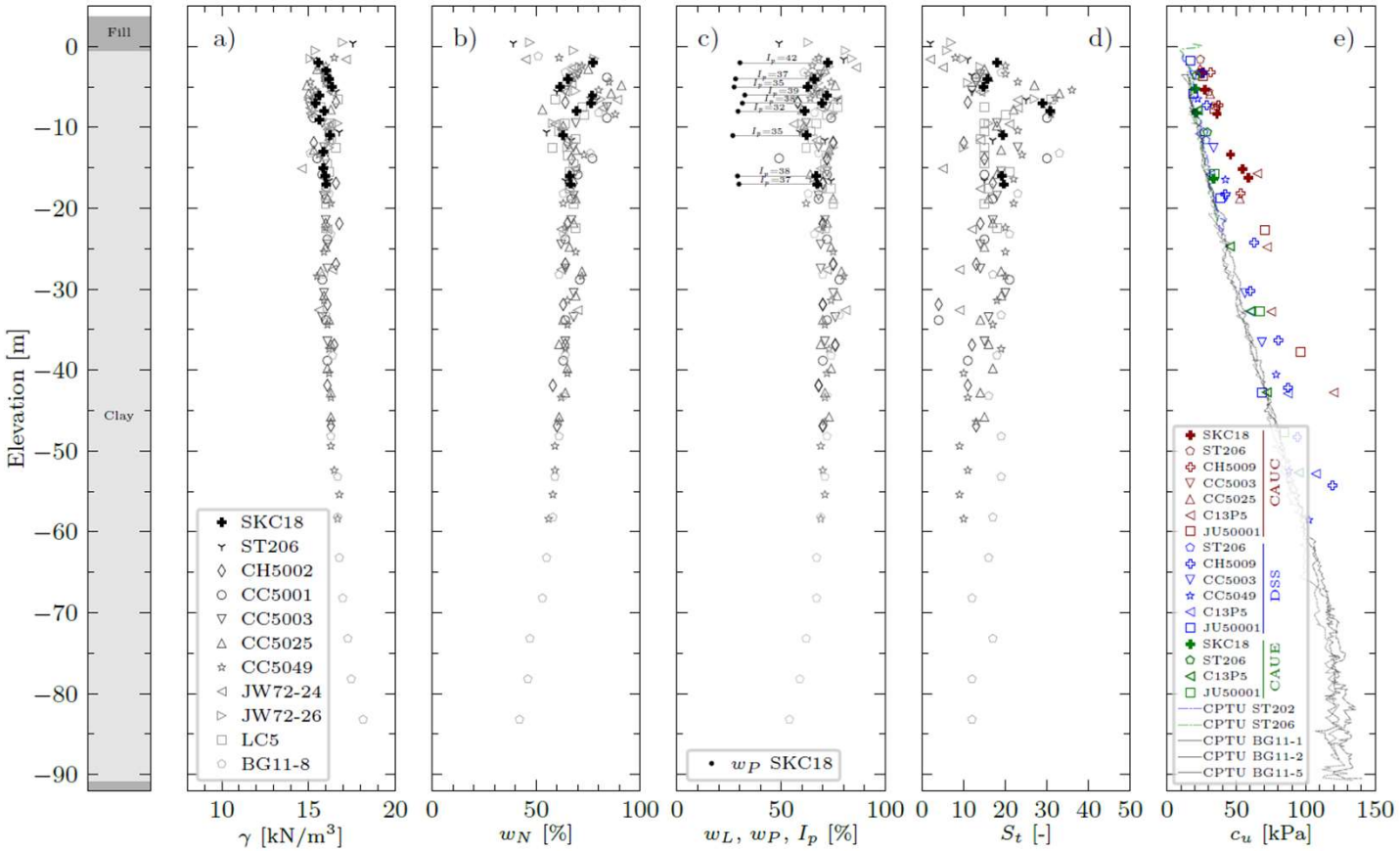


Paper C: Instrumented site in Gothenburg



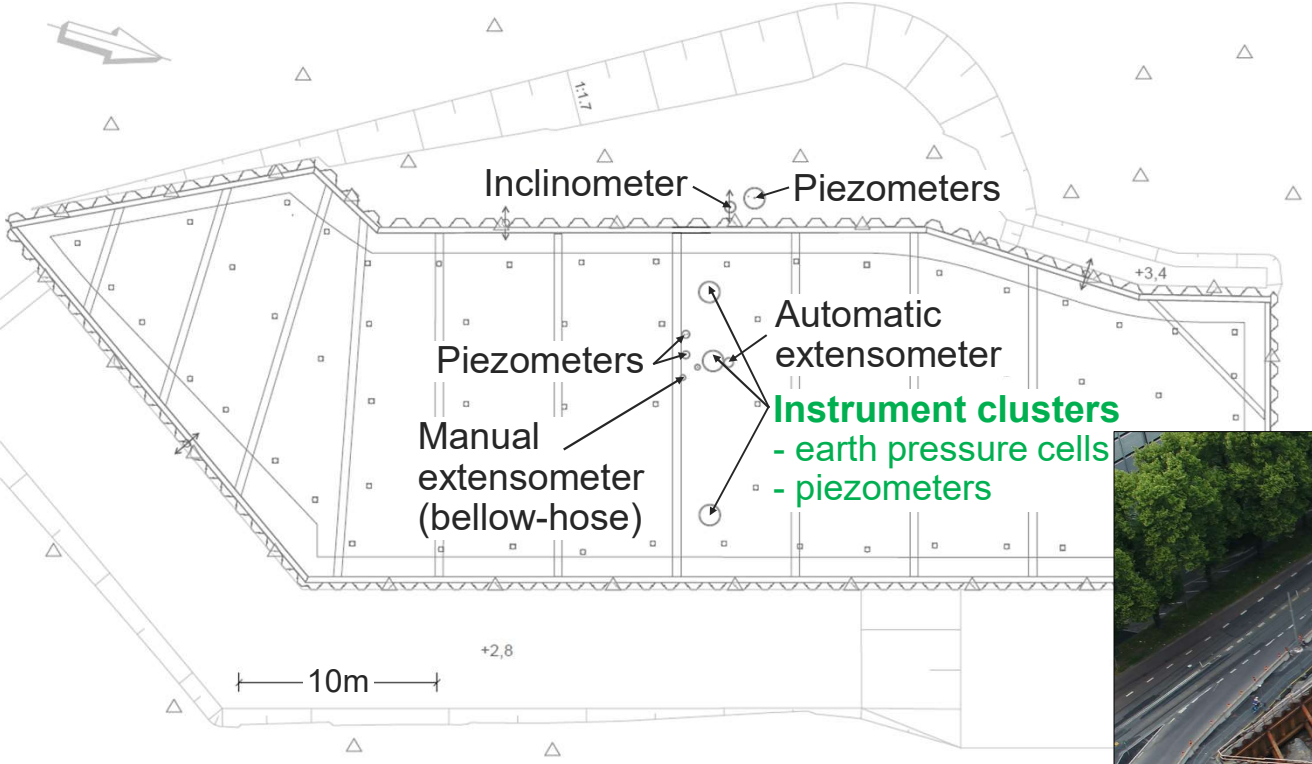
Tornborg et al. (2024a)

