Imperial College London

KIVI Geotechniekdag 2025

Geotechnical engineering for a sustainable society

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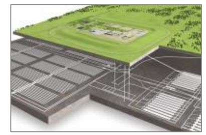
KIVI ie-net

11th November 2025, Amersfoort, The Netherlands

Outline

- Sustainable development
  "meeting the needs of the present without compromising the ability of future generations to meet their own needs"
  (United Nations Brundtland Commission, 1987)
- Setting the scene in the context of Civil / Geotechnical Engineering

economy	improving design efficiency / reducing over-conservatism
environment	protecting resources / reusing / reducing carbon emissions
society	protecting lives and improving wellbeing


Outline

- The role of computational analysis in sustainable design

Challenges & uncertainties:

site conditions
- geology
- layering, inhomogeneity, multi-phase
- initial stresses, ground water, geological history

soil behaviour
- in-situ testing
- sampling, sample disturbance, laboratory testing
- interpretation and derivation of parameters for design and for constitutive modelling

analysis
- any method of analysis idealises this input through mathematical forms and numerical algorithms to aid geotechnical design

available tools:

established numerical methods
- Finite Element (FE)
- Finite Difference (FD)
- Boundary Element (BE) ?
- Random Field FE ?

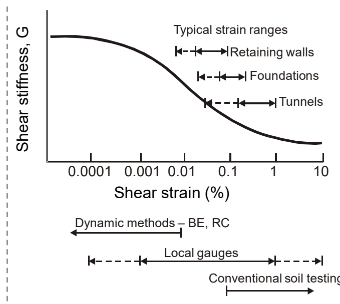
⟺

emerging numerical methods
- Data Science / Machine Learning
  - Bayesian Inference (BI)
  - Neural Networks (NN)

Outline

- Existing UK experience: example
  - Serviceability design & predictions of ground movements

UK 1980's industry lead on soils' small strain modelling:
- new active underground construction
- the need to reduce an unnecessary protection measures for the prevention of building damage
- Simpson et al. (1978)
  - BRICK model in Safe
- Potts et al. (1986)
  - nonlinear elastic models in ICFEP
- Benz (2007)
  - nonlinear elastic hysteretic model in PLAXIS

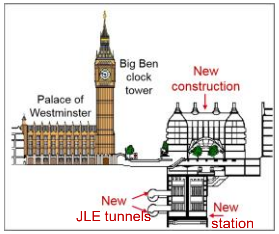
experimental evidence
after Atkinson & Sallfors, 1991

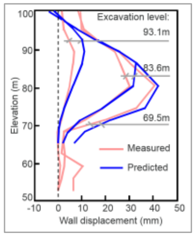
Outline

❑ Existing UK experience: example

➢ Serviceability design & predictions of ground movements

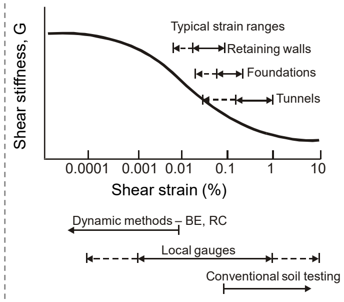
Higgins et al. (1994)





Westminster station Wall movements

Example: Jubilee Line Extension tunnels



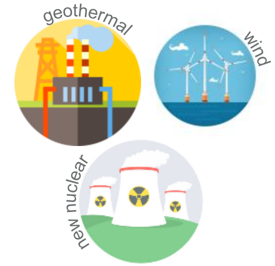
experimental evidence
after Atkinson & Sallfors, 1991

Outline

❑ Complexities of geotechnical design are increasing

lifecycle assessment

reduction in carbon emissions



energy transition

❑ Example applications:

➢ A energy transition: offshore wind
➢ B reuse of existing infrastructure
➢ C nature-based design and lifecycle assessment
➢ D radioactive waste disposal

❑ Software: Imperial College Finite Element Program (ICFEP), Potts & Zdravkovic (1999, 2001)

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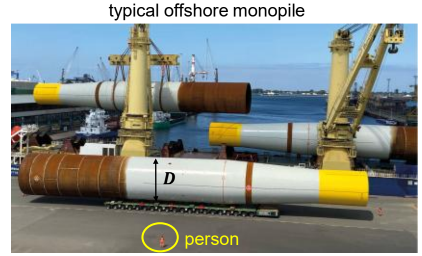
A Energy transition: offshore wind

