香港岩土及岩土環境工程專業協會
ASSOCIATION OF GEOTECHNICAL &
GEOENVIRONMENTAL SPECIALISTS (HONG KONG)

AGS (HK) Technical Seminar

Machine Learning Back Analysis & Observational Method

Data-driven design solutions in Ground Engineering

Dr Ying Chen | 27 June 2024
(ISSGME TC206 Vice Chair / FICE)

Contents

Observational Method (OM)

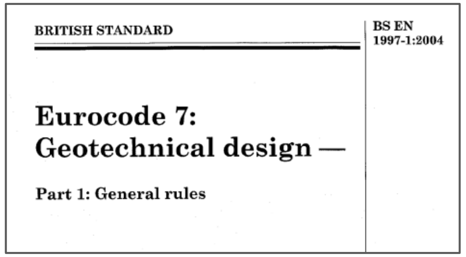
The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review which enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety.

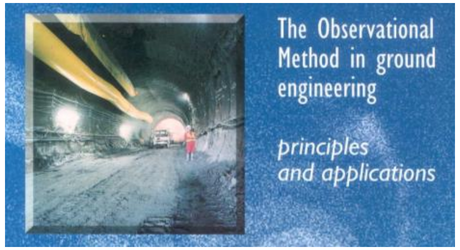
Ciria R185 (Nicholson et al., 1999)

The Observational Method

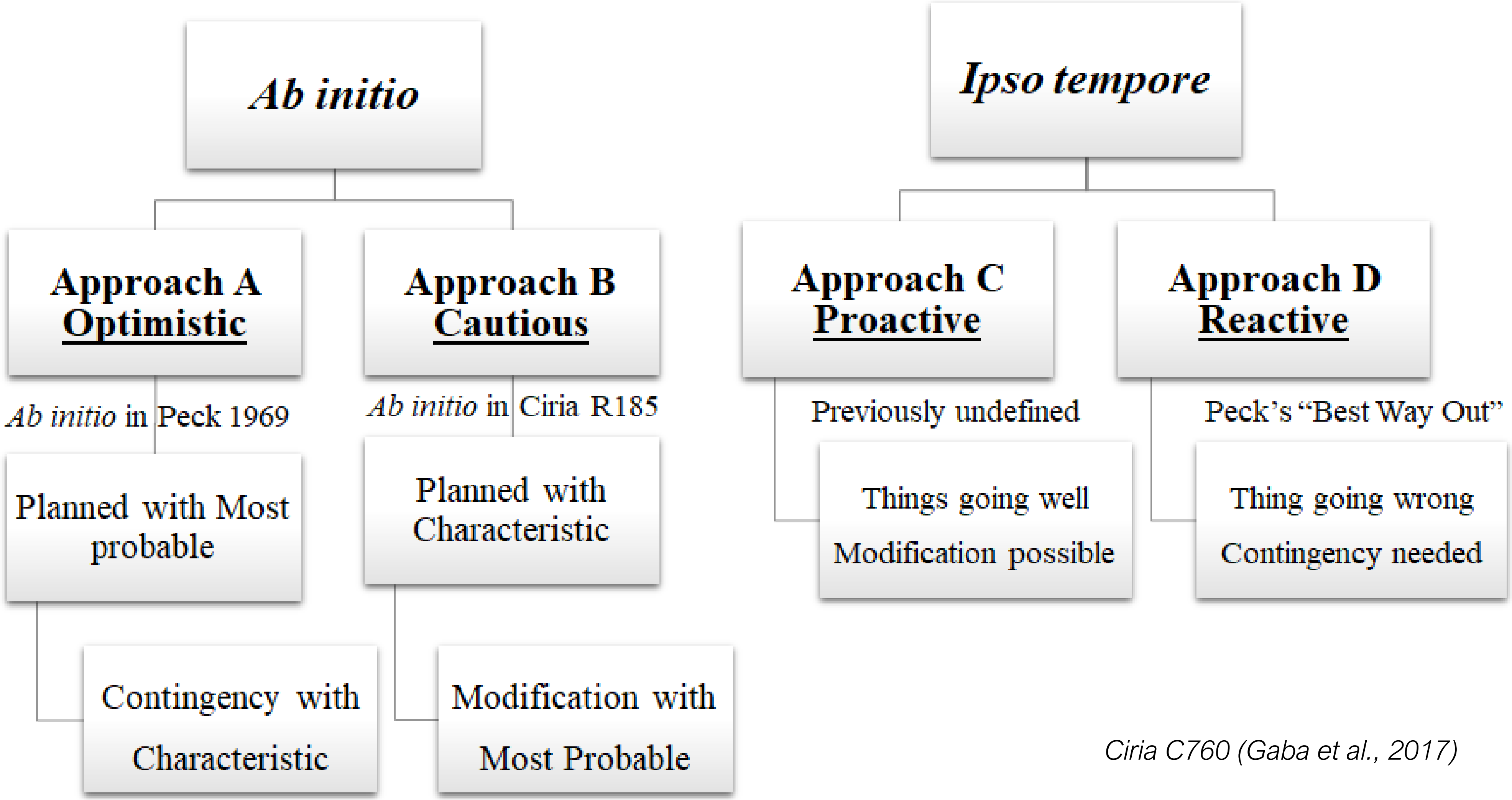
Background

- 1940s – 1960s: Terzaghi "*learn – as – you – go*"
- 1969 : Peck's Rankine Lecture - Observational Method introduced with two approaches of *Ab-initio* & Best-way-out
- 1970s – 1990s: Progressive Modification
- 1999: Ciria R185 – OM definition with updated Ab-initio (cautious)
- 2000s: EC7 / Ciria C760



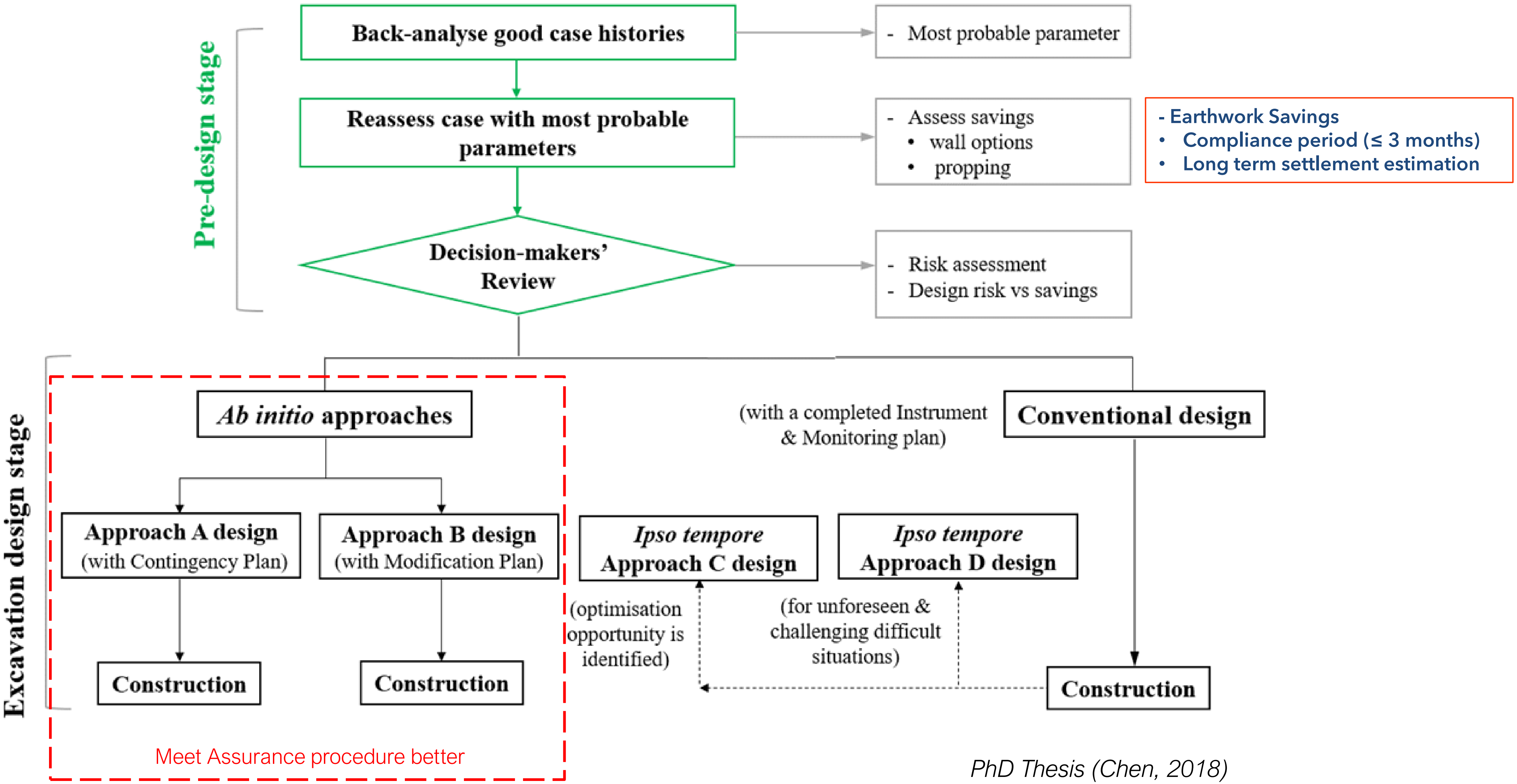


New OM Framework (Ciria C760)



Ciria C760 (Gaba et al., 2017)

OM approach selection flowchart



PhD Thesis (Chen, 2018)

OM new development

ISSMGE TC206 (Since 2020)

- Practice Barriers
  - Contractual issue Working Group – Guidance on value engineering clauses, contract format for OM;
  - Codes & Standards Working Group – Guidance on the OM terms written in design codes and standards (e.g., new EC7 edition by 2023 July);
  - Tunnelling OM Working Group – Compare and feedback the similarity & difference in practising OM in tunnelling Vs ground engineering;
- Technical Barriers
  - Instrumentation & Monitoring Working Group – data (Collaboration with TC220);
  - Real Time back analysis Working Group – Optimization Machine Learning Algorithms & linked parameters for efficient back analysis (Collaboration with TC104 & TC309);
- EC7 2nd Generation updating OM terms and clauses / CIRIA Guide on OM to be updated.

The Observational Method

What is it ? (for new development)

- An integrated + interactive design + construction control method, linking design to observed performance (I&M) during construction.
- The intent is to use observed structural + ground performance to enable **pre-planned** OM design (**optimistic | modified)** during construction.
- Well established technical basis – Ciria R185, Ciria C760, EC7. Example in UK: Crossrail Tottenham Court Road Station, Crossrail Moorgate Shaft, Limehouse Link.

