MOTT MACDONALD

Creating value through Observational Control

Tony O’Brien
Keynote presentation - ISFMG
September 2022

Outline

1. Why important – reduce over-conservatism in geotechnics (ICE podcast) / The Observational Method – background + illustrative case histories
2. Some Observations on I&M
3. Looking to the Future – Real-time back-analysis + Digital Twins / A Way Forward for O.M.
4. Summary + Conclusions

The Observational Method

What is it; essential requirements

What is it?

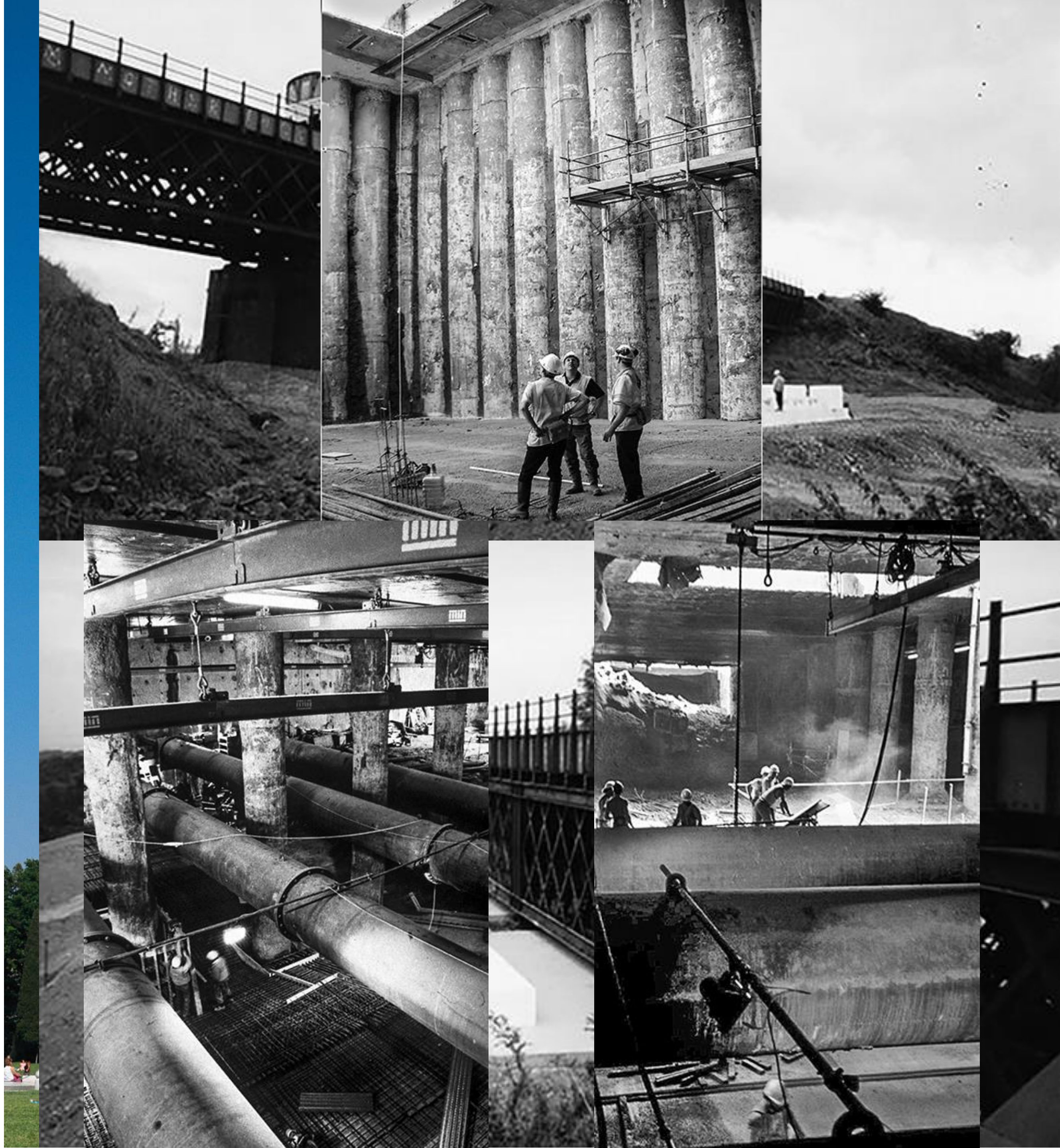
- An integrated + interactive design + construction control method, linking design to observed performance during construction.
- The intent is to use observed structural + ground performance to enable pre-planned design modifications during construction.

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

The Observational Method:
Wide Range of Applications

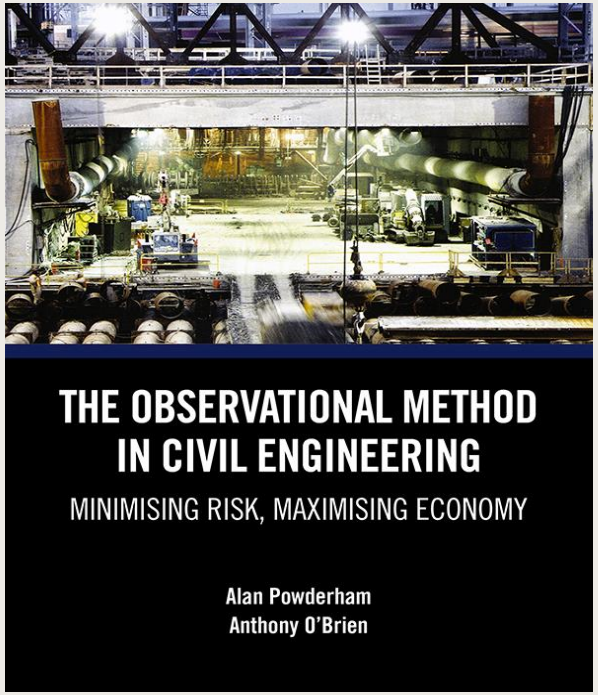
- Retaining walls + shafts
- Tunnels
- Protection of existing infrastructure
- Embankments
- Pile Groups
- Offshore structures
- Dams
- Dewatering / depressurisation
- Ground improvement
- Protection of Ancient Monuments



The Observational Method:

Experience, Added Value, Challenges

- Powerful technique – maximises economy whilst assuring safety
- Well established technical basis (eg CIRIA C185) and proven track record (eg Powderham and O'Brien, 2020)
- But – conventional Contracts (and Culture) leads to significant under-use
- Design Assurance, Checker Approvals – also a challenge, depends on experience / expertise
- Way Forward – ?