❑ New design methods for offshore wind turbine monopiles

➢ preferred foundation system in shallow waters

wind farm

typical offshore monopile



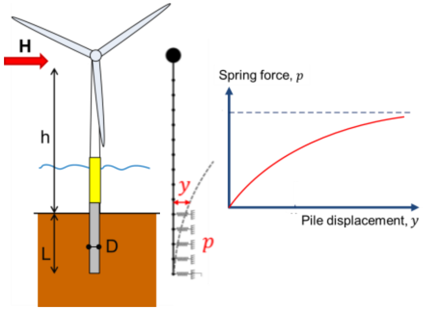
$D \geq 10$ m $L/D < 5$

Hornsea 2 monopiles, UK, Orsted

https://orsted.co.uk/energy-solutions/offshore-wind/our-wind-farms/hornsea2

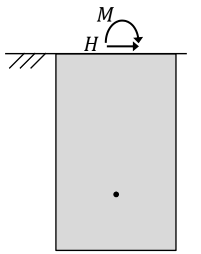
Technical challenge

- Industry-led new design methods



empirical $p-y$ relationships from field tests on **slender piles**, $D\sim1$ m; $L/D>20$

oil & gas piles



$D\geq 10$ m; $2\leq L/D\leq 6$

overconservative design

how to improve?

✗ no full-scale testing

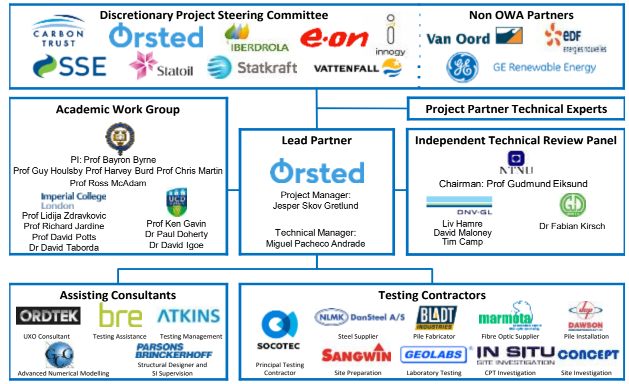
✗ no correlations from scaled testing

√ yes to numerical modelling, with scaled field testing

OWT monopiles

PISA project team

- **PI**le **S**oil **A**nalysis (PISA) Joint Industry Project (JIP), 2013-2018



Ground and soil characterisation

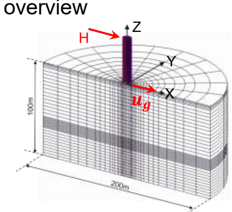
- Site locations for PISA pile testing, ground investigation and sampling

- 40m of low plasticity overconsolidated glacial clay till, PI ~18%;
- extended Modified Cam Clay model
- dense natural marine sand, $D_R\sim75$ % overlayed by hydraulic sand fill, $D_R\sim100\%$
- bounding surface plasticity model

PISA project

- High level overview

ground characterisation & 3D FE class A (blind) predictions



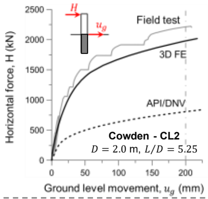
Design

reduced scale field testing

PISA project

- High level overview

comparison of FE blind predictions and field tests



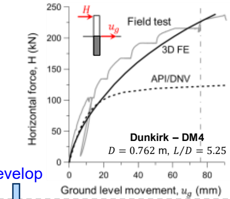
Design
Validate

reduced scale field testing

PISA project

- High level overview

comparison of FE blind predictions and field tests

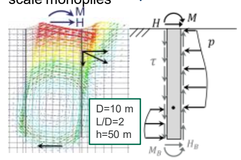


Design
Validate

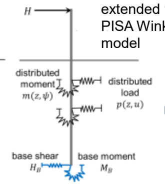
reduced scale field testing

Develop

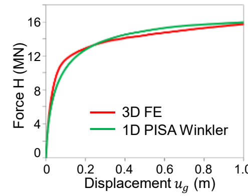
>100 3D FE analyses of full scale monopiles



extended 1D PISA Winkler model



Apply



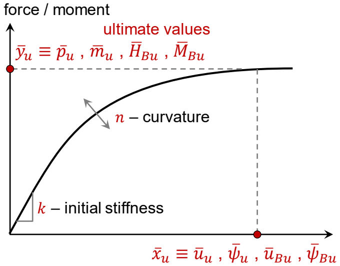
accurate response prediction with 1D PISA Winkler model