Paper C: Site characterisation



Tornborg et al. (2024a)

Paper C: Layout of monitoring

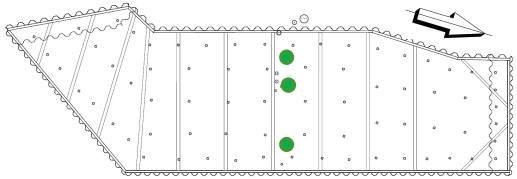




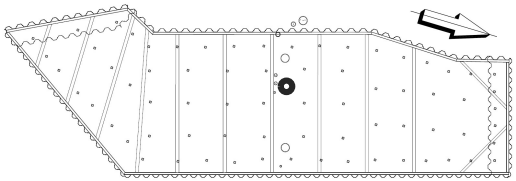
Paper C: Instrument clusters below the slab

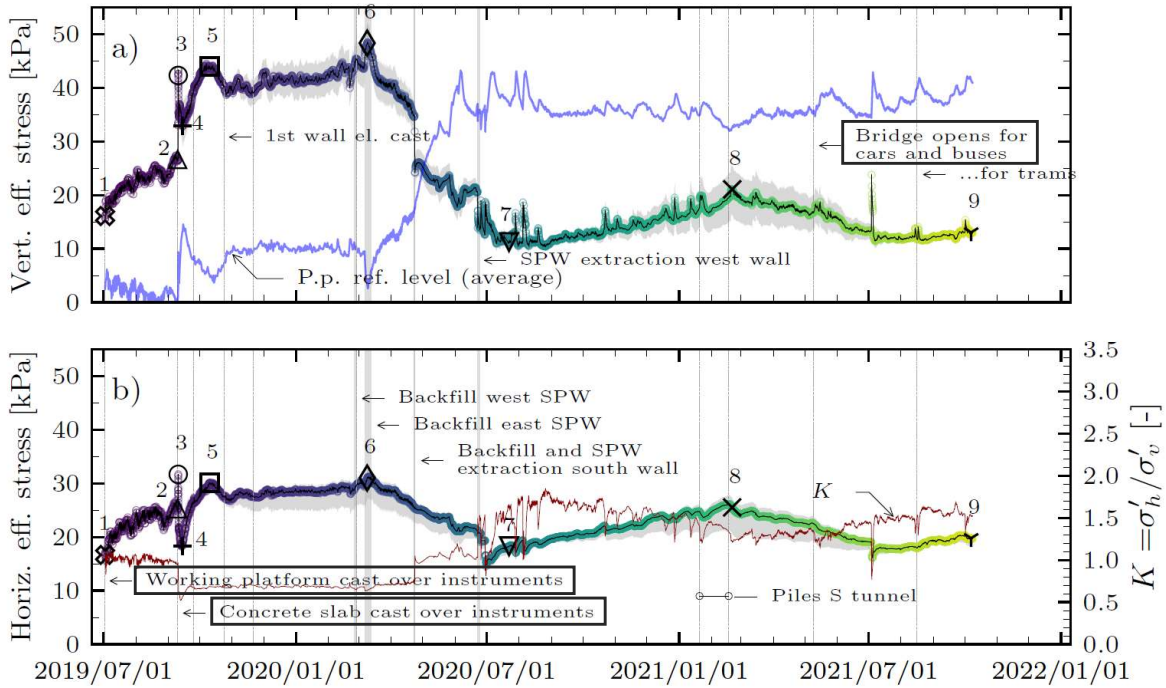
- Hydraulic earth pressure cells (vertical and horizontal total stresses)
- Piezometers
- Extensometer (clay-slab relative vertical displacement)