Project	Project Type	Location	Benefits
Northern Line Extension.	Retaining wall, deep excavation	London, UK	3 months reduction in 2 year schedule. US $5 million saving.
Boston Central Artery, Contract 9A.	Jacked Tunnel below operating railway	Boston, USA	1 year reduction in 6 year schedule US$ 300 million saving
Liantang	Tunnel Portal	Hong Kong, China	3.5 month saving in schedule US$ 40 million
DTSS2	Retaining walls / deep shafts	Singapore	8 month reduction in schedule US $ 3.4 million

Observational Method + Contracts

Contract Type		Key Features	Collaboration between designer and Contractor	Opportunity for OM
Traditional **(Design/Bid/Build)**		Client appoints designer, design completed, successful contractor builds design	Very Limited. Typically, designer separated from Contractor	Very limited, unless a Value Engineering (VE) clause is used in the contract
Design and Build		Client's designer prepares a 'reference design'. D&B team completes final design and builds project.	Intense time pressure during tender may limit opportunity to build rapport and trust.	Client approvals and independent checkers may hinder. Need a VE clause to incentivise to pursue OM.
Early Contractor Involvement (ECI) **(aka – progressive design/build)**		Stage 1 - agreed scope, prices, programme and risk allocation. Stage 2 is often a target contract.	Better than conventional D&B, due to reduced time pressures. Opportunity to develop innovation	Good potential – MORE TIME during Stage 1; build trust between parties.
Alliancing		Multi-party delivery framework. Promote trust, risk and responsibility sharing. Alignment of commercial interests.	Very good. Innovation promoted through more collaborative environment.	Potentially excellent. Alignment of commercial interests and risk sharing is conducive to OM. Longer term relationships, should enhance OM opportunities.

Observational Method + Contracts

New guidance, TC206

1.

Conventional Contracts need to change – KEY ENABLER

2.

ISSMGE TC206 – Guidance on Contract Conditions to encourage wider use

3.

Synergy – both OM and I&M have similar issues

Contents

SIMSG ISSMGE

Observational Method + Contracts

NEC example (Note – **new** NEC creates more opportunity for the OM)

Alignment of commercial interests is key

Additional effort needed + we need

- Close co-ordination: client, contractor, designer, checkers
- Non-adversarial environment – teamwork
- Trust

To Stimulate

- Need commercial incentivisation clauses in contract
- share benefits
- **V.E. has been a "game changer" when introduced (for any type of Contract!!)**

NEC ECC4

- Payment Mechanisms, A to F (Target Cost preferred)
- **Early Contractor Involvement (secondary option X22)**
- **New clause in NEC ECC4, Clause 16 – Value Engineering**

Illustrative Case Histories, O.M. Implementation

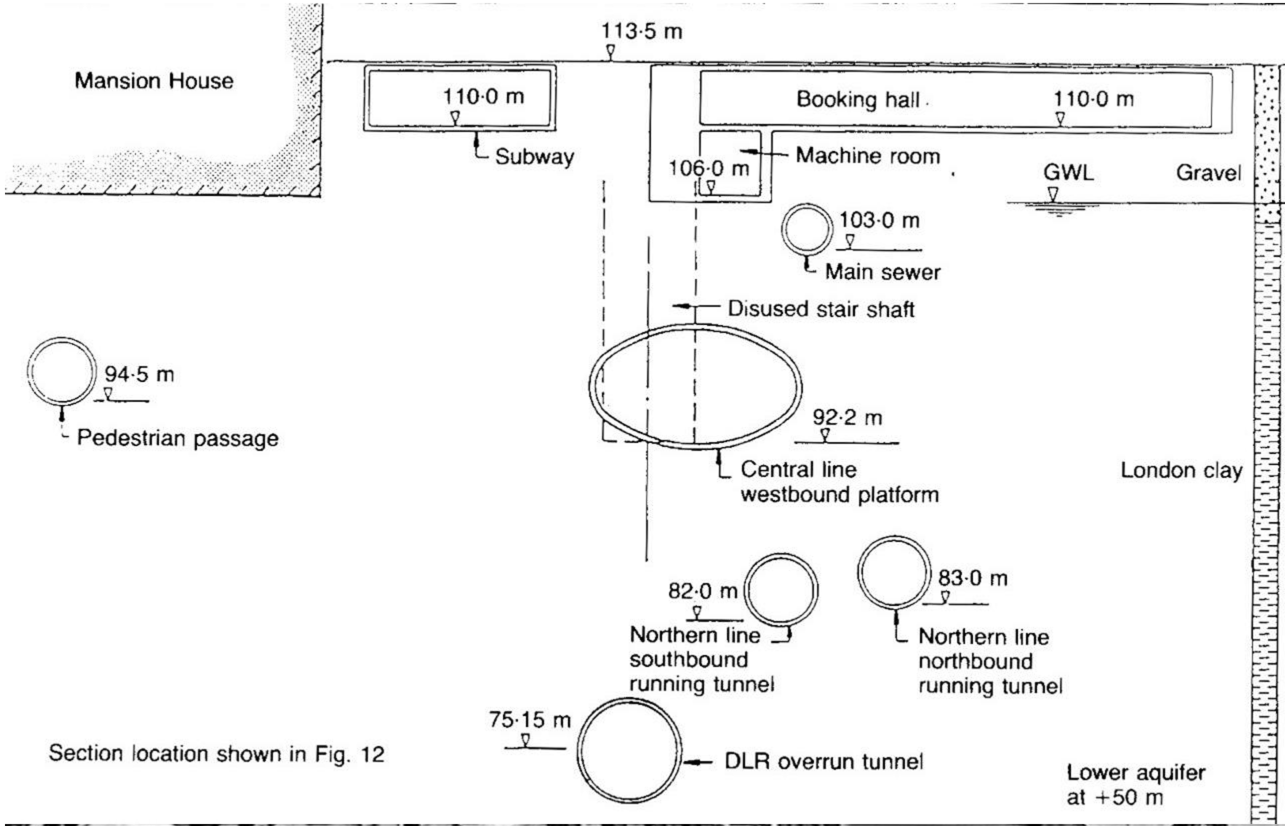
The following need to be recognised:

- the limits of what can be analysed and "predicted"
- how risks can be safely managed through O.M.
- uncertainty is NOT just about the Ground (therefore cannot be dealt with through manipulating geotechnical parameters !!)

Mansion House

Profound Influence of Structure-Ground-Structure Interaction

- **18th Century Palace, Grade 1 National Heritage**
- **Remarkable interior, delicate plasterwork**
- Experienced multiple modifications, considerable differential settlement (circa 200mm) historically.
- Building is 60m by 30m in plan, 5 storeys high
- Adjacent building is 1-6 Lombard St, substantial masonry structure
- Historic tunnelling: LUL Central + Northern Line c1900
- **DLR Extension –** small pedestrian tunnel created major concern, esp large ‘time-dependent’ settlements
  - future DLR tunnelling, serious concerns about damage
  - **DLR project stopped, CRISIS**
  - **How to move forward??**



Tunnelling works close to the Mansion House from 1900 to 1990s

Spatial relationship of Mansion House (on right) and 1-6 Lombard Street

Mansion House

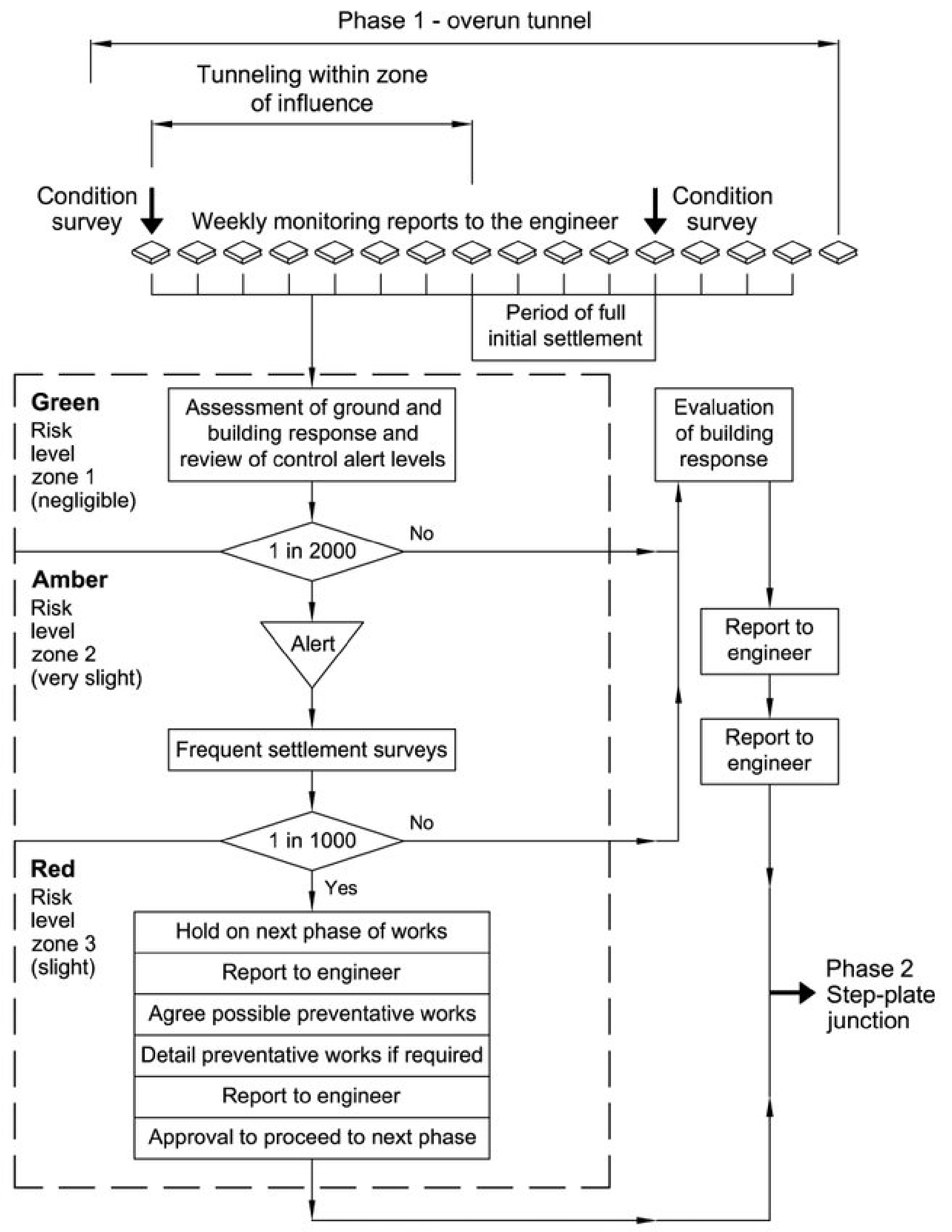
Achieving Agreement to use OM

Crisis – provokes extreme reactions!