New design method: formulation

- 3D FE-based PISA design method
  - Formulation of 4 reaction curves

$\bar y \equiv \bar p\ , \bar m\ , \bar H_B\ , \bar M_B$

distributed load / moment or base force / moment



- conic function:

$$-n\left(\frac{\bar y}{\bar y_u}-\frac{\bar x}{\bar x_u}\right)^2+(1-n)\left(\frac{\bar y}{\bar y_u}-\frac{\bar x k}{\bar y_u}\right)\left(\frac{\bar y}{\bar y_u}-1\right)=0$$

Normalised variable	Non-dimensional form for clays	Non-dimensional form for sands
$\bar p$	$p/(S_u D)$	$p/(\sigma'_{vi} D)$
$\bar u$	$(uG_0)/(S_u D)$	$(uG_0)/(\sigma'_{vi} D)$
$\bar m$	$m/(S_u D^2)$	$m/(pD)$
$\bar\psi$	$(\psi G_0)/S_u$	$(\psi G_0)/\sigma'_{vi}$
$\bar H$	$H_B/(S_u D^2)$	$H_B/(\sigma'_{vi} D^2)$
$\bar M$	$M_B/(S_u D^3)$	$M_B/(\sigma'_{vi} D^3)$

$\bar x \equiv \bar u\ , \bar\psi\ , \bar v_B\ , \bar\psi_B$

lateral displacement or pile cross-section rotation

- clay: Byrne et al. (2020)
- sand: Burd et al. (2020a)
- layered: Burd et al. (2020b)

A Energy transition: offshore wind

- Site-specific numerical modelling enabled
  - quantification of ground response
  - confidence in optimising monopile design
  - development of new design methods

SAVING in embedded steel alone up to 35%
For a typical windfarm of 100 turbines:
SAVING in steel alone = 31,000 tonnes or

Cementation SKANSKA

PISA project:
winner of the
2017 BGA Fleming Award
for
excellence in geotechnical design

- Rapid uptake and application in industry since 2015
  - reduced the use of materials and cost of foundations
  - helped unlock the expansion of wind farms in the North Sea
  - reduced the cost of wind-produced electricity in the UK

Outline

- Complexities of geotechnical design are increasing

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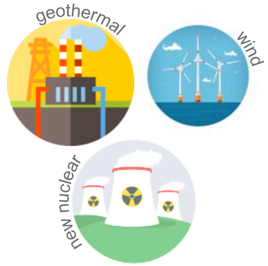
reduction in carbon emissions



energy transition

- Example applications:
  - A energy transition: offshore wind
  - B reuse of existing infrastructure
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- Software: Imperial College Finite Element Program (ICFEP), Potts & Zdravkovic (1999, 2001)

B Reuse of existing infrastructure

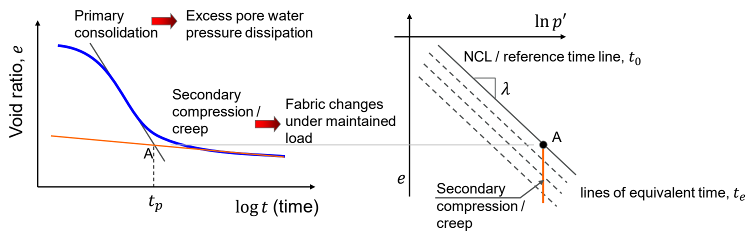
- Building foundations
  - building refurbishment or re-development
- Ageing flood embankments / levees
  - raising to adapt to climate change (sea-level rise)
- Technical challenge
  - being able to quantify the possible additional capacity of the ground, after structures being in place for several decades

Lincolnshire, UK; October 2023

Soil characterisation & constitutive modelling

- Long-term evolution of clay behaviour
  - Transient processes of consolidation and creep

concept of isotach viscosity

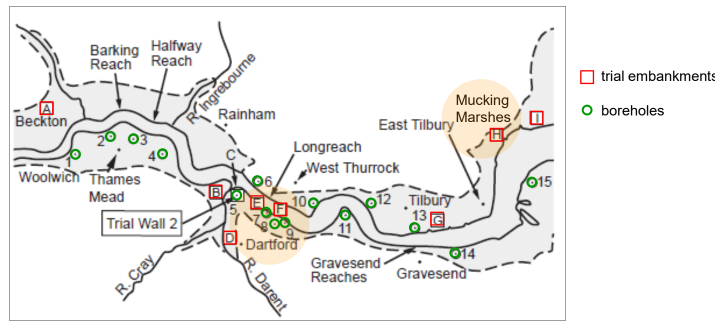


- Creep leads to
  - continued reduction of the pore space volume and continued settlements
  - increase in undrained shear strength