The Observational Method

Essential Requirements:

- Reliably obtain critical observations in a timely way + ability to implement timely pre-planned contingencies.
- Avoidance of progressive and/or sudden collapse.
- Stakeholder support – close teamwork + trust

  - Contractor/Designer/Client/Checkers

  - MUST work as a single team (no "them/they"! BUT "we/us" are key)

Real-Time Back Analysis - RTBA

- Linkage of Constitutive Model Parameters
- Collection case histories (testing back analysis)

2020.11

- Working Group Set-up
- 14 Active members
- Head: Fadi Haddad (Bauer) / Dr Franze Tschuchnigg (Graz University, Austria)

Monthly Talk & Discussion / Joint Symposium & Conference

(Since 2022.01)

2021.09 Joint Workshop TC206 / TC304 / TC309

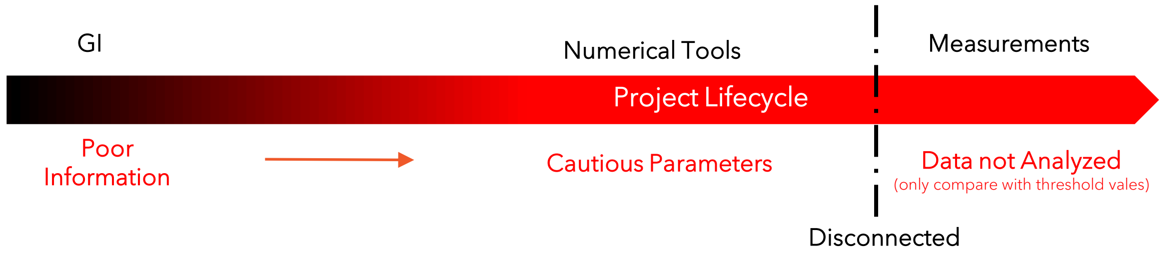
2024.02

- ISSMGE – Special Session 10 “Back analysis using ML for the OM – Lessons learnt and Future Directions”
- XVIII ECSMGE – Joint Workshops with TC103 & TC309 & ERTC7

https://www.ecsmge-2024.com/

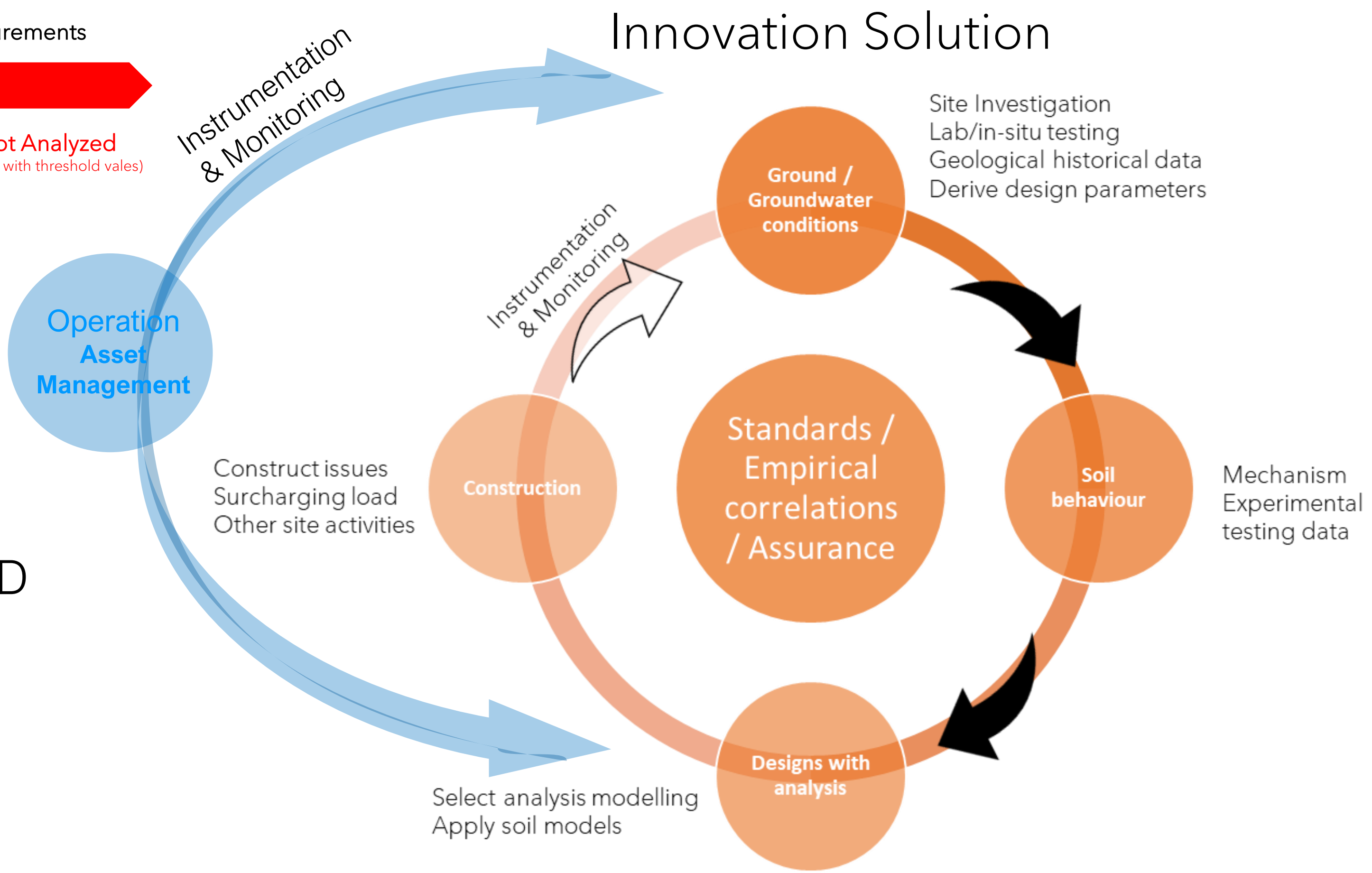
Why Back Analysis ?

" Uncertainty on the ground has a consequence of high environmental & financial costs to the construction industry "



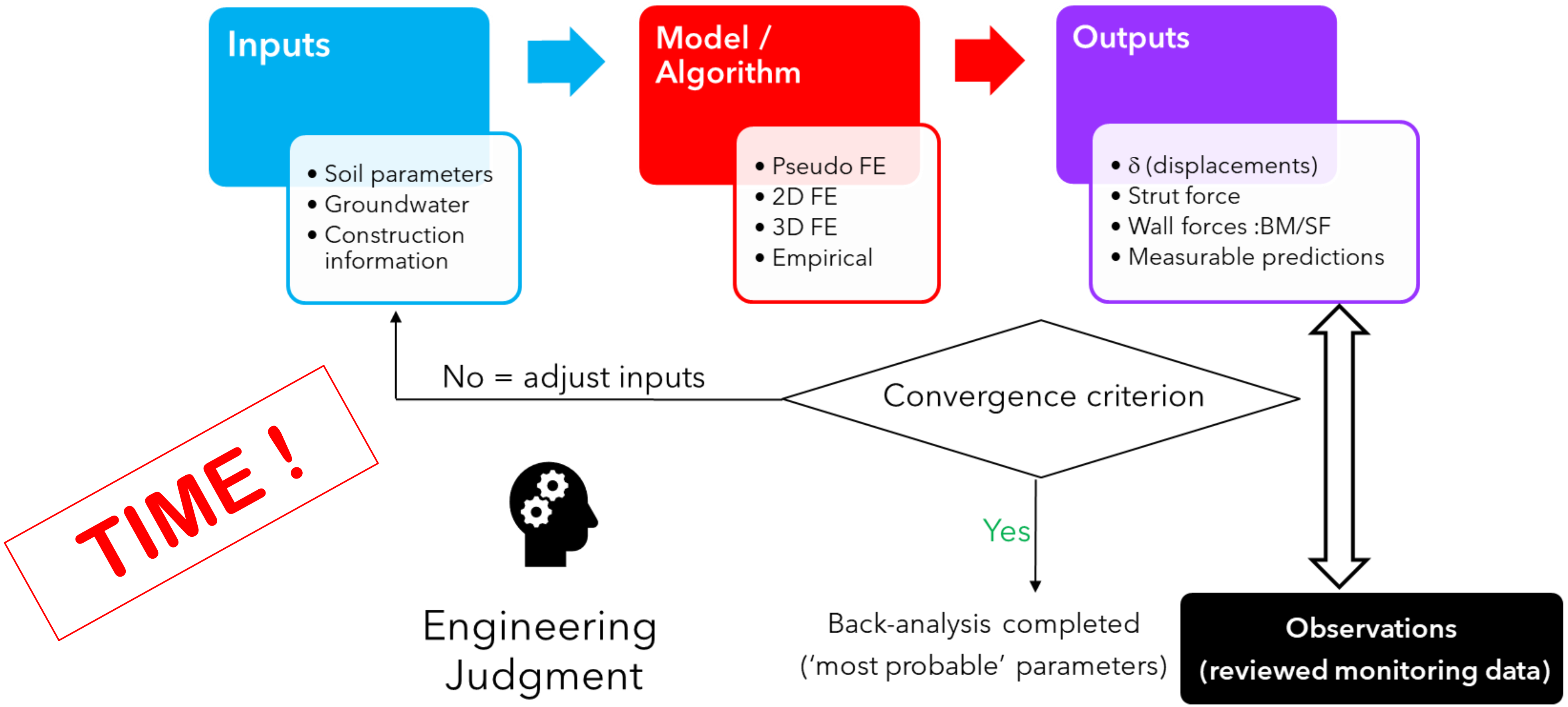
Current Approaches:

- Increase GI (pre-design)
- Use advanced soil constitutive models & 3D FEM (design)
- Measure real response (construction)



Manul Back Analysis

Conventional manual back-analysis process



Machine Learning Back Analysis

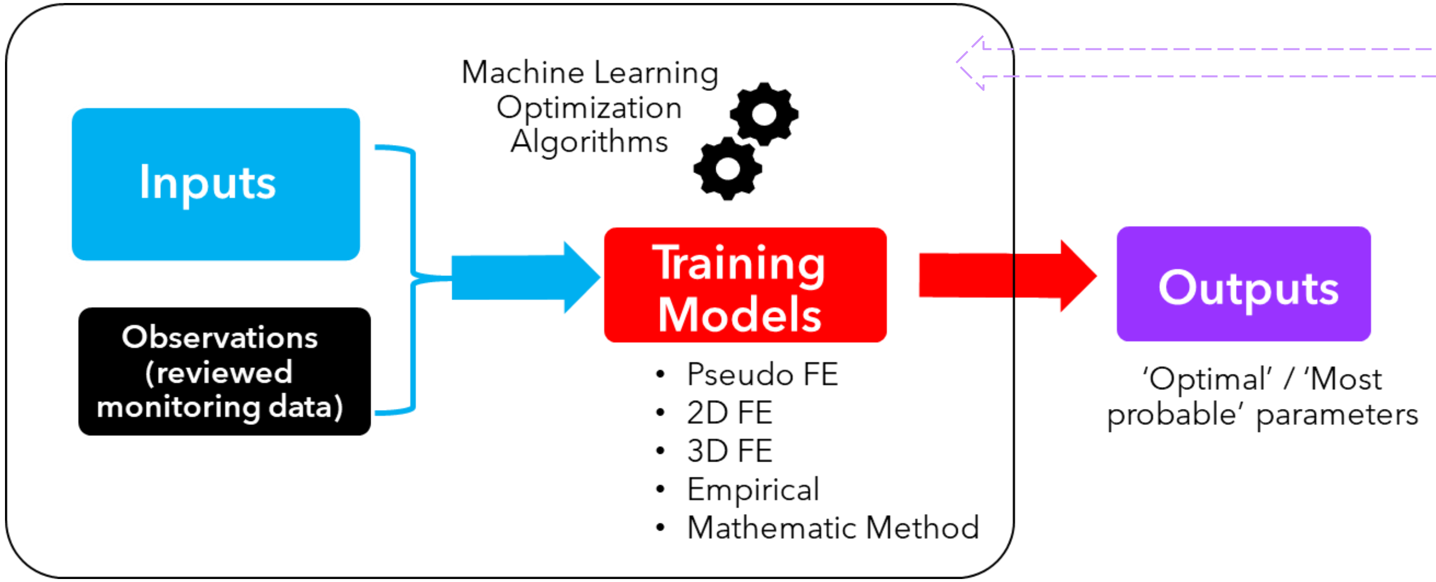
CONSTRUTCION

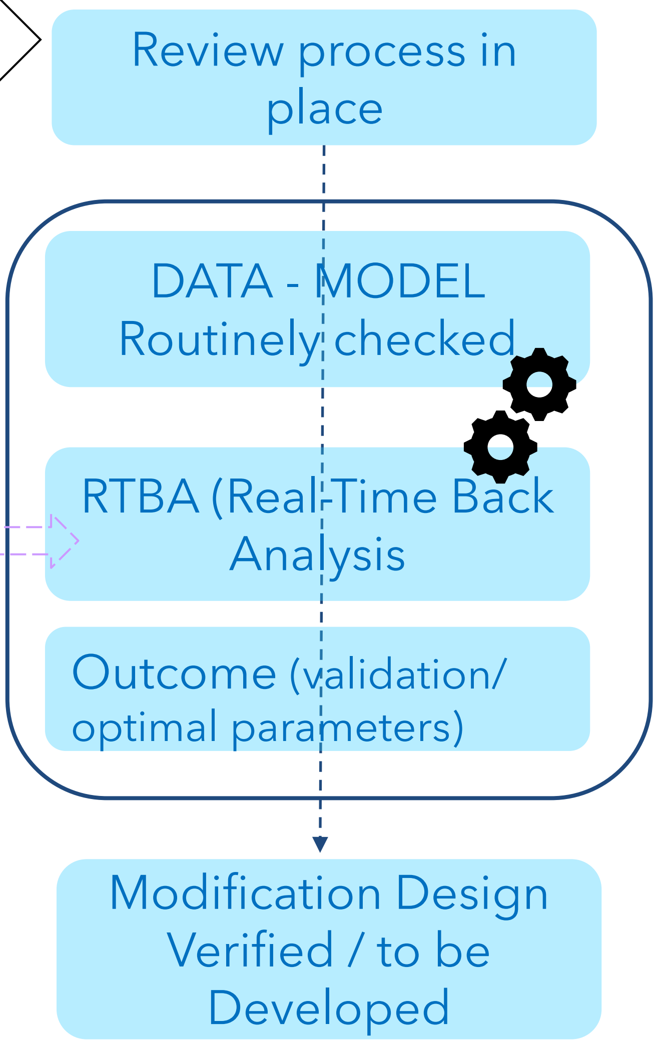
Machine Learning back-analysis process

Optimization Algorithms:

- Deterministic Algorithms.
- Stochastic Algorithms.