- major protective works proposed; deep wall (shield) or total underpinning and jacking system
- huge costs + delays (both for preventative works + DLR's delays + costs)
- new risks of damage due to protective works ???

Enhanced construction control – OM through Progressive Modification

- "most probable" conditions: fraught with complexity (site history?? Stakeholder views??)
- tunnelling sequence modified, incremental phasing of works
- risk of damage: conservative basis, Boscardin & Cording + greenfield settlements
- traffic lights: start at negligible risk + demonstrate (step by step) risk maintained within acceptable levels
- construction control flow chart for OM risk management
- contingencies: in-tunnel; building – lateral ties

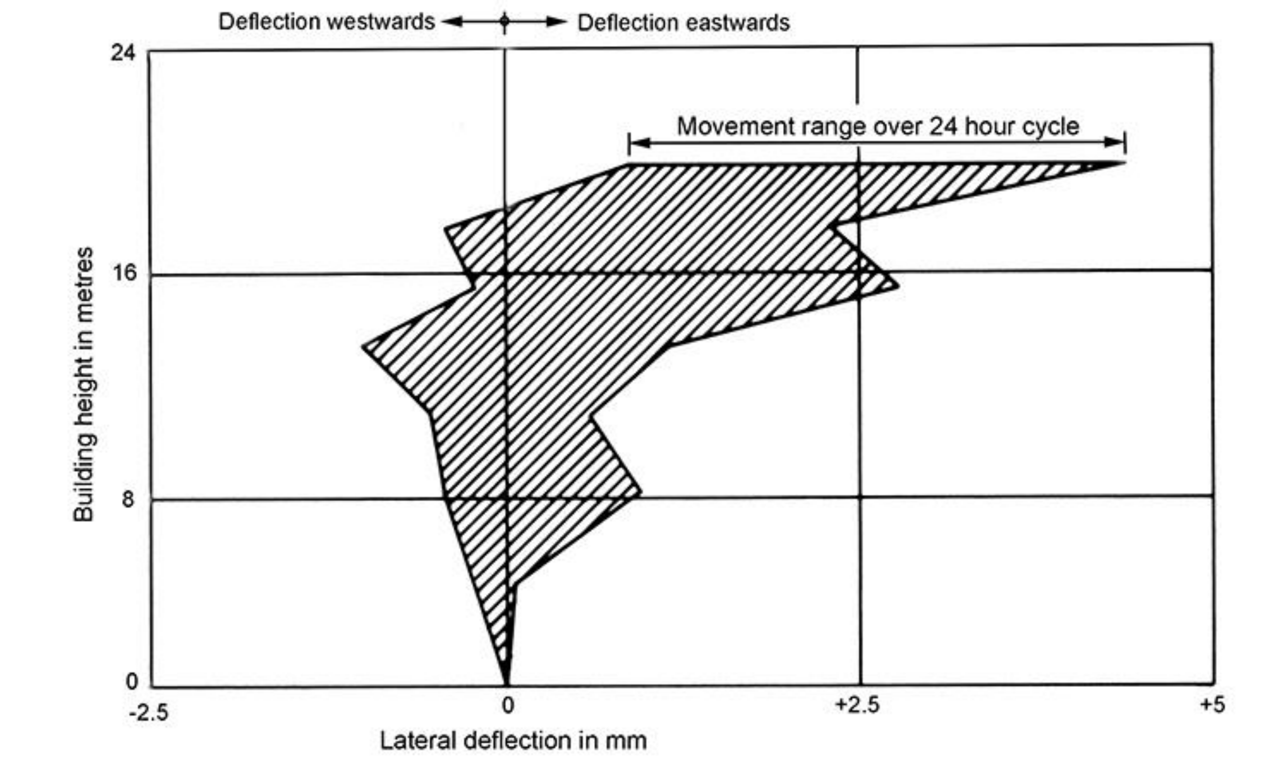


Flow chart for risk levels and respective responses within the traffic light system

Mansion House

Instrumentation & Monitoring

- OM Performance limit – ‘critical observation’ based on angular distortion
- Very high accuracy essential (good installation of I&M critically important)
- Primary system – horizontal + vertical arrays of ‘strings’ of electrolevels, supplemented by precise levelling
- Other ‘secondary’ instrumentation installed – NOT used for OM control
- Condition surveys + tunnel construction records – as important as I&M, for data interpretation
- Real-time monitoring – daily temperature induced movements of building (> short-term construction effect of DLR over-run tunnel!!)



Diurnal cyclic movement measured by vertical electro-level string on west elevation