Isotropic compression

Adaptation to climate change

- Thames Estuary trial flood embankments – BRE test sites in 1970s and '80s

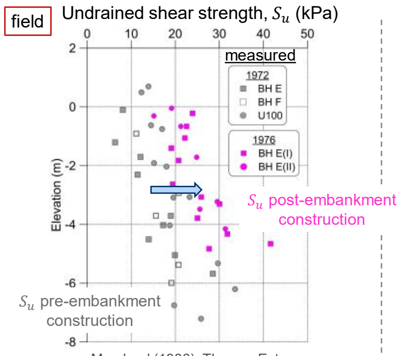


Study locations: Mucking Marshes (Sheehy, 2005; Losacco, 2007)
Dartford (Guo, 2021; Tan, 2022; Leung, 2023)

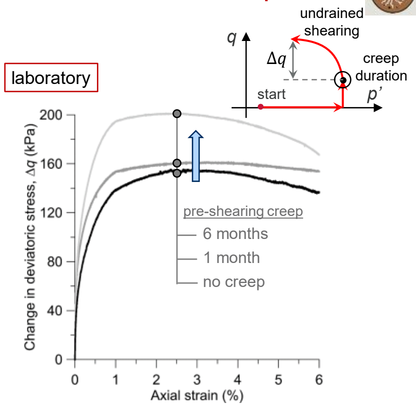
data curtesy of Dr John Powell

Transient processes: consolidation and creep

- Gain in undrained shear strength



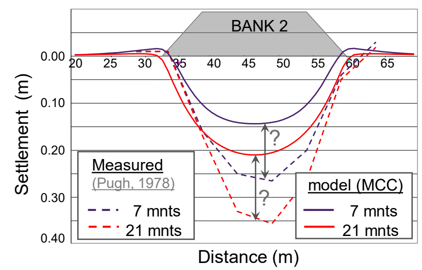
Marsland (1986), Thames Estuary



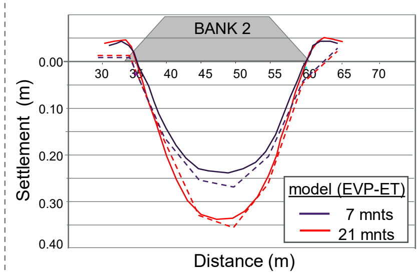
San Francisco Bay Clay, Al Haj et al. (2017)

Transient processes: consolidation and creep

- Trial embankment (Bank 2) at Mucking Flats, Thames Estuary
  - Extended modified Cam Clay model
  - Generalised elasto-visco plastic equivalent time framework (from Yin & Graham, 1999)



- long-term settlement prediction accounting for consolidation only

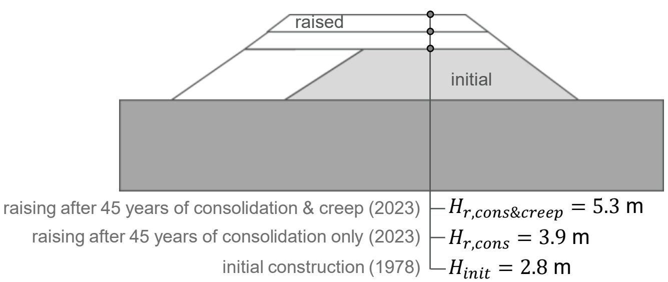


- long-term settlement prediction accounting for consolidation and creep

Zdravkovic et al. (2019)

Adaptation to climate change: embankment raising

- Trial embankment (Bank 2) at Mucking Flats, Thames Estuary
  - Generalised elasto-visco plastic equivalent time model (Bodas Freitas et al., 2015)

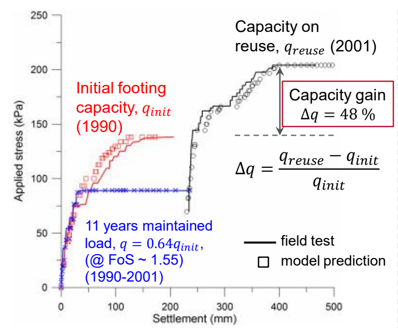


Trial embankment raising

Zdravkovic et al. (2019)

Foundation reuse

- Single footings in Bothkennar clay
  - Gain in foundation capacity due to consolidation and creep



Testing applied to footings

field loading of 2.2 × 2.2 m square footings

field test (Lehane & Jardine, 2003)

Bodas Freitas et al. (2015)