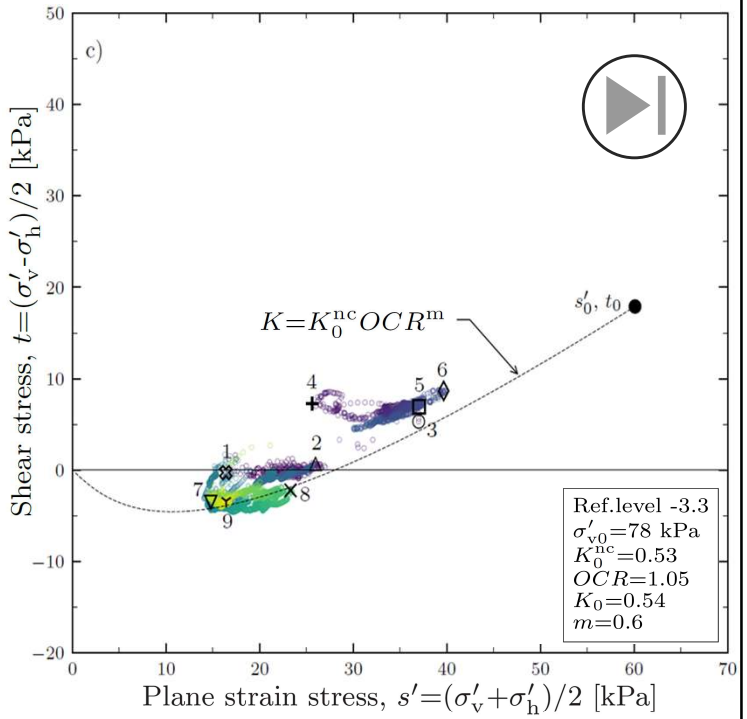




Paper C: Example – effective stresses







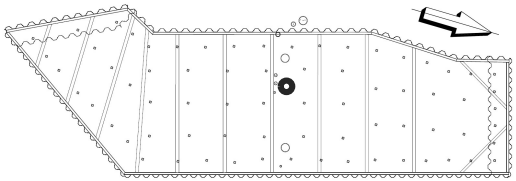
Grey range illustrates uncertainty in temperature compensation for the hydraulic earth pressure cells

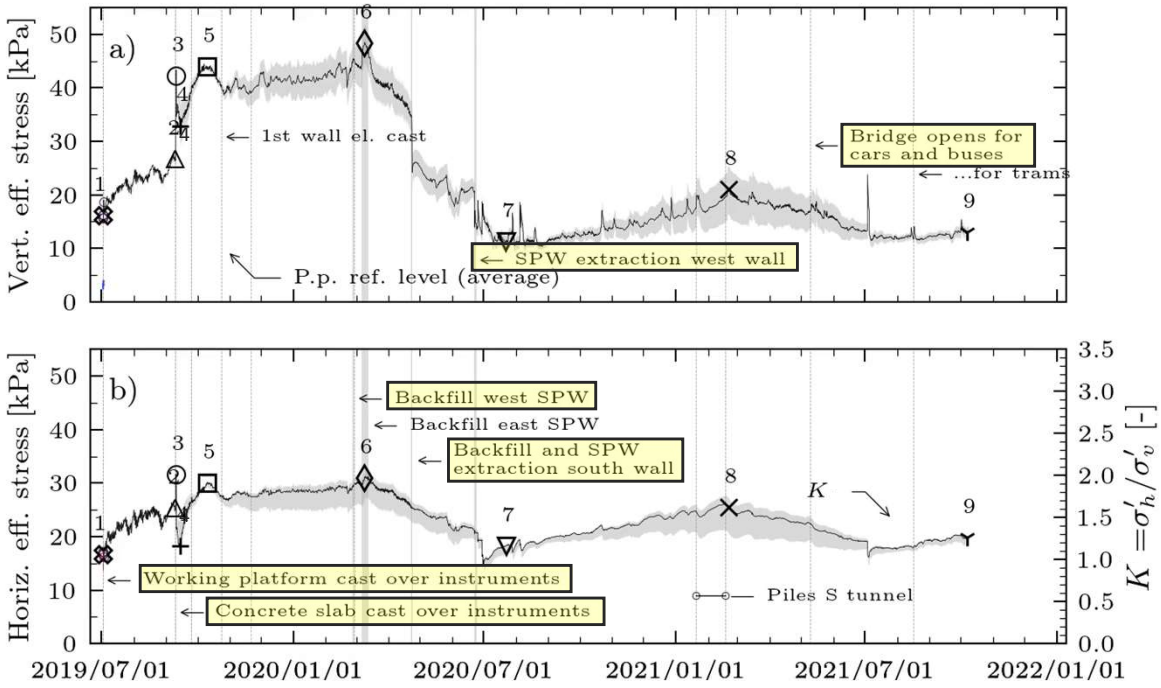
Tornborg et al. (2024a)

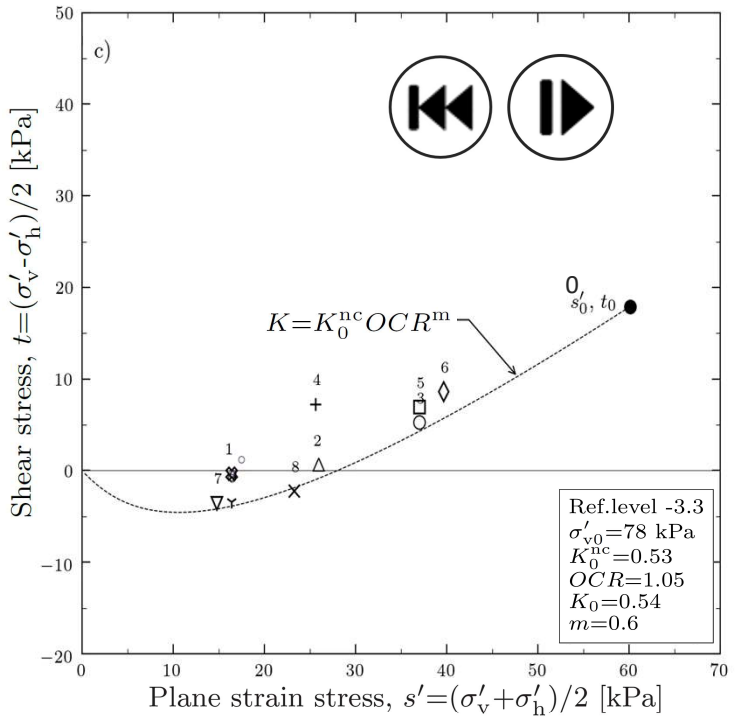
Background | Method | Results - part 1 | Results - part 2 | Results - part 3

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Paper C: Example – effective stresses