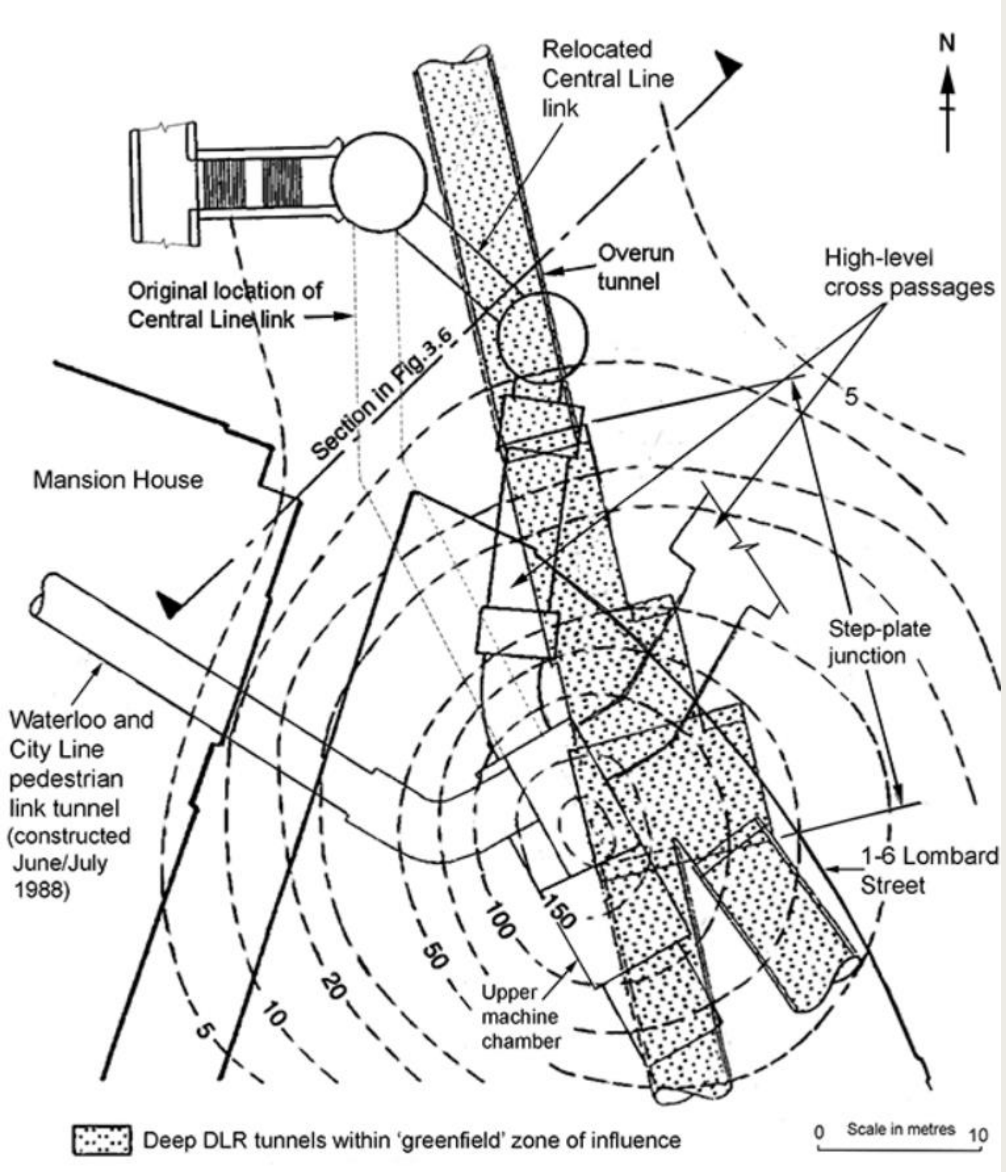
Mansion House

Arrangement of DLR tunnels + Greenfield settlement

- North-east corner, experience max settlement; greenfield approx. 5-10mm
- Early recognition, building stiffness, extends + flattens ‘greenfield’ settlement trough
- Maximum settlement beneath 1-6 Lombard St

Observed settlements

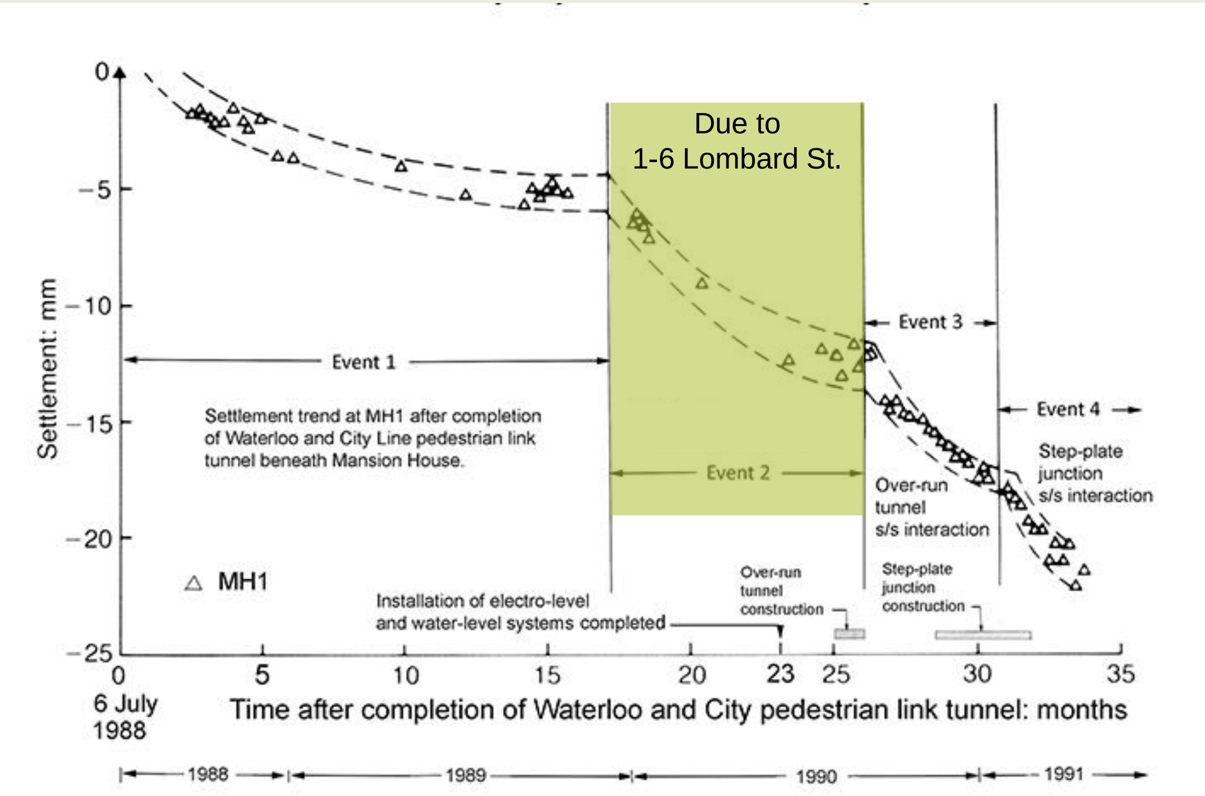
- 1-6 Lombard St : Max settlement – c 65mm; angular distortion c 1 in 1000 to 1 in 2500.
- Mansion House: Max settlement – c 30mm; angular distortion < 1 in 7000; No Damage
- Both Buildings – tilted to North