Foundation reuse

- Single footings in Bothkennar clay
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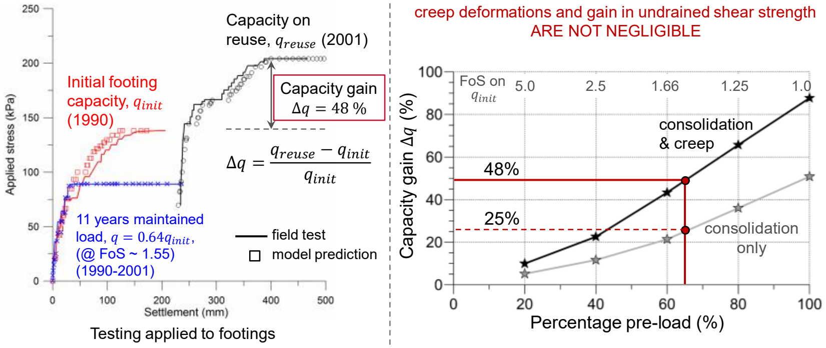

Bodas Freitas et al. (2015)

B Reuse of existing infrastructure

- Accounting for creep, in addition to consolidation, in numerical models
  - explains the measured deformations and gains in soil capacity
  - demonstrates the significance of creep strains
  - has the potential to reduce the use of materials, costs and construction time

Lincolnshire, UK; October 2023

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- Complexities of geotechnical design are increasing

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energy transition

- Example applications:
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- Software: Imperial College Finite Element Program (ICFEP), Potts & Zdravkovic (1999, 2001)

C Nature-based design and lifecycle assessment

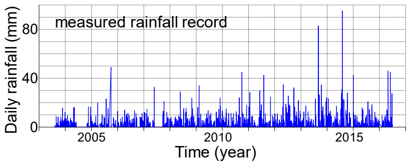
- Infrastructure embankments and slopes, earth dams
  - exposed to soil-atmosphere-vegetation interaction
  - climate-induced changes in weather patterns (rainfall & drought)
  - vegetation and its maintenance

- Technical challenge
  - unsaturated soil states
  - initial and current stress states
  - weather changes are seasonal
  - rainfall projection in long-term

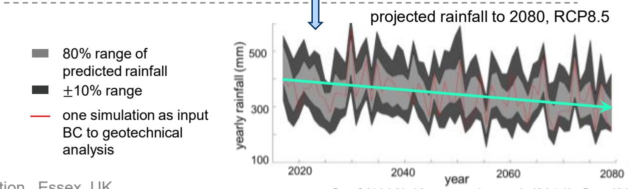
Buxton to Manchester line, UK, June 2016

Climatic and hydrological analysis

❑ Future rainfall projections with climate change effects



- statistical / stochastic modelling (BLRP+GLM)
- projection of climate variables by 2100 from UKCP18
- Representative [CO2] Concentration Pathways (RCP) scenario by 2100



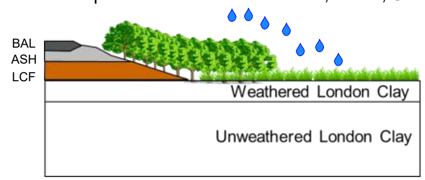
Example: Rayleigh station, Essex, UK

Onof (1992), Kaczmarska et al. (2014), Guo (2021)

Lifecycle assessment of infrastructure

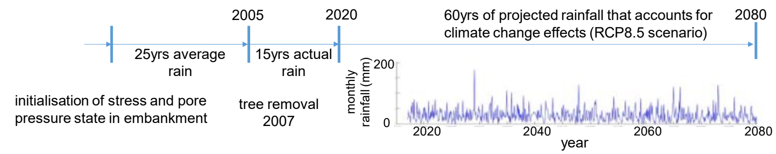
❑ Geotechnical lifecycle numerical model

example Network rail embankment, Essex, UK



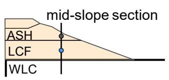
advanced numerical analysis

- unsaturated HM modelling framework
- vegetation: root water uptake & evapotranspiraton
- precipitation: infiltration / runoff

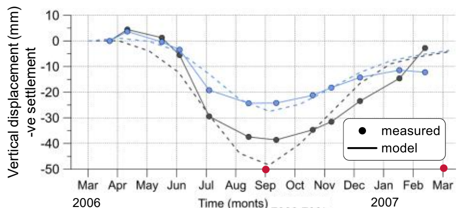


Lifecycle assessment of infrastructure

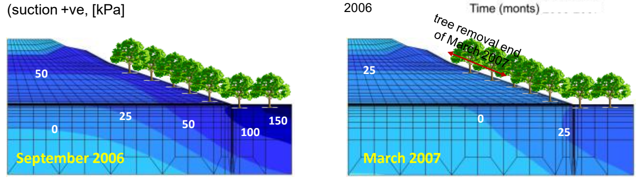
❑ Rail embankment in Essex, UK: model validation 2006 - 2007