(e.g., Probabilistic Bayesian / MCMC / Genetic Algorithm)

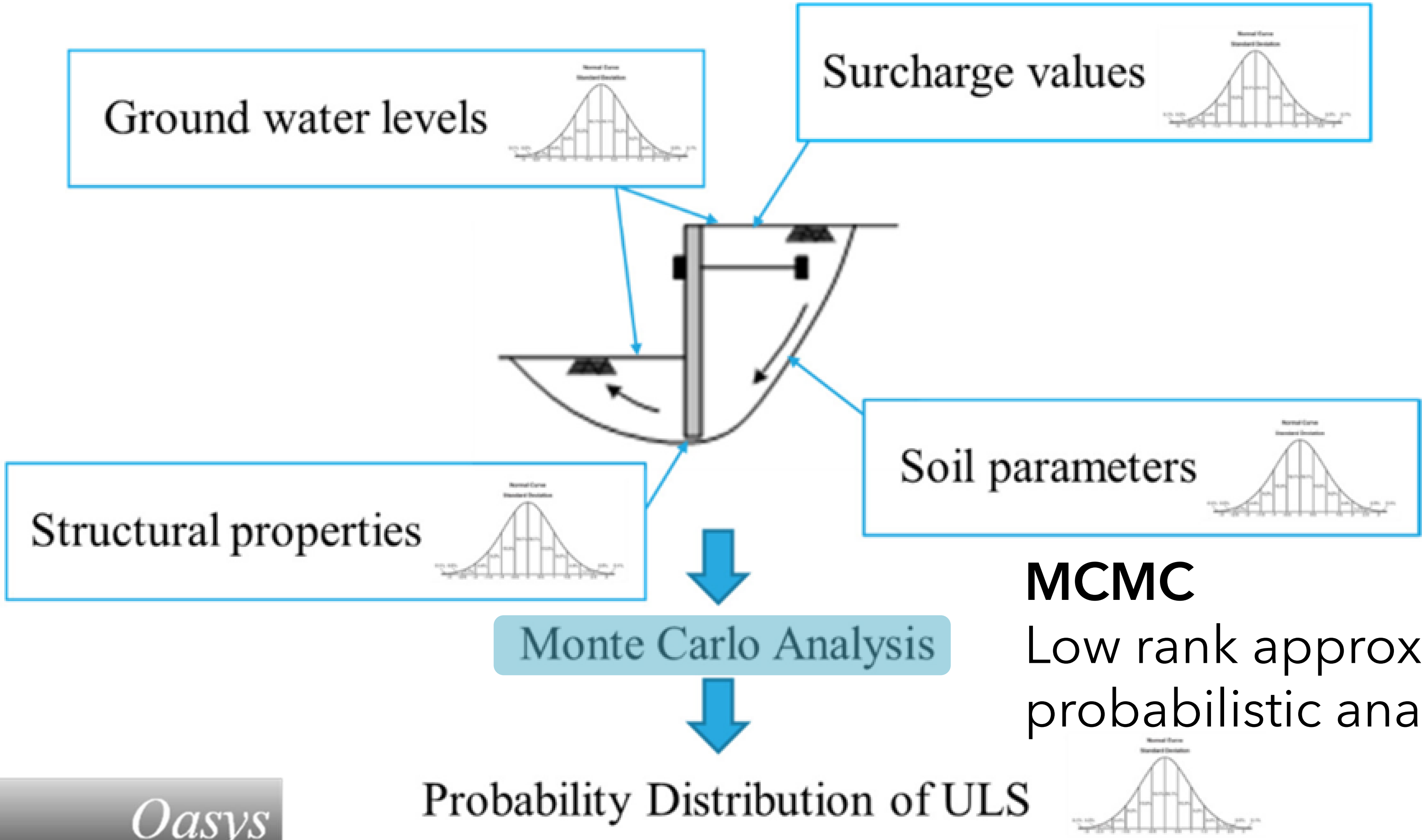




Explored ML-BA Tools

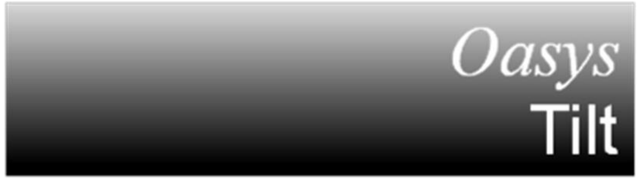
Tilt (developing)	DAARWIN (Cloud - Platform)	Meta Model (Cloud - Platform)
Bayesian Method	**Genetic Algorithm**	**Statistical Bayesian Method**
Oasys Tilt	DAARWIN SAALG GEOMECHANICS	BAUER

Bayesian Method



MCMC

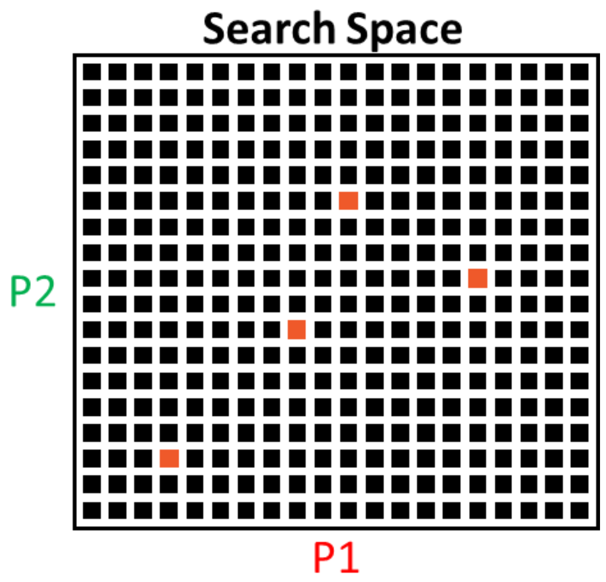
Low rank approximation probabilistic analysis



Genetic Algorithm

Based on mechanism of natural evolution (Darwin)

DAARWIN



Initial Population

- random combinations

Check fitness between 'estimations' & 'observations'

Second Generation Population

- random combinations surround the 'good' result obtained in the Initial Population

Create generations until the best fitness obtained (control)

End Generation Population

- Optimal combination(s)

Case History: Crossrail TCR-WTH

- Located at center point of London (U.K.)
- Excavation in over-consolidated London Clay
- Bottom-up Construction Sequence for 30m deep excavation
- OM Ipso-tempore Approach C modification

Imagery ©2019 Google, Map data ©2019 Google 500 m

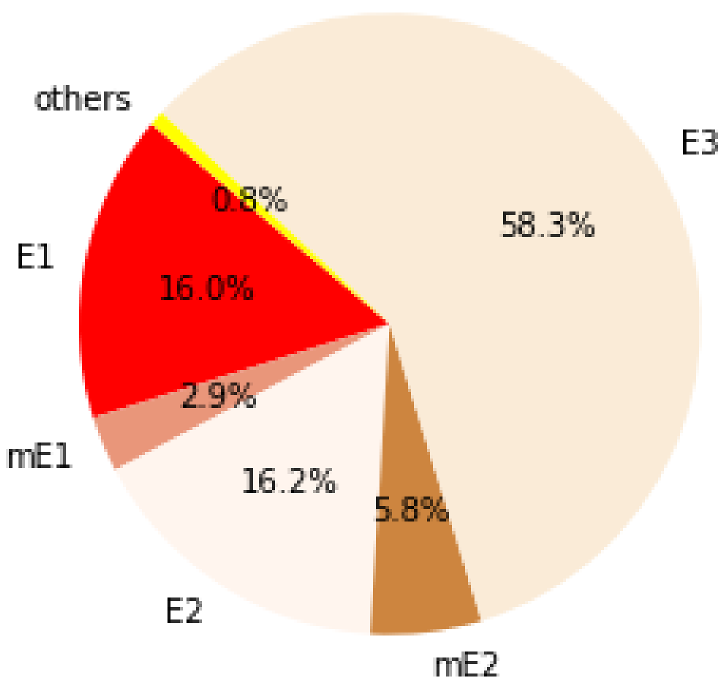
Back Analysis TCR-WTH

Back Analysis	As-built Approach C	Bayesian Method (Tilt)	Generic Algorithm (DAARWIN)
Method	Manual	ML	ML
Time Period	4 weeks (including OM design)	**< 24** hours[1]	**8 - 24** hours[2]
Approx. numbers of Analysis	< 100	~ 1,000	3,000 – 8,000
FEM	Pseudo FEM (validated in FEM)	Plaxis 2D	Plaxis 2D
RTBA	Not	To be tested	Trialled in the UK

1. *Single desk station computational time, Mohr-Coulomb soil model & Single stage back analysis in Tilt.*
2. *Depending on Soil constitutive models, Single or Multiple stage(s) back analysis, computational time varies on DAARWIN.*

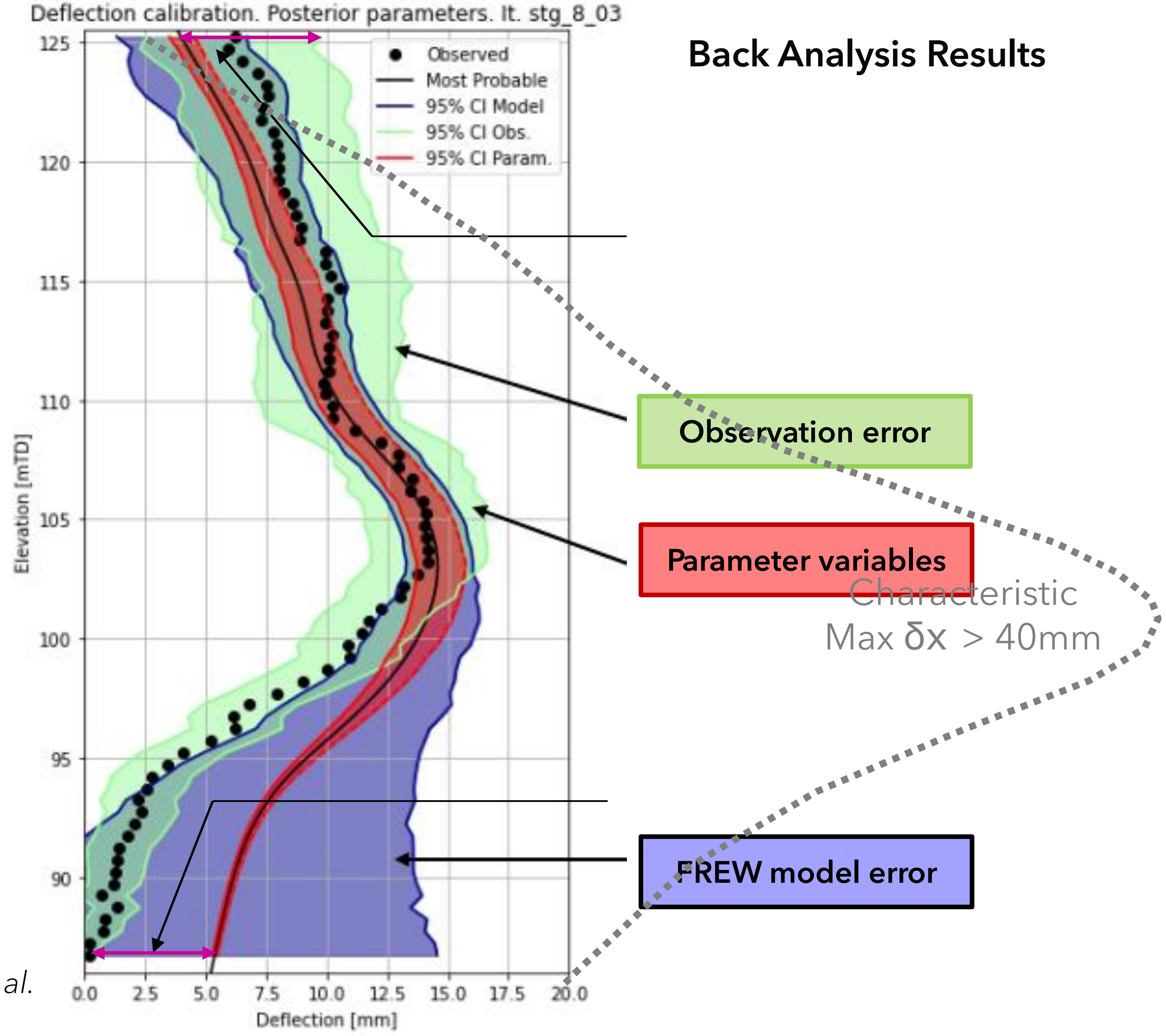
Tilt (Bayesian Method) – with Antonio Canavate-Grimal