Plan arrangement of tunnels for the DLR and associated works beneath Mansion House + 1-6 Lombard St. Surface settlements (in mm) for ‘greenfield’ conditions for the over-run tunnel + step-plate junction

Time-dependent settlement + building/building interaction

- settlement continued even when no tunnelling activity (event 2)
- time-dependent settlement c two-thirds of total
- not a "drainage" effect (see Anketell-Jones + Burland, 2001), historic tunnelling already "drained" the area
- building stiffness, redistributes 'greenfield' settlement, leads to time-dependent settlement
- Mansion House, about one-third of settlement, due to 1-6 Lombard St
- actual settlement trough c 4 times larger than 'greenfield'; triggers building to building interaction



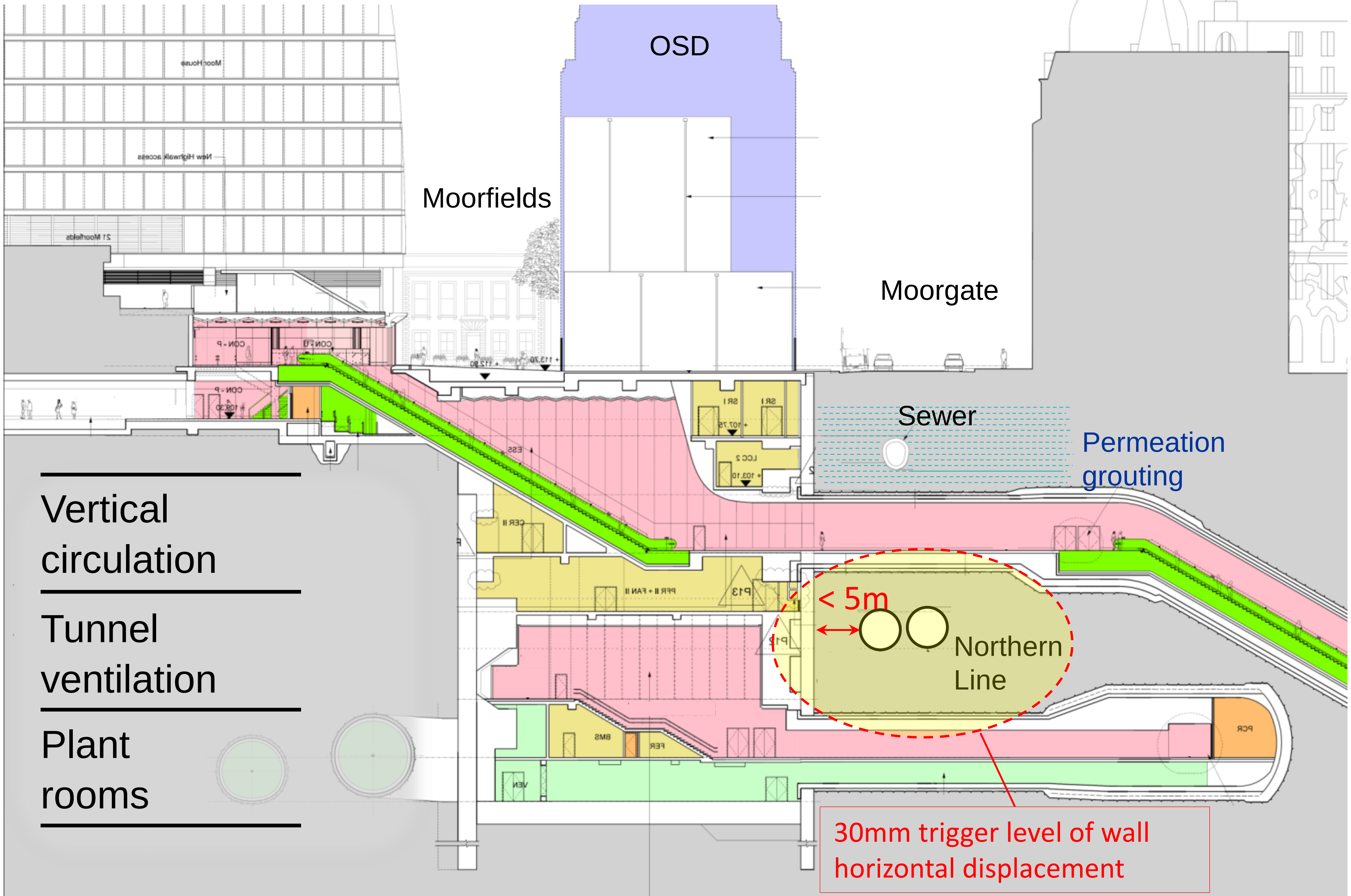
Inferred settlement 'events' at survey station MH1 in NE corner of Mansion House

Mansion House - Summary

- The O.M. when used (commonly for Urban areas) then key constraint is minimising damage to EXISTING infrastructure and buildings
- The key issue is then NOT just geotechnics parameters
- Often Geo Practitioners think about GROUND-structure interaction, ie focus is really on ground
- In practice, the issue may be STRUCTURE-ground interaction, ie focus on the structure !!
- This case history represents 1st use of OM by Progressive Modification, with a traffic light system enabled by real-time I&M
- Agreement to use OM – achieved despite extreme positions initially taken by stakeholders
- Sophisticated analysis was not necessary, but sophisticated thinking was essential (backed by excellent I&M) !!