Field measurements
(Smethurst et al., 2015)



pwp contours:
(suction +ve, [kPa])

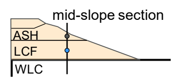


large suctions – shrinkage & settlement

reduced suctions – swelling & heave

Lifecycle assessment of infrastructure

❑ Rail embankment in Essex, UK: model validation 2007 - 2011



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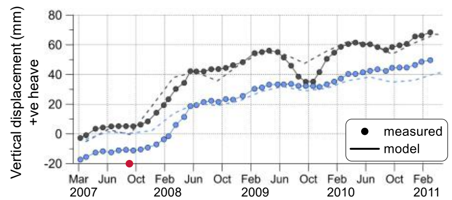

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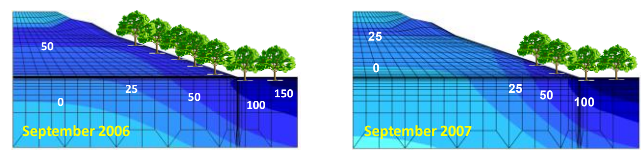
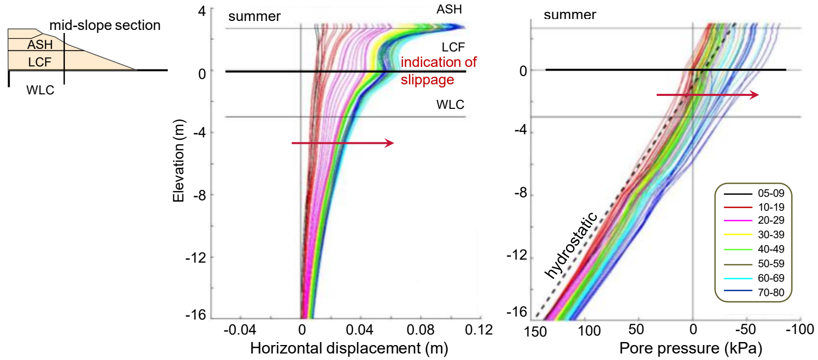


large suctions – shrinkage & settlement

reduced suctions remain in embankment due to tree removal

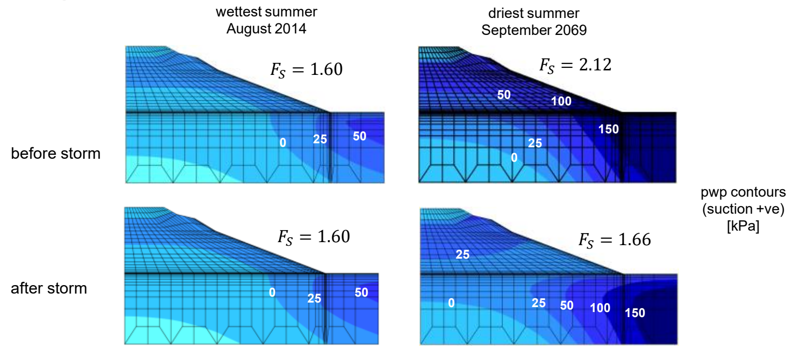
Lifecycle assessment of infrastructure

- Rail embankment in Essex, UK: assessment to 2080
  - **serviceability**: projected lateral displacement and pore pressure evolution to 2080



Lifecycle assessment of infrastructure

- Rail embankment in Essex, UK: assessment to 2080
  - **stability**: resilience to storm & antecedent conditions - maximum recorded rainfall 95 mm/day



Guo (2021)

C Nature-based design and lifecycle assessment

- combining hydrological and geotechnical analyses
  - takes account of climate change effects on rainfall and evapotranspiration
  - has the potential to expose maintenance / stability issues
  - can lead to a more sustainable use of vegetation growth and maintenance
- to validate and update long-term predictions requires monitoring data
  - rainfall and evapotranspiration
  - movements and pore pressures

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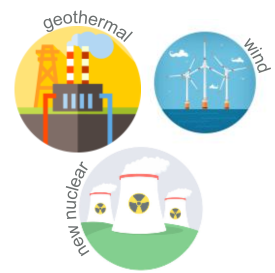

energy transition

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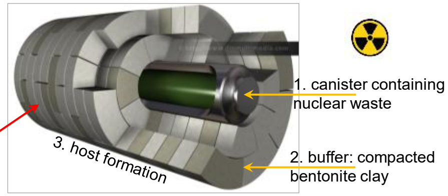
D Radioactive waste disposal