ARUP



Sensitivity Analysis Results

Back Analysis Results

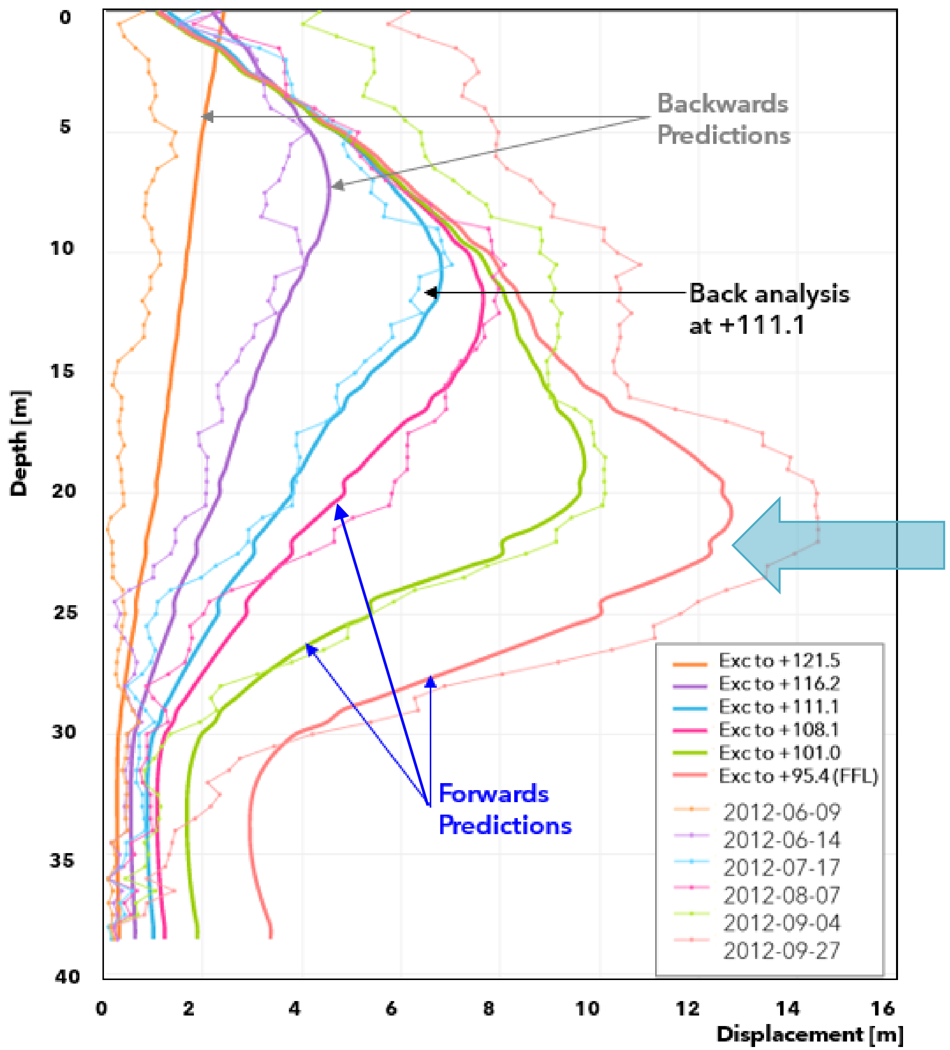


A Probabilistic analysis to assess the most probably design parameters for use in the Observational Method, Grimal et. al. 2022

DAARWIN (Genetic Algorithm) – with SAALG

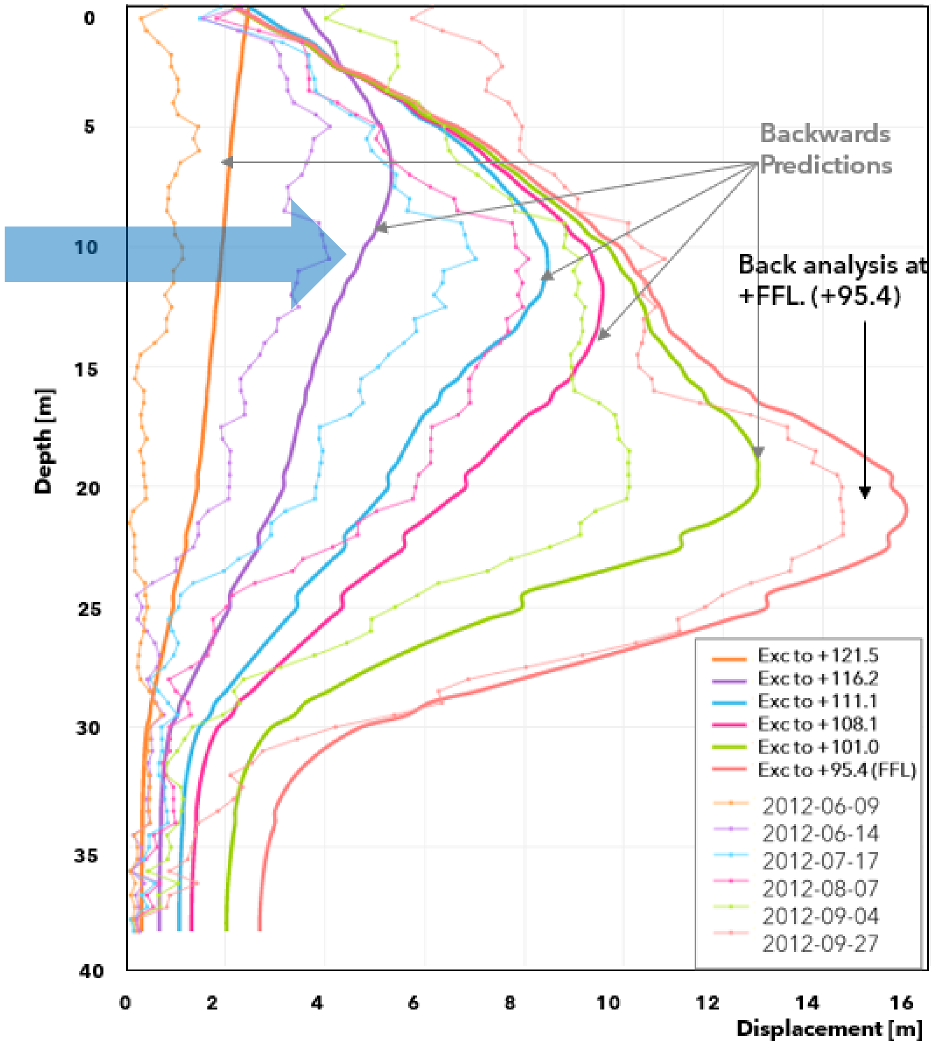
MOTT MACDONALD | SAALG GEOMECHANICS

Single stage back analysis – Mohr-Coulomb Soil model



Over-estimate
Optimal' stiffness is SOFT for early stages)

Under-estimate
Optimal' stiffness is STIFF for later stages)



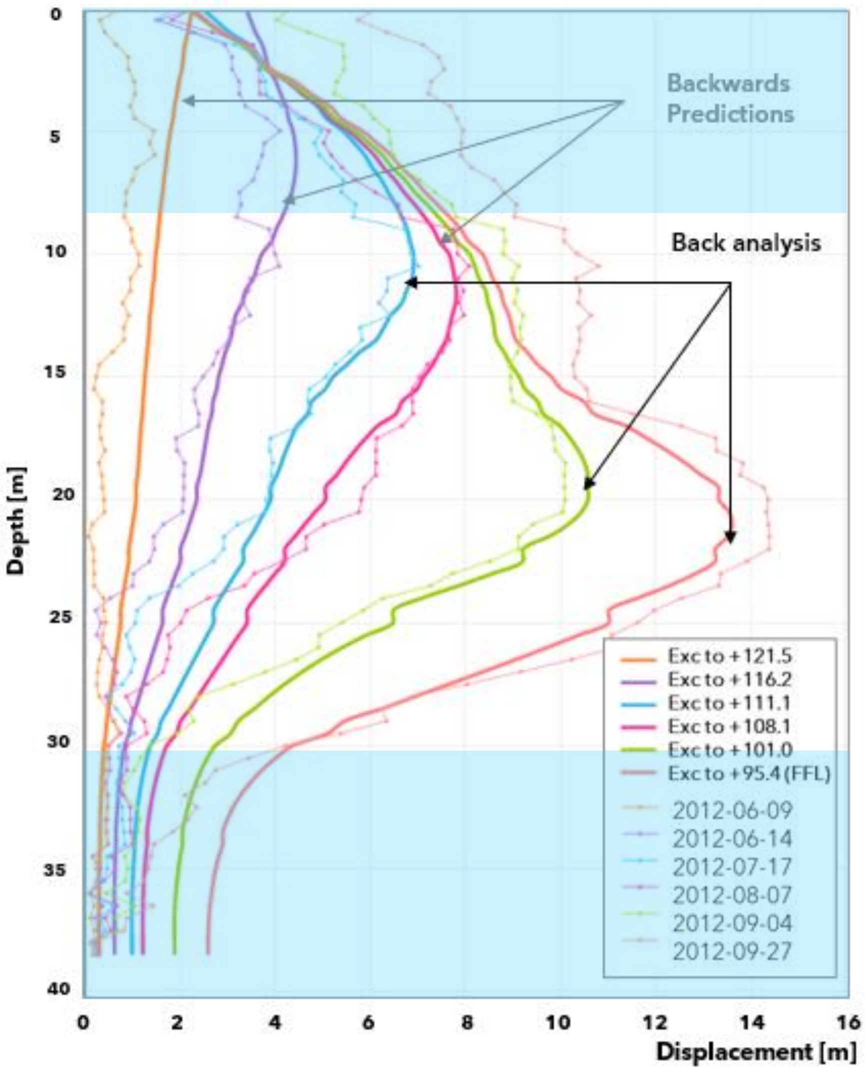
A case study of excavation back analysis using two machine learning optimisation algorithms, Proceedings of the 4th ISMLG, University College Cork, Ireland, Chen, Y., 2023