Crossrail, London, Design Assurance + OM. Moorgate Shaft - Location

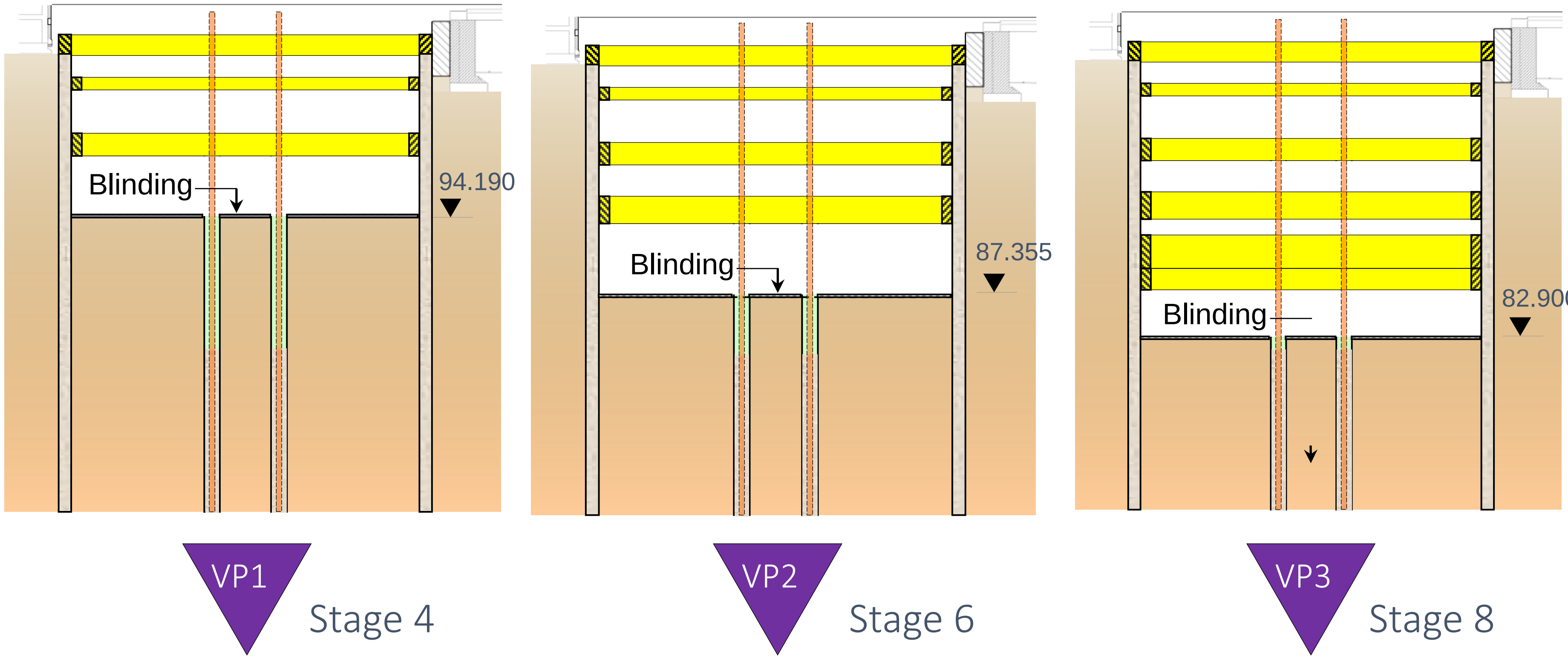
Section through Moorgate Shaft, East Wall critical



Verification Process – key construction stages

3 Verification Points (VPs) defined:

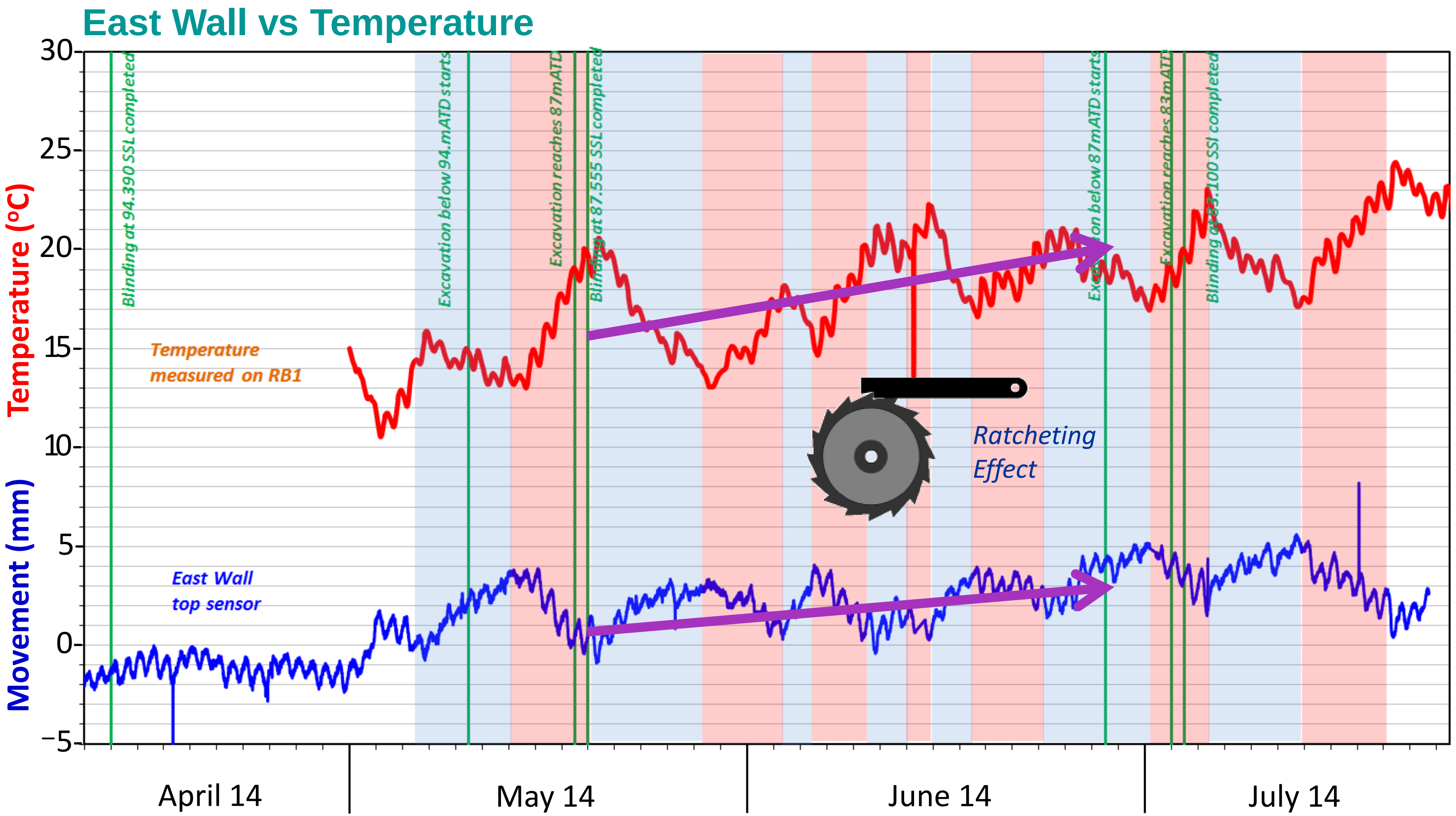
- Influence of various construction issues assessed at each stage
- Back-analysis: non-linear 3D model updated at each VP, forward predict to next VP + construction stages
- At each VP: designer + checker assess if BENEFICIAL changes ok for next construction stages (if not keep original assured design)