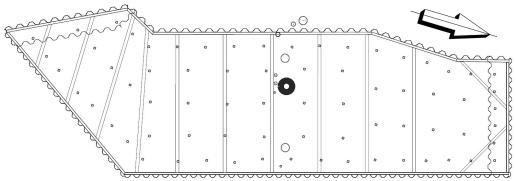


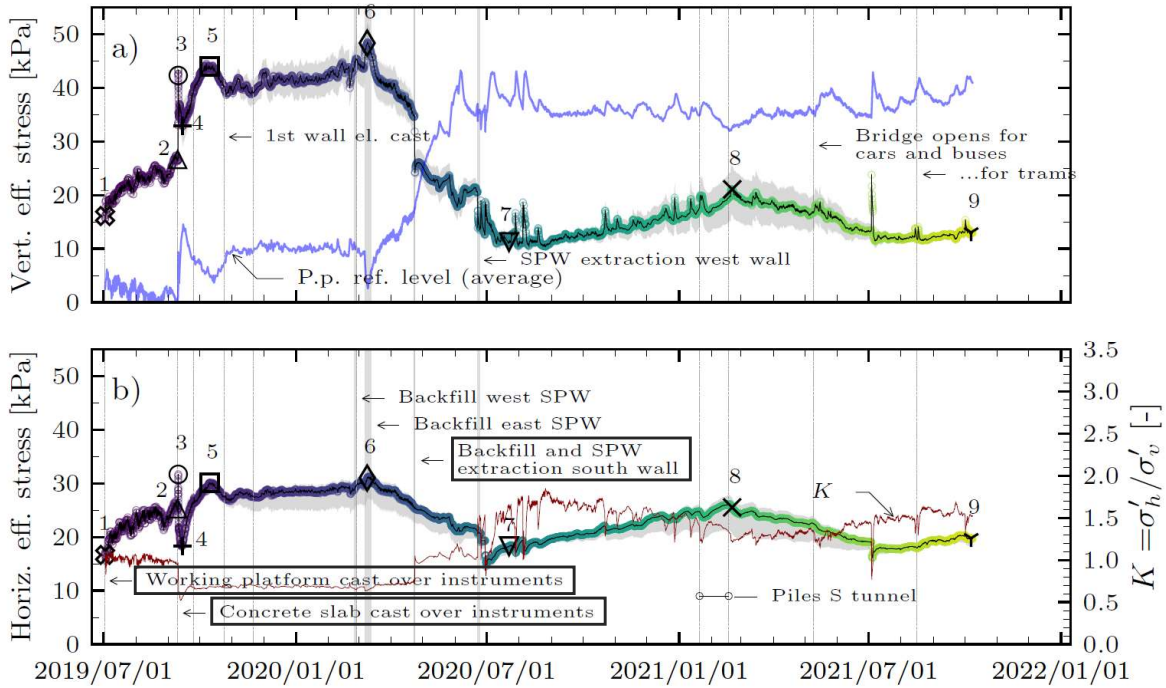


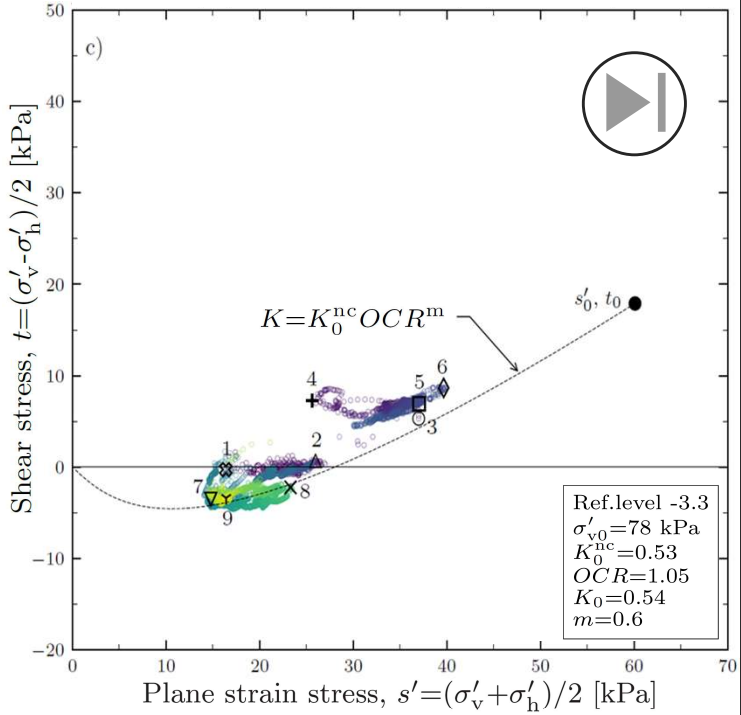
Grey range illustrates uncertainty in temperature compensation for the hydraulic earth pressure cells

Tornborg et al. (2024a)