DAARWIN (Genetic Algorithm) – with SAALG

MOTT MACDONALD

SAALG GEOMECHANICS

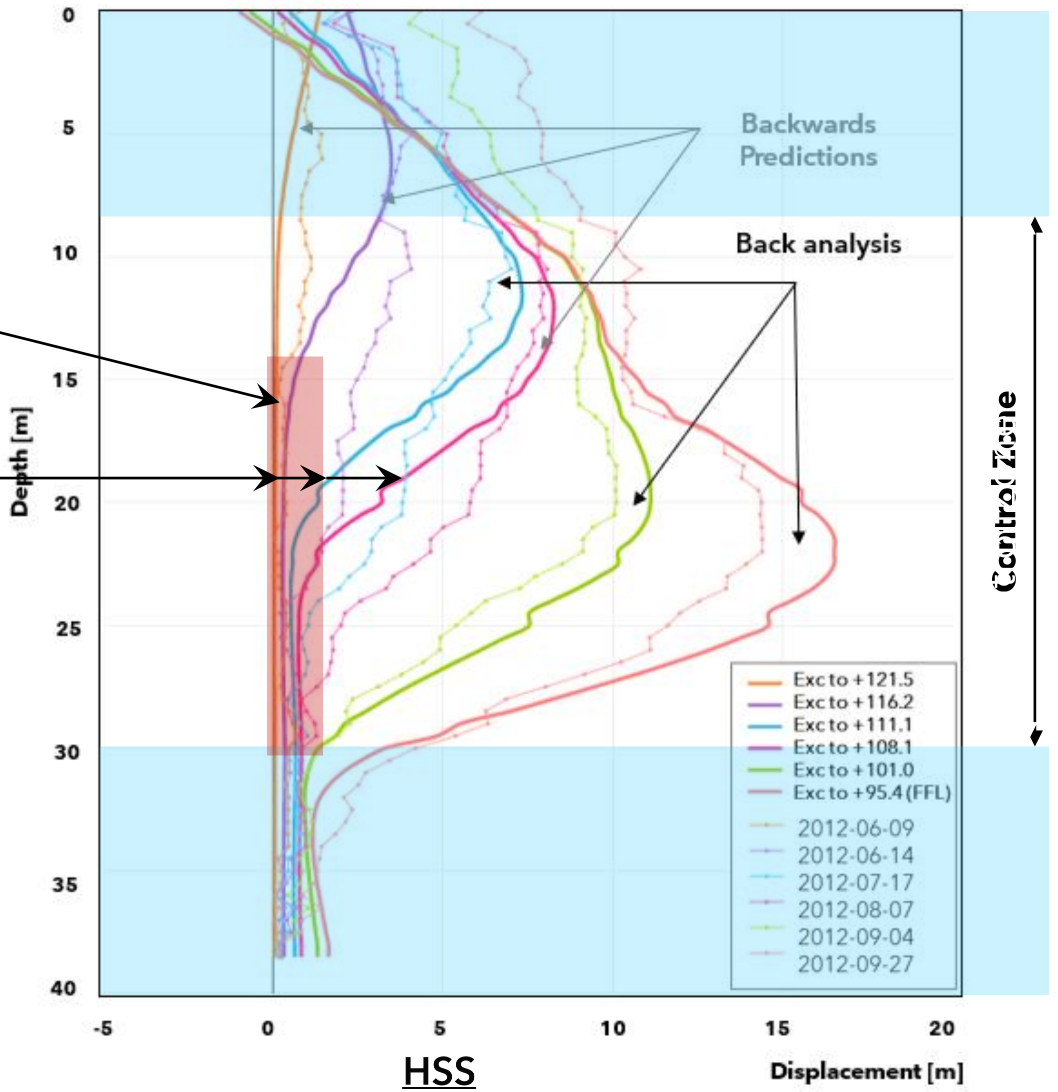
Multiple stages' back analysis – Mohr-Coulomb Vs HSS Soil models



Mohr-Coulomb

Control Zone

- HSS – Stiffer response at small strain level.
- HSS – Not very responsive when strain experienced rapid increase.
- Mohr-C – less precise prediction at very small stiffness, but fitted-well at each dig stages !



HSS

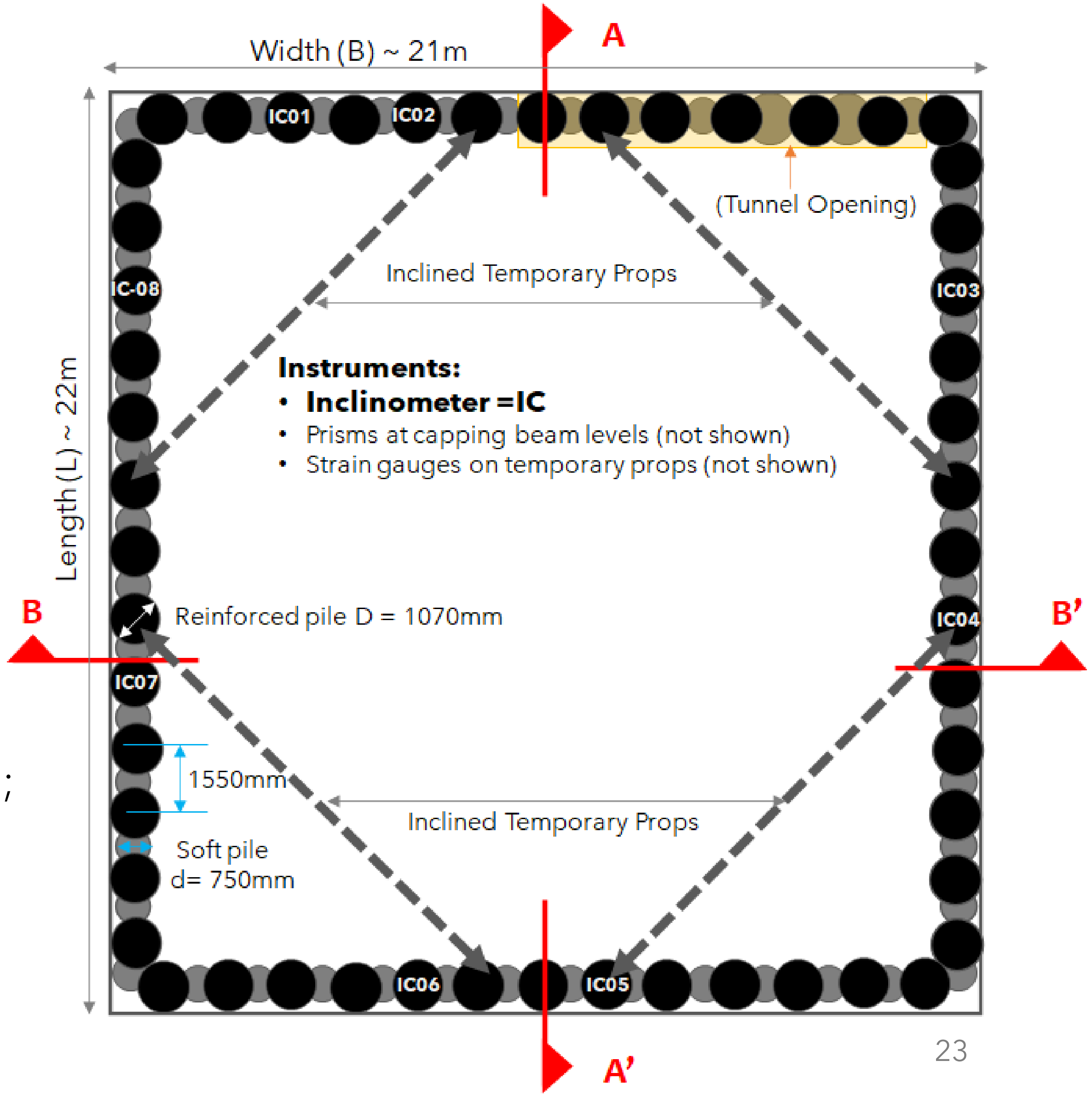
Machine Learning Back Analysis

Key Point:

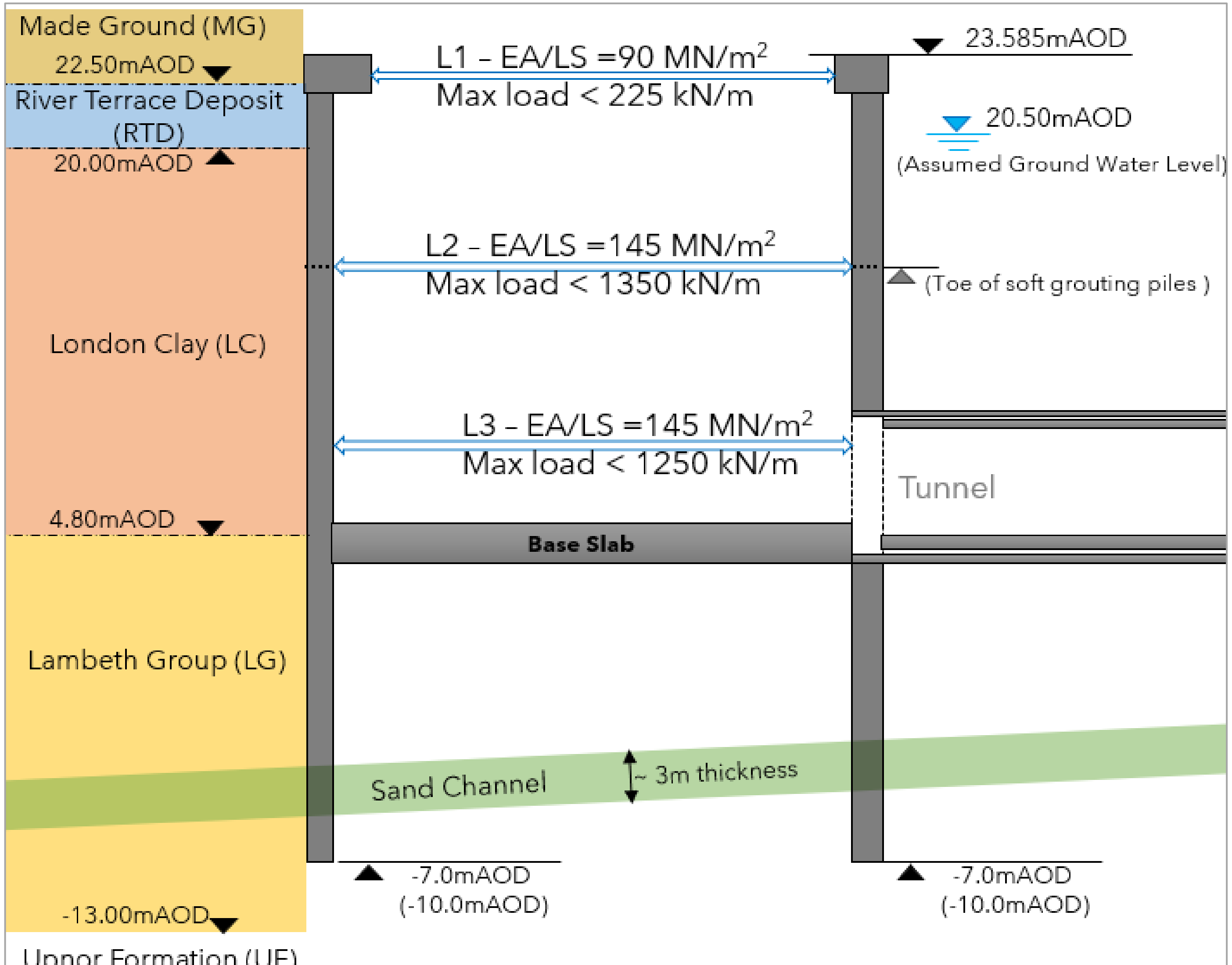
- Machine Learning Optimization Algorithms – improve back analysis efficiency & accuracy.
- Capacity to work with 2D / 3D Geotechnical modelling, and the advanced soil constitutive models.
- Timely available I&M data (e.g., I&M data Platform), and reliability of observations are critical for a good real-time back analysis.
- Interpretation with Engineering knowledges (NOT AI yet !)