- Disposal of high-level radioactive waste (HLW)
  - proposed solution: deep burial in a Geological Disposal Facility

GDF – Geological Disposal Facility

Disposal tunnels with a multi-barrier system

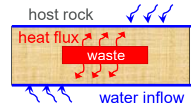


- repository depth 200 to 1,000 m
- footprint 15 to 20 km^2
- thermo-hydro-mechanical-chemical coupling in the buffer and in the host environment

exceptionally long design life due to radioactive decay

Technical challenges

- Long-term disposal of high-level waste (HLW)
  - objectives for buffer design
    - hydration to promote swelling and sealing of construction gaps
    - mobilisation of design swelling pressures
  - existing international experience based on
    - laboratory scale element tests
    - laboratory scale model tests
    - full scale prototype experiments in the field
    - numerical modelling
  - ICL experience – development of numerical tools
    - governing FE THM formulation (Cui, 2015)
    - constitutive modelling of bentonite (Ghiadistri, 2019)
    - temperatures in excess of 100^oC (Alexandropoulou, 2025)
    - groundwater chemistry (Lai, 2027)

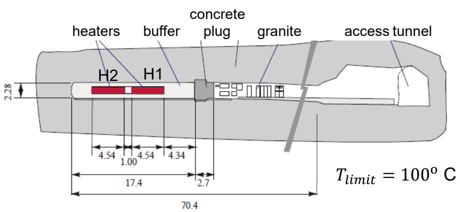


Nuclear Waste Services | SKB EBS Task Force | BEACON Bentonite Mechanical Evolution

Current state of the art

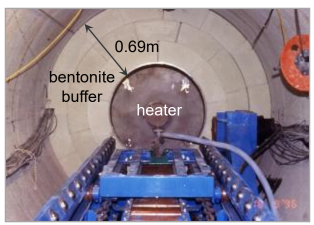
- Disposal of high-level radioactive waste (HLW)
  - current learning: from a handful of field-scale experiments of limited duration

longitudinal section



$T_{limit} = 100^o$ C

transverse section



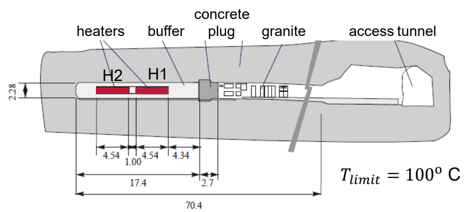
installation

FEBEX experiment (ENRESA, 2000) – 18 years

Current state of the art

- Disposal of high-level radioactive waste (HLW)
  - current learning: from a handful of field-scale experiments of limited duration

longitudinal section



$T_{limit} = 100^o$ C

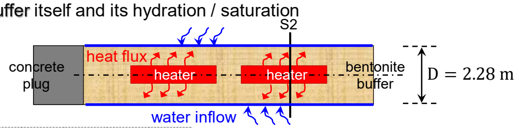
transverse section

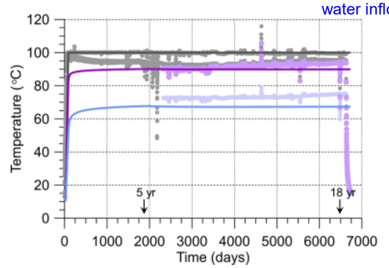
dismantling and coring of specimens

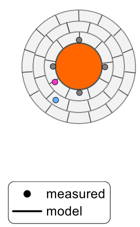
FEBEX experiment (ENRESA, 2000) – 18 years

Current state of the art

- Disposal of high-level radioactive waste (HLW)
  - one challenge: **buffer** itself and its hydration / saturation





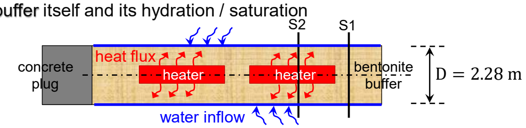


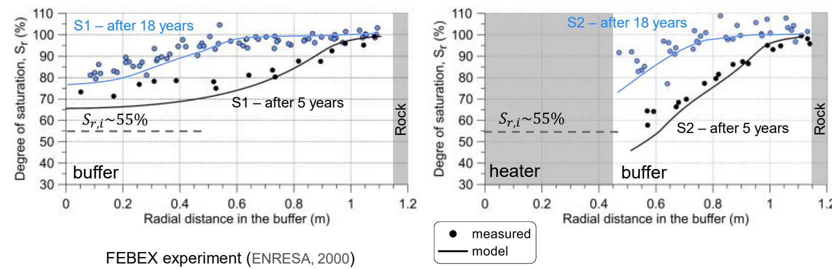
- temperature field develops very early
- stable temperature gradient across buffer thickness