Paper C: Example – effective stresses







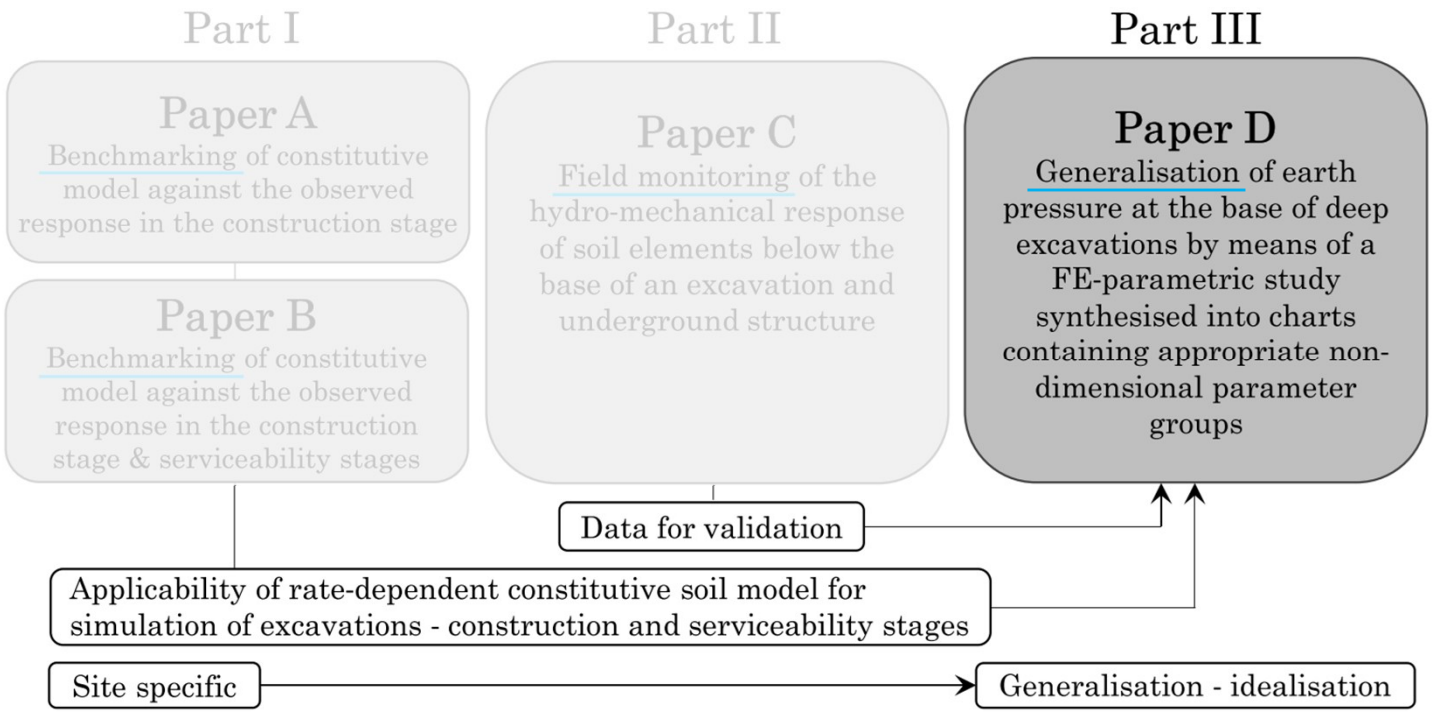
Grey range illustrates uncertainty in temperature compensation for the hydraulic earth pressure cells

Tornborg et al. (2024a)

Paper C: Main conclusions

- Clustered instruments enabled unique observations of the evolution of effective stresses at soil element level in situ.
- The results enabled comparison to laboratory established relationships of the stress ratio $K = \sigma'_{\mathrm{h}}/\sigma'_{\mathrm{v}}$. The general trend approximately follows the relationship $K = K^0_{\mathrm{nc}} OCR^{\mathrm{m}}$ (with $K^0_{\mathrm{nc}} = 0.5$ and $\mathrm{m} = 0.6$).
- The effective stresses continued to increase in the instrument clusters after casting the working platform and the slab.
- When the pore pressure regained the effective stresses reduced considerably. The structural load is primarily carried by water pressure and/or the piles.
- Monitoring limited to one setting → generalise these results

Methodology

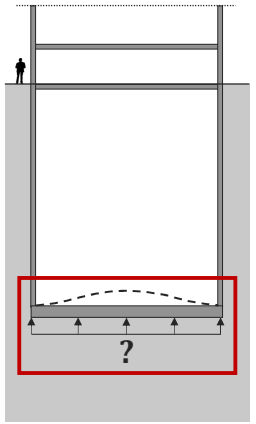


Tornborg (2024b)

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Part 3: Background

- In soils with low permeability, unloading results in a temporal evolution of effective stresses and delayed heave
- What is the magnitude of the action when delayed heave is restrained by a structural element?
- Factors that affect the response, e.g.
  - Amount of heave dissipated before activation of restraint. Controlled by geometry and normalised time, *T*
  - Soil-structure interaction: the relative displacement and stiffness of the structure and adjacent soil
  - Rate-dependent soil behaviour (background settlements)
- Previous studies
  - Simpson (2018) & Chan et al. (2022) stiff clay, one *T*, no water pressure on slab.
  - Alén & Sällfors (2001) project-specific analysis for Göta Tunnel.