Euston Station TSS Shaft – RTBA Trial

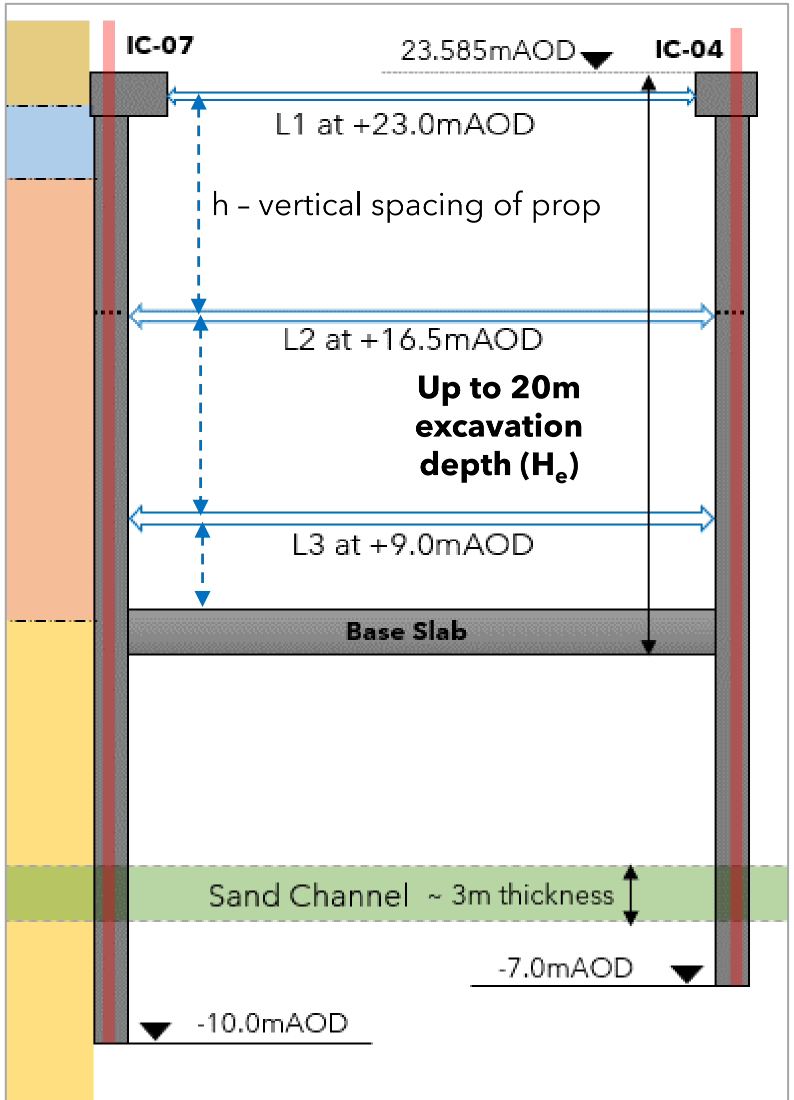
- **Square Shaft** (~ 21 m by 22m);
- **Maximum excavation depth over 20m;**
- **Contiguous Piled-Wall** (1.07m ∅ @ 1.5m spacing c/c);
- **Bottom-up construction method;**
- **'Three-levels' temporary props** (diagonal corner props);
- **I&M: In-Place-Inclinometers / Prisms / Strain-gauges for temporary props**



TSS - Sections



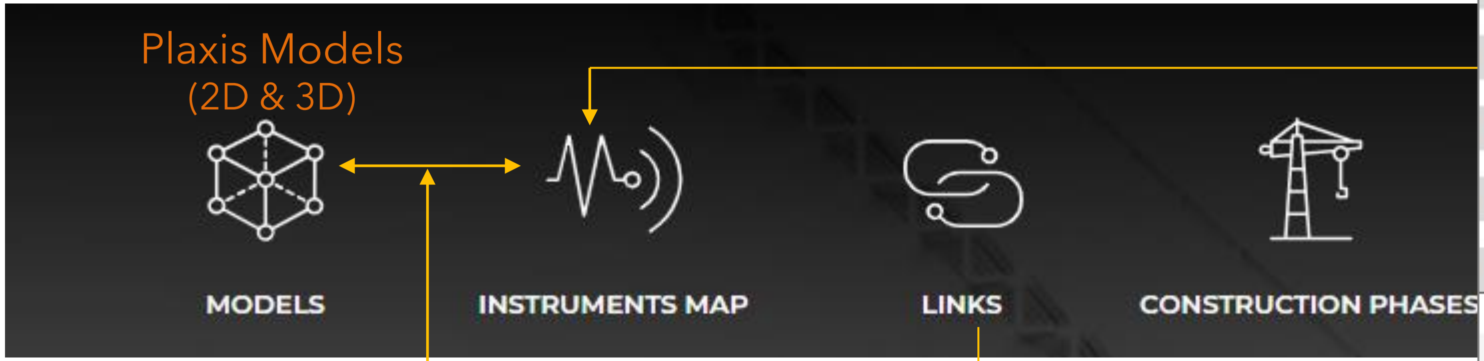
Section A-A'



Section B-B'

DAARWIN

SAALG GEOMECHANICS



create connections
control points in BA

- Define stages in m
- Filter data into stag

- **DAARWIN – Cloud-based data platform**
- **Sensitivity Study Function**
- **Machine Learning Back-analysis Function**
- **'Digital-Twin' visualizing design vs monitoring**
- **Project Data-base**

CONSTRUCTION PHASES

As-built record confirmed with construction progress

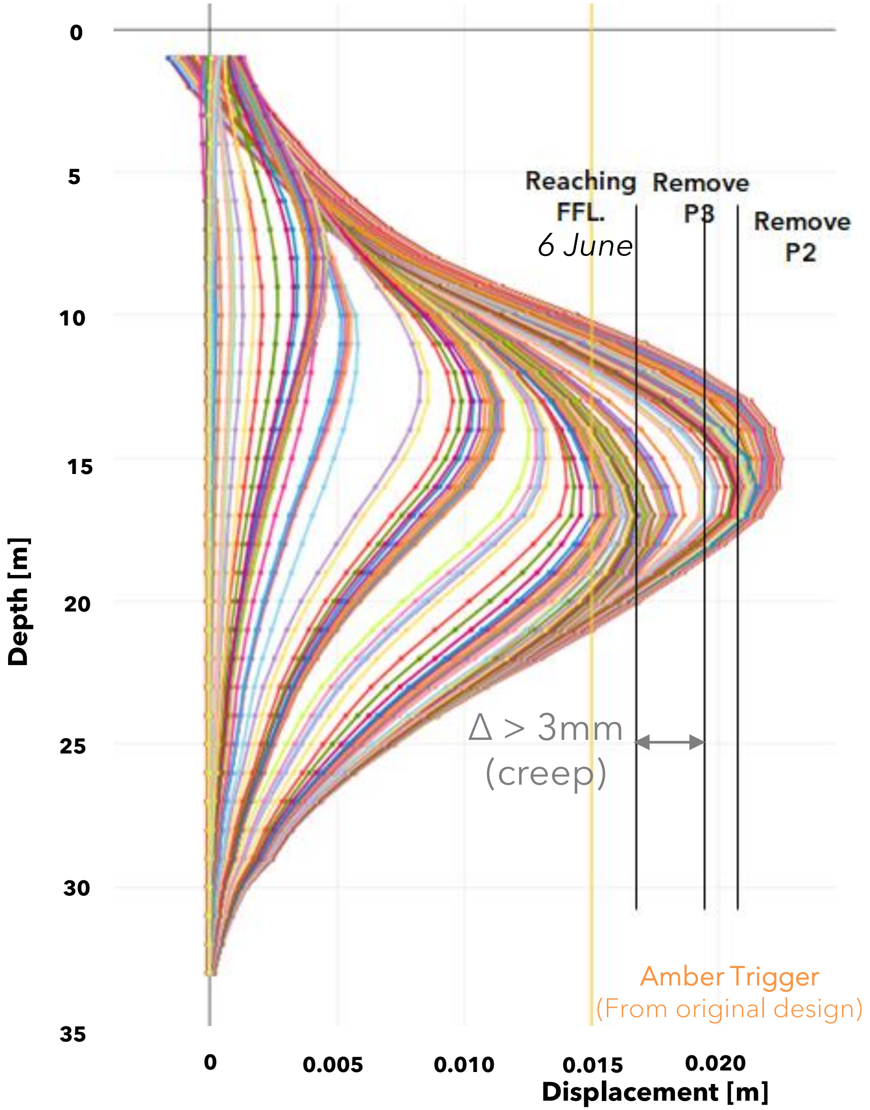
Piled Wall installation	**2021-07-16**	**2021-11-20**
Northern ventilation tunnel formation	**2021-11-20**	**2022-04-20**
Excavate for Capping beam construction	**2022-01-03**	**2022-03-29**
Excavate to below Level 2 props	**2022-03-26**	**2022-04-26**
Excavate to below Level 3 props	**2022-04-27**	**2022-05-20**
Dig to +12.2mOD	2022-04-27	2022-05-05
Dig to +9.0mOD	2022-05-06	2022-05-10
Dig to 7.7mOD	2022-05-11	2022-05-15
Install Prop 3 at +9.0mOD	2022-05-16	2022-05-20
Excavate to formation levelConstruct Base Slab - RC preparation	**2022-05-21**	**2022-07-16**
Dig to +4.9mOD	2022-05-21	2022-05-28
Dig to FFL +3.84mOD	2022-06-06	2022-06-09
CE-95 Eath Mat Installation works	2022-06-10	2022-06-20
Construct Base Slab - RC preparation	2022-06-20	2022-07-14
Construct Base Slab - Cast Concrete	2022-07-15	2022-07-16
Construction Shaft Structure (Date TBC)	**2022-07-25**	**2022-11-16**
Remove Temporary P3	2022-07-25	2022-07-29
Walls, columns & slabs to +15mOD	2022-08-01	2022-08-19
Remove Prop P2	2022-08-22	2022-08-27
Walls, columns, slabs up to +24mAOD	2022-08-30	2022-09-18
Construct Floor Slab	2022-11-14	2022-11-16