FEBEX experiment (ENRESA, 2000)

Current state of the art

- Disposal of high-level radioactive waste (HLW)
  - one challenge: **buffer** itself and its hydration / saturation

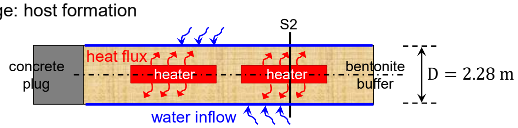


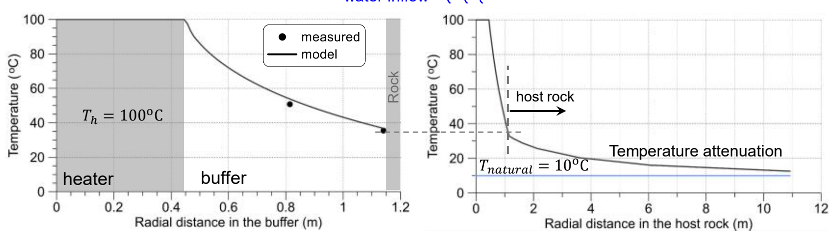


FEBEX experiment (ENRESA, 2000)

Current state of the art

- Disposal of high-level radioactive waste (HLW)
  - separate challenge: host formation

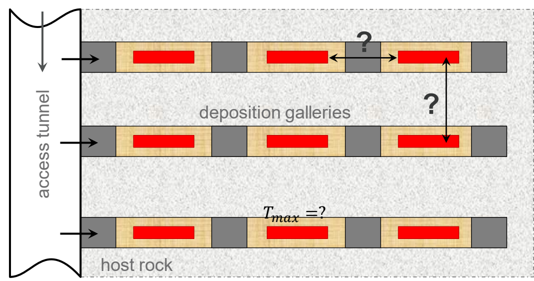




raised temperature at the rock interface

Current state of the art

- Disposal of high-level radioactive waste (HLW)
  - GDF design has many variables



- tunnelling at large depths
- canister size and temperature limit on the buffer
- number and spacing of canisters in a gallery
- spacing between galleries
- ......

D Radioactive waste disposal

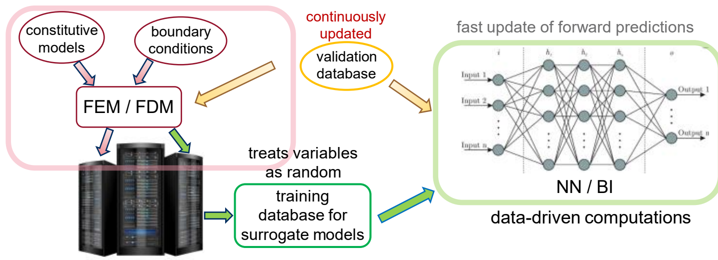
- Disposal of high-level waste (HLW)
  - possibly the most complex geotechnical example
    - multiple levels of coupling
    - exceptionally long design life
    - demanding constitutive behaviour
  - geotechnical analysis
    - can accommodate these complex phenomena
    - is validated over relatively short periods of time
    - currently being used as a tool to produce a safe design

Outlook on the future of computational analysis

- Highly **coupled phenomena** are becoming prevalent in geotechnical engineering design
- **Computer-aided design** is pivotal for many of the current pressing problems and **sustainability targets**
- It relies on realistic ground models, intelligent interpretation of soil data and robust numerical models and algorithms

THE NUMBER OF SOIL PARAMETERS,
their uncertainty and
their inter-connectivity
ARE INCREASING SUBSTANTIALLY

complex FE analyses are computationally demanding



Outlook on the future of computational analysis

- Highly **coupled phenomena** are becoming prevalent in geotechnical engineering design
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THE NUMBER OF SOIL PARAMETERS,
their uncertainty and
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- **Data-driven** approach has the potential to assist in a more **automated manner** with complex interactions of the increasing number of variables, but …
  - input data (soil behaviour, monitoring) need to be curated
  - numerical analyses need to be robust and accurate
- With long design lives of infrastructure, continuous **geotechnical monitoring** becomes increasingly necessary

Thank you

for the invitation

and

for your attention today

KIVI Engineering Society ie-net NAF