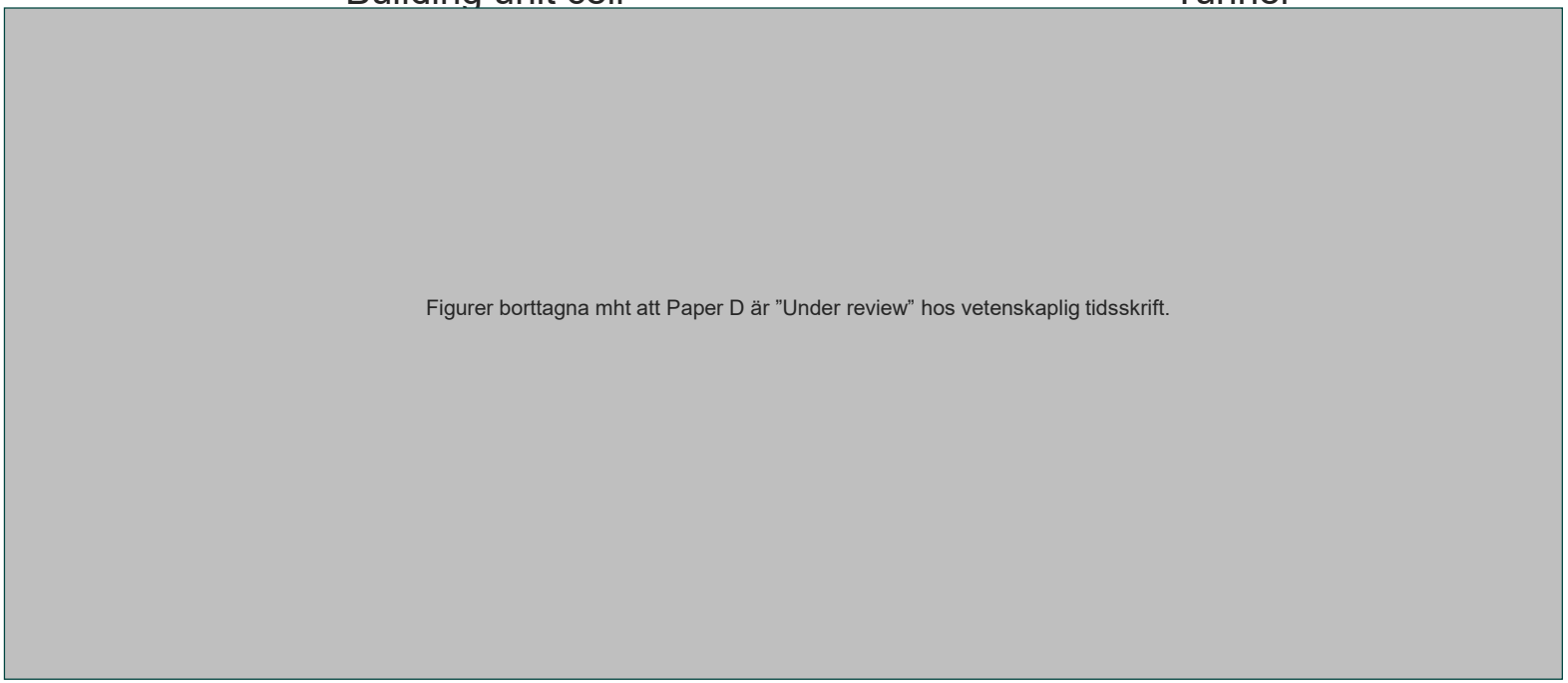


A systematic study on the development of heave pressure at the base of deep excavations is needed

Paper D: Geometries & adding complexity

Building unit cell

Tunnel



Paper D Fig. 1

Mohr-Coulomb → Mohr-Coulomb
SClay1S
Creep-SClay1S → Groundwater table at i) excavation base
ii) 1m below ground level

Paper D: Parametric study

- Variables that affect the magnitude of EHP, consider:

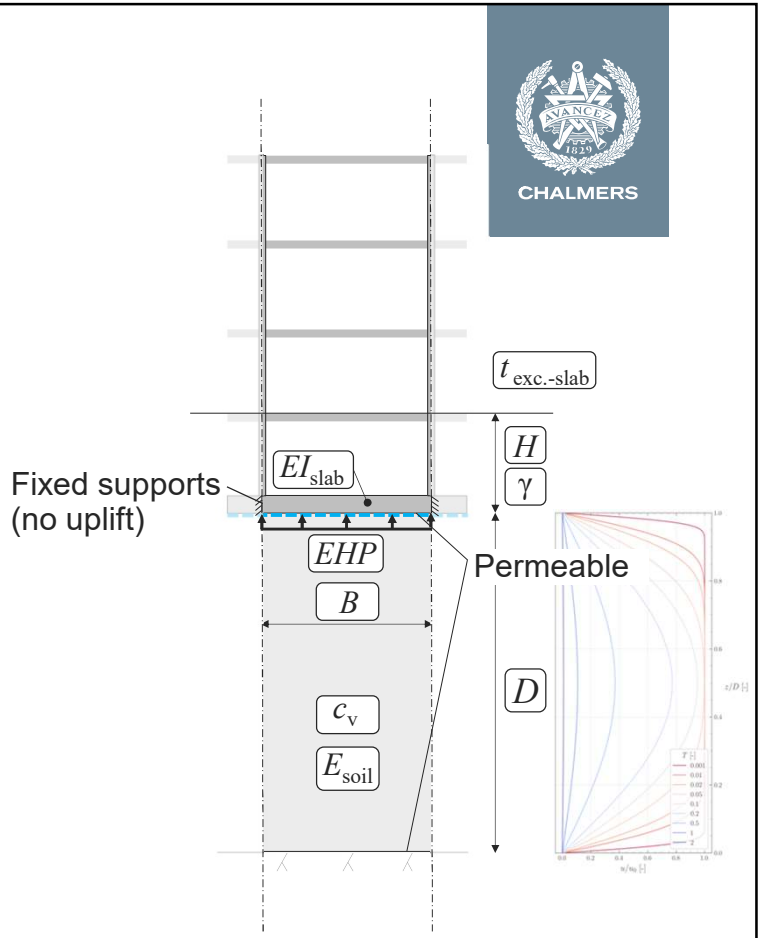
$$EHP = f(E_{\text{slab}}, I_{\text{slab}}, E_{\text{soil}}, B, c_{\text{v}}, t, \gamma, H, D)$$

- Which can be arranged into dimensionless groups:

$$\frac{EHP}{\gamma H} = f\left(\frac{EI_{\text{slab}}}{E_{\text{soil}}B^3}, \frac{c_{\text{v}}t}{D^2}\right)$$

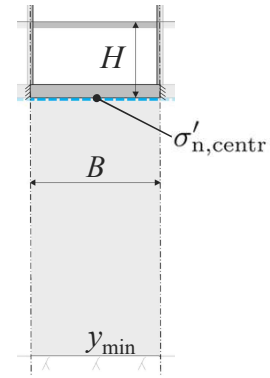
- Experiments (numerical modelling) to establish relationships between these groups.

Input to model → Build model, Run simulation, Save files → Process results



Paper D: Building unit cell w. MC model

Scenario with a weightless slab:



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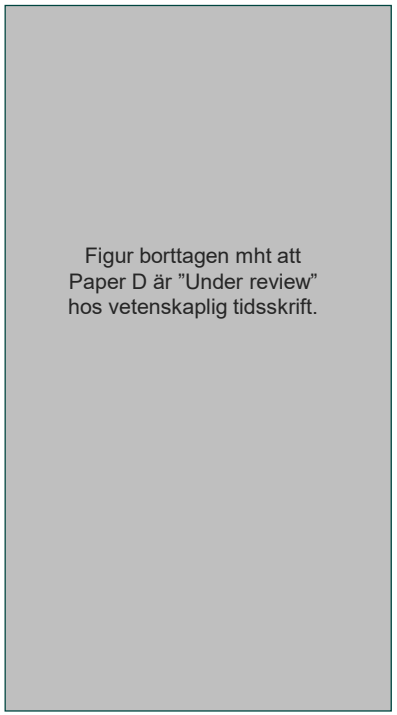
$$\frac{EHP}{\gamma H} = f\left(\frac{EI_{slab}}{E_{soil}B^3}, \frac{c_v t}{D^2}\right)$$

R T_v

Paper D also includes normalised displacement, normalised bending moments and impact of slab self-weight.