Planned

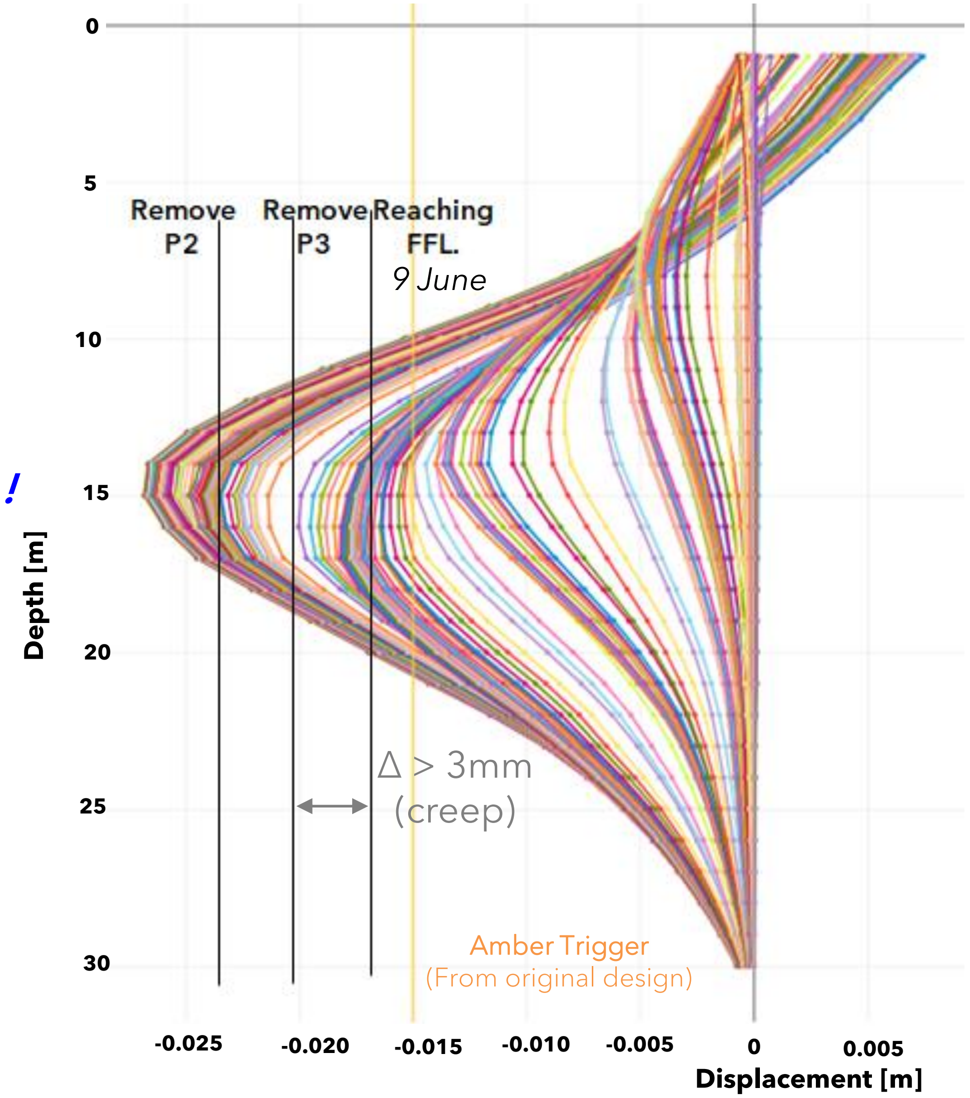
Monitoring Data Review

Data taken from March 2022 to November 2022

IC07 data



IC04 data

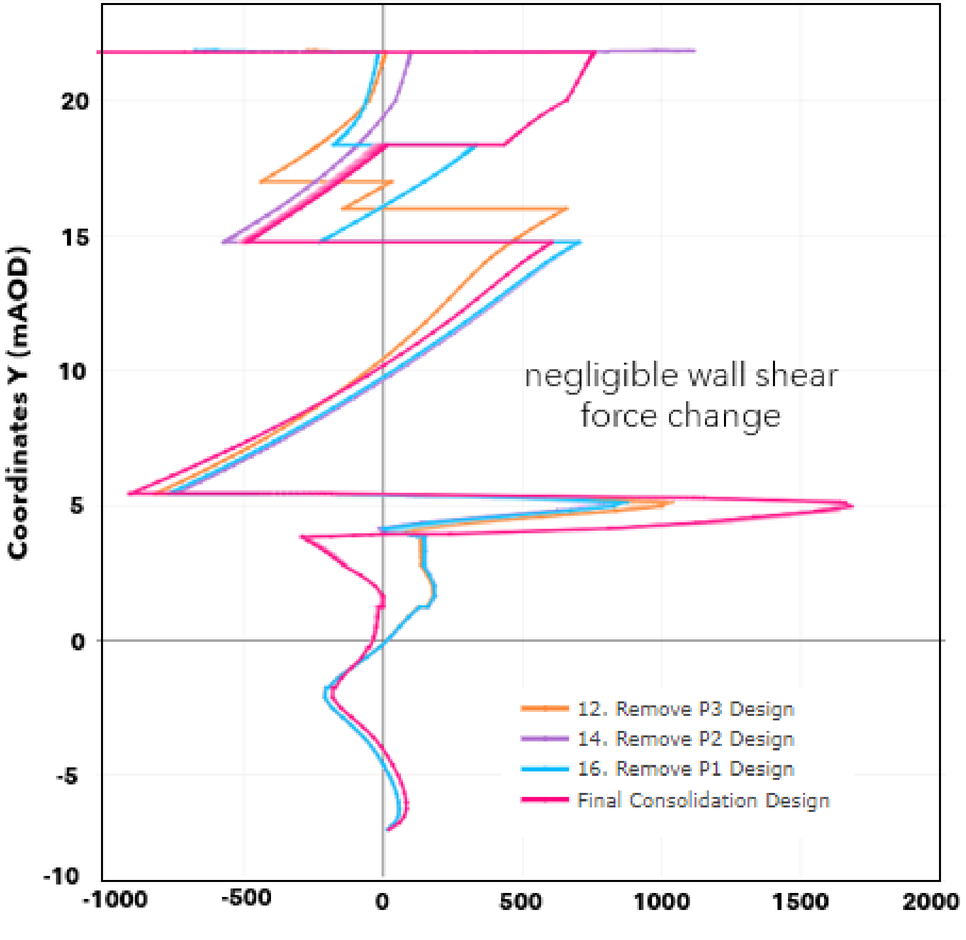


Cross-checking the construction activities !

Section B-B′

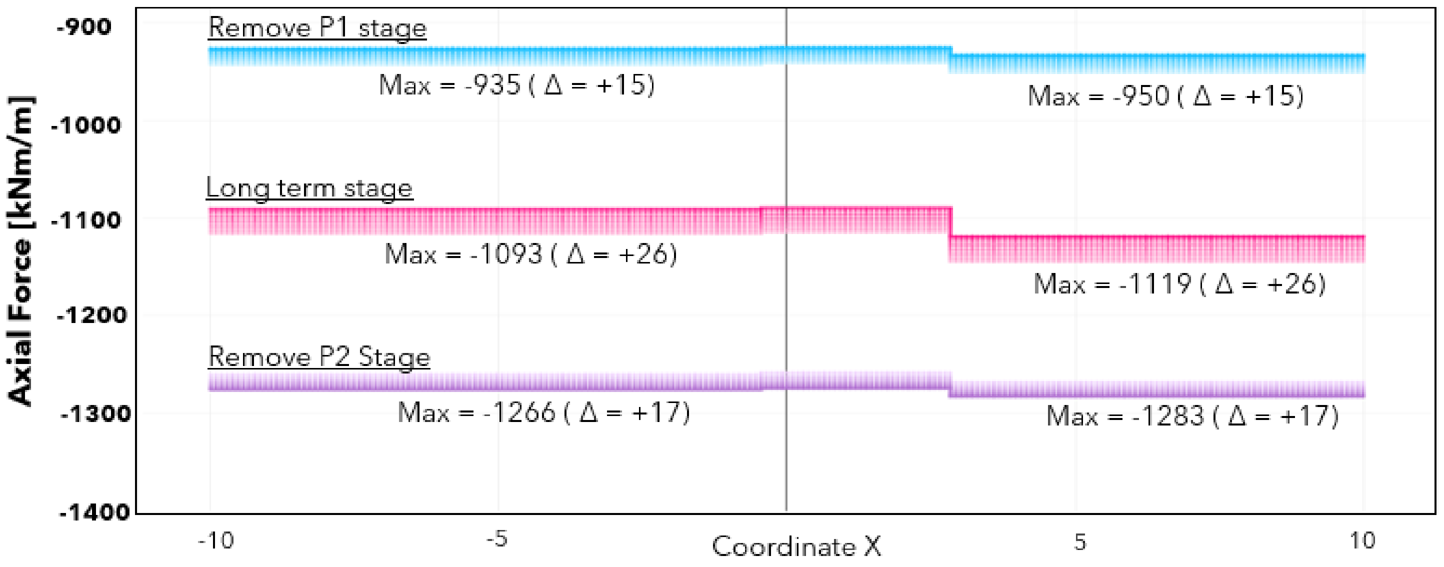
Sensitivity Study

Concrete Stiffness E from 16GPa (7 days) to 25GPa (28 days)



Shaft Wall Shear Force (kN/m)

Permanent Concrete Slab (B-1) Axial Force



Parametric study is useful to support the Construction – Successfully removed temporary props 2-3 weeks earlier than Planned !

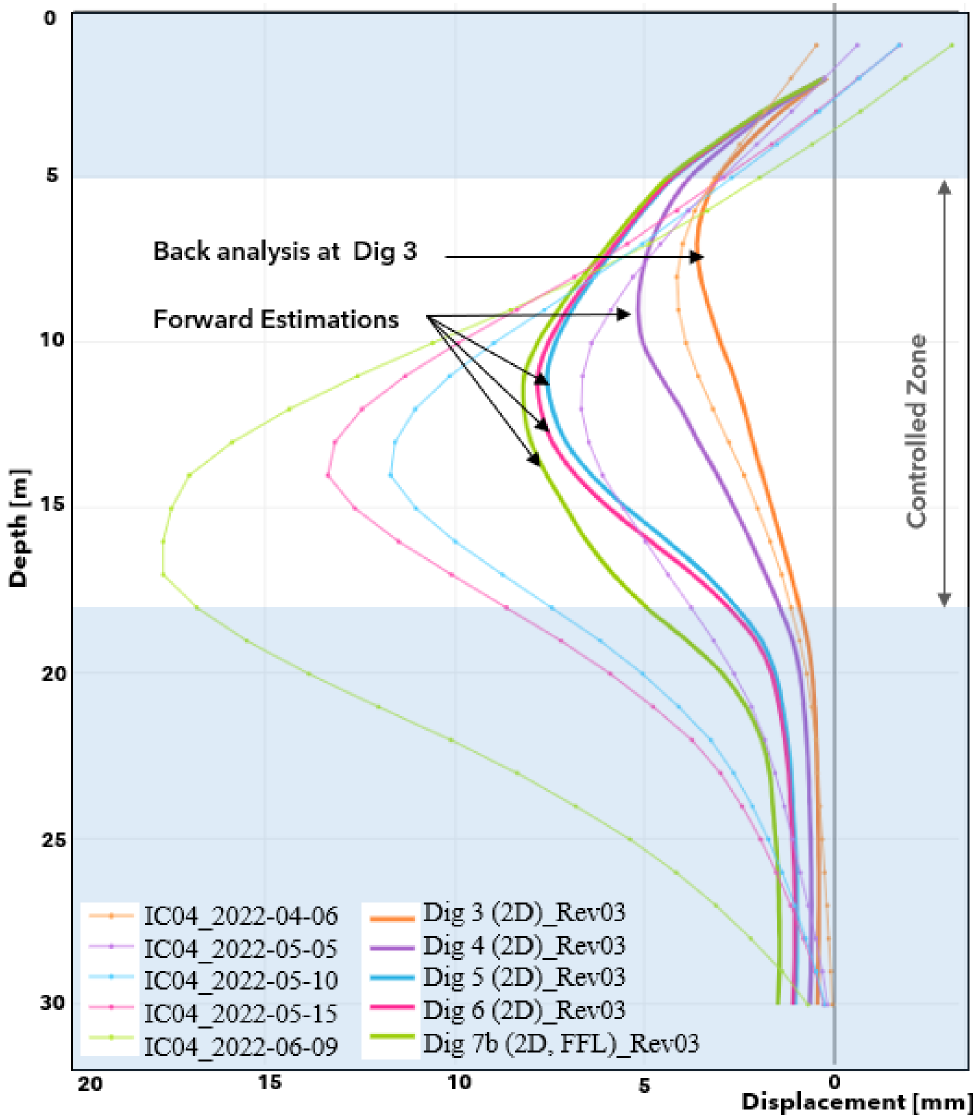
Back Analysis Study

Single stage back analysis (Mohr-Coulomb Soil model)

- Fitting well at the back analysed stage;
- Under-estimated for future excavation stages;
- Update Model:

  - Split LC into sub-layers: LC-A3, LC-A2 and LC-A1, each layer with own MC parameters;
  - Adopt advanced soil model;
  - Define a few MC stiffness values representing the stiffness at variable strain status, e.g., E value at small, medium and large shear strain level.