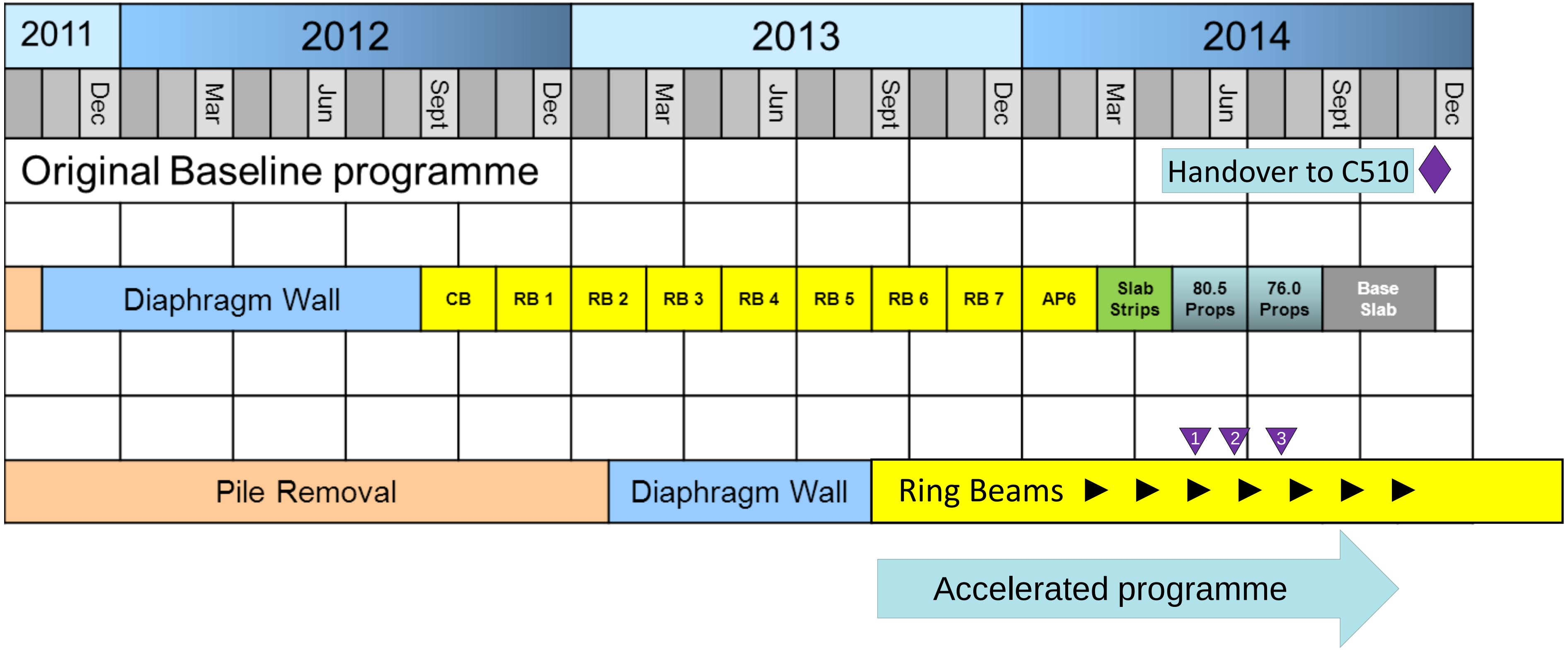
East Wall - early identification of construction related impacts

and SAFE management

- Complex interactions, thermal movements of shaft with local permeation grouting (separate contract!)



Accelerated Programme



The Observational Method through Progressive Modification + Verification Process

- delivered 14 week programme saving
- base slab completed 2 weeks early
- potential 11 months delay overcome
- handover to SCL contractor hit Project critical milestone
- no damage to adjacent infrastructure

Instrumentation and Monitoring

Bad / Good / How can we do better?

Purposes of I & M

Currently – often unclear + poor commercial alignment, so high quality unlikely

Protective (current focus)	Beneficial (future focus?)
3rd Party Protection; legal + P.R.	Implement the O.M.
Is Main Contractor causing a problem?	Learn from experience
if no problem, no analysis (+ NO value??)	Stimulate - Innovation + Future Practice (eg reliability-