Paper D Fig. 2c and d

Paper D: Building unit cell



In summary, within the boundary conditions and idealisations made, it is possible to estimate heave, effective heave pressure and bending moments using the developed non-dimensional charts

→ next step: the tunnel geometry

Paper D: Tunnel geometry - MC-model

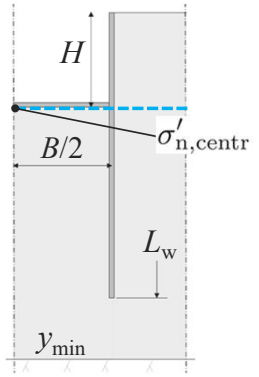
$\frac{\sigma'_{n,centr.}}{\gamma H}$ [-]

$\frac{\sigma'_{n,centr.}}{\gamma H}$ [-]

$\frac{\sigma'_{n,centr.}}{\gamma H}$ [-]

$\frac{\sigma'_{n,centr.}}{\gamma H \times \mu_i}$ [-]

Figurer borttagna mht att Paper D är ”Under review” hos vetenskaplig tidsskrift.



Even for very small T, the EHP-ratio does not approach 1.0 as for the Building unit cell

↓ Separate the impact of geometry and consolidation

Influence factor μ_i to quantify that a portion of heave is instant. I.e., EHP affected (purely) by geometry.

T_{2D} to normalise horizontal component of consolidation

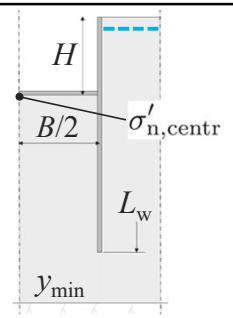
μ_i and T_{2D} combined: generalise the effects of geometry & consolidation

Paper D: Tunnel geometry – (Creep-)SClay1S

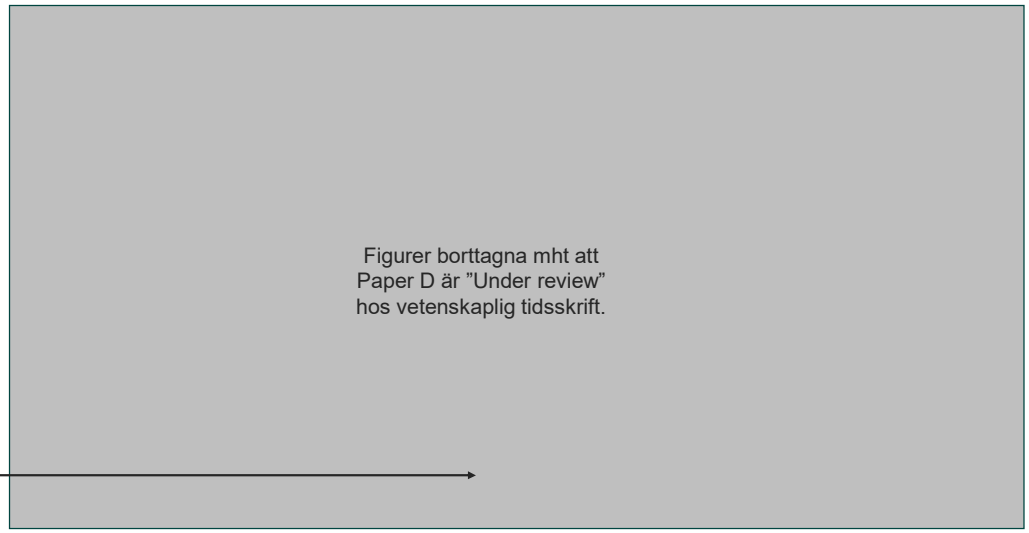
- For Creep-SClay1S the plotted values are maximum EHP, which evolve due to rate-dependency (the 120-year values are shaded).
- The MC, SClay1S and Creep-SClay1S maximum values are similar. The results compare well to physical model tests.
- The benefit of the advanced models in this study is, e.g., to compute the long-term evolution of EHP due to creep.
- Effect of considering small-strain stiffness → in NGM2024 paper.



Paper D: Tunnel geometry – ground water table at 1m depth b.g.l.