A shaft excavation in London Clay using the Contiguous Piled wall - modelling and back analysis, *Proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering, London, UK.* Chen, Y., 2023



Model Rev03

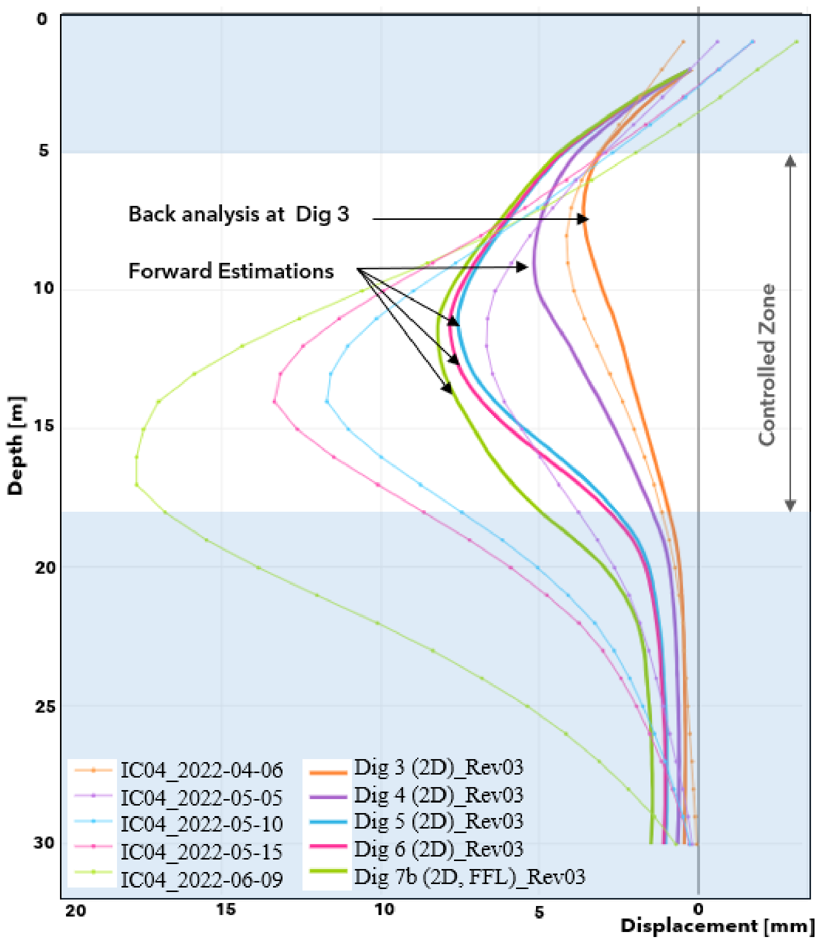
Back-analysis on DAARWIN

SAALG GEOMECHANICS

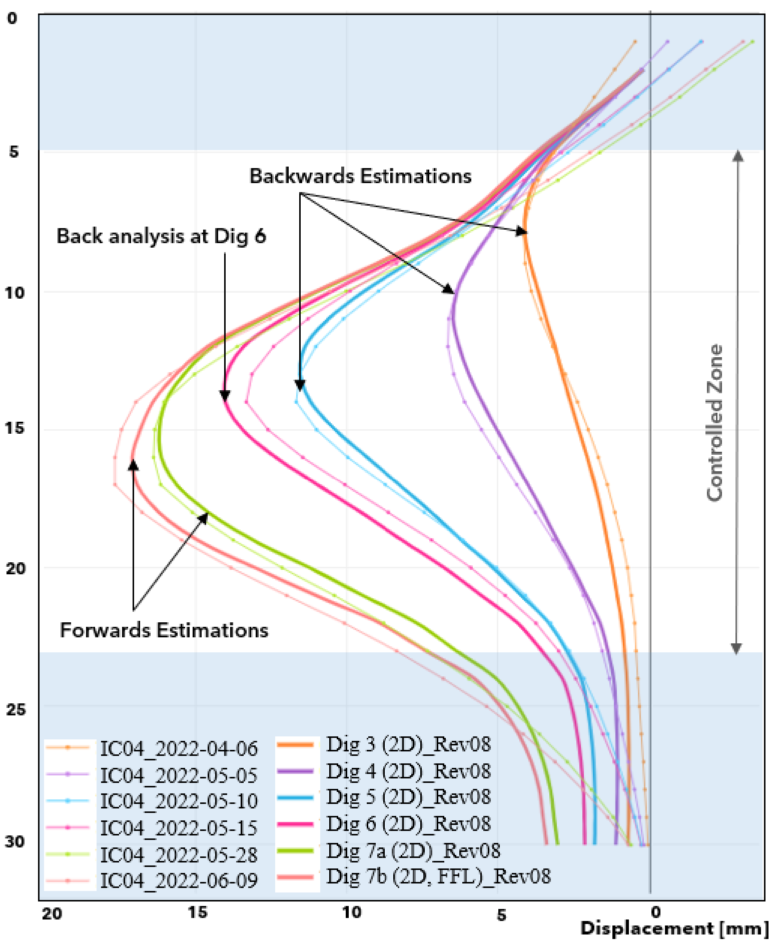
Example of Back-analysis

- Model Rev03 Back-analysis
- Model Rev08 Back-analysis
- RTBA calibrated the ‘best-estimated’ London Clay parameters for excavation using flexible retaining wall structure.

Model Rev03

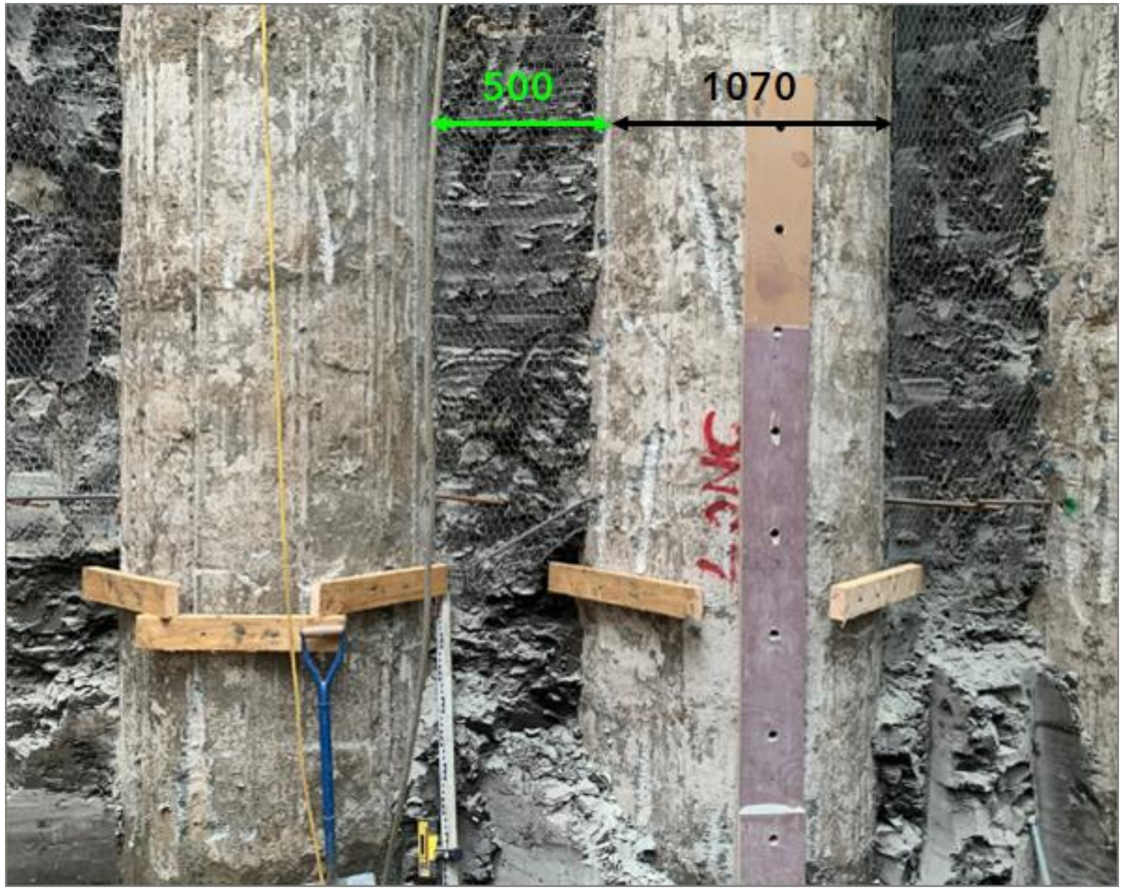


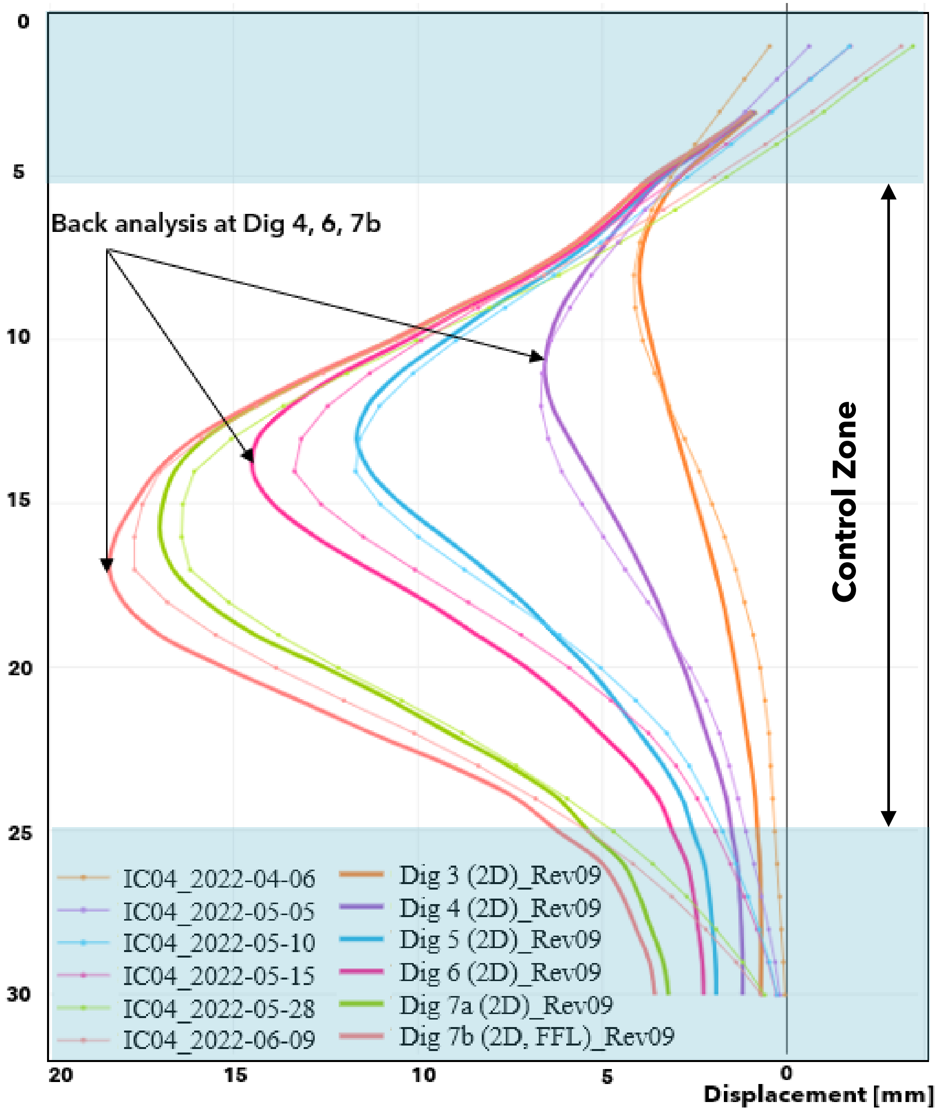
Model Rev08



Challenges & BA Attempts

- Creep movements after reaching F.F.L.
  - Add 'Stress Relaxation' zone behind wall; and
  - Back analysis targeted multiple dig stages.





Model Rev09

TSS RTBA Trial

Outcomes:

- It is possible to conduct back analysis in parallel with fast-paced construction project with the ML supported back analysis tool (e.g., DAARWIN)
- DAARWIN as a back analysis tool is useful which offers better understanding on construction performance – support construction.
- It is essential to interpret Observations & Outcomes for a qualitative back analysis.

Summary

- Machine Learning Optimisation Algorithms significantly enhance the **efficiency** & **accuracy** of back analysis, enable the '**Real-Time Back Analysis**'.
- **Timely available** I&M data (e.g., I&M data platform), and **reliability** of Observations is '**KEY**' in RTBA.
- **Interpretation** of Back Analysis is compulsory to ensure physical and engineering are meaningful.
- With RTBA tools, OM is an attractive option for **Digital Construction** / a **Data-Driven** design approach, keep up with the fast-paced construction.
- For any Construction projects, RTBA its "Digital-Twin" can provide regularly check identifying opportunity for optimisation / detect potential faults for early warning, improve construction safety control.

Summary

1. Application of observational method at Crossrail Tottenham Court Road Station, UK. Yeow *et. al.* 2014
2. Application of observational method on deep excavation retaining wall design in London Clay, PhD Thesis. University of Cambridge, Chen Y. 2018
3. A Probabilistic analysis to assess the most probably design parameters for use in the Observational Method, Grimal, A.C., Chen, Y., and Nicholson, D.P. 2022
4. A case study of review excavation monitoring data for the reliable back analysis, Proceedings of the 11th International Symposium on Field Monitoring in Geotechnics, London, UK. Chen, Y. and Nicholson, D.P. 2022
5. A shaft excavation in London Clay using the Contiguous Piled wall - modelling and back analysis, Proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering, London, UK. Chen, Y., 2023
6. An innovative method to interpret prop monitoring data through the signal filters, manuscript submitted to ICE Proceeding of Geotechnical Engineering (under Peer Reviewing), Cheng, W.K. and Chen Y. 2024

Thank you & Questions

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