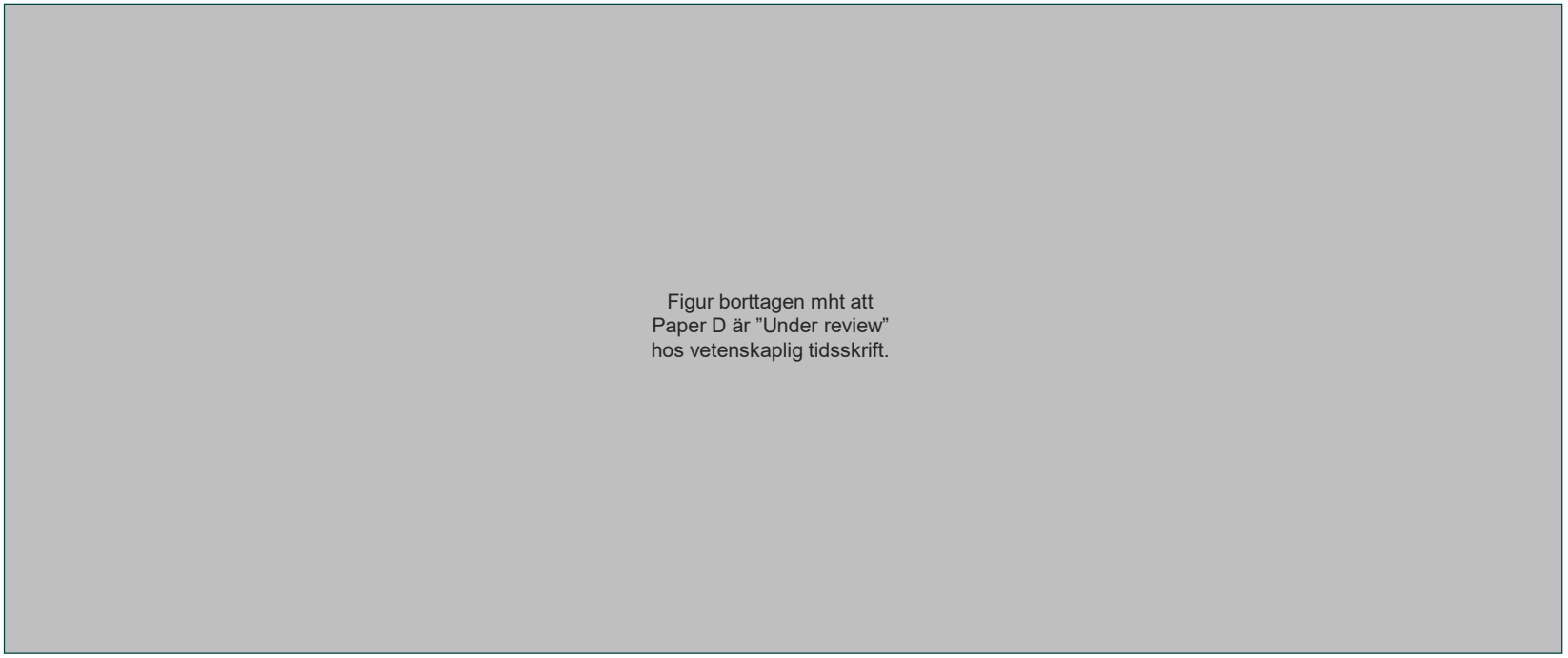
- Previous results were with a groundwater table located at the excavation base
- The evolution of EHP is affected by the return of water pressure under the slab
- The long-term 120-year value is, however, nearly unaffected by when the water pressure returns
- This specific scenario allows for validation: compare the results to the field monitoring data in Paper C



Paper D Fig. 12

Paper D: Tunnel geometry – validation

Comparison of simulation in parametric study to monitoring data in Paper C



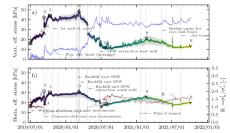
Paper D Fig. 13

Main conclusions of this project

- Part 1: Benchmarking of the Creep-SClay1S model demonstrated that it can be used to compute the magnitude and evolution of earth pressures acting on underground structures in soft clays with sufficient accuracy.



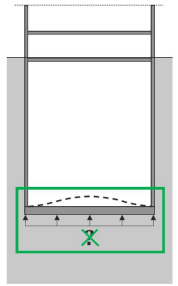
- Part 2: Monitoring of the hydro-mechanical response enabled unique observations of the evolution of effective stresses at soil element level in situ, below an excavation base and slab. This bridges a gap in the literature.



- Part 3: The combination of field monitoring, dimensional analysis and numerical modelling have been integrated into non-dimensional charts, which increase our knowledge on the system response and evolution of earth pressures in deep excavations.

Figur borttagen mht att Paper D är ”Under review” hos vetenskaplig tidsskrift.

- The results can readily be used as a tool for industry to assess the magnitude of effective heave pressure and complement detailed project-specific analyses.



Recommendations

- Design of deep excavations in soft soils should consider that the response during the construction stage affects the actions in the serviceability stage. EHP is a prime example, and now we have a tool to quantify it.
- For sustainable underground structures, the best practice should include:
  i. independent project-specific analyses that may lead to further optimisation of construction material volumes
  ii. field observations which aim to increase the knowledge base of earth pressures on underground structures
- Industry including the asset owners should set out to monitor the system performance of underground structures during the construction and serviceability stage.
- Complexity can be added to the generalisation presented in Paper D considering e.g. impact of pile installation and tensile forces in piles induced by soil heave.
- Dimensional analysis greatly enhances the understanding of complex systems.

Acknowledgements

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Reference group
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Bengt Askmar (Norconsult)
Torbjörn Edstam (Skanska)
Gunnar Holmberg (Skanska)
Leif Jendeby (COWI)
Jenny Langford (NGI)
Sven Liedberg (Skanska)
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Johan Spross (KTH/BIG)
Johan Vium-Andersson (WSP)
Tara Wood (Ramboll)
Jorge Yannie (GEN monitoring)



SKANSKA





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Referenser

Paper A Tornborg, J., Karlsson, M., Kullingsjö, A., & Karstunen, M. (2021). Modelling the construction and long-term response of Göta Tunnel. *Computers and Geotechnics*, 134, 104027. https: //doi.org/10.1016/j.compgeo.2021.104027

Paper B Tornborg, J., Karlsson, M., & Karstunen, M. (2023). Permanent Sheet Pile Wall in Soft Sensitive Clay. *Journal of Geotechnical and Geoenvironmental Engineering*, 149(6), 1–13. https://doi. org/10.1061/JGGEFK.GTENG-10955

Paper C Tornborg, J., Karlsson, M., & Dijkstra, J. (2024a). Temporal effective stress response of soil elements below the base of an excavation in sensitive clay. *Canadian Geotechnical Journal*. https://doi.org/10.1139/cgj-2023-0355

Tornborg, J. (2024b). On the temporal evolution of earth pressures in deep excavations in soft clay. PhD thesis, Chalmers University of Technology. https://research.chalmers.se/en/publication/540291

Paper D Tornborg, J., Karlsson, M., Dijkstra, J., & Karstunen, M. (2024c). On the development of effective heave pressure in deep excavations. Manuscript. Submitted to journal paper, status ”Under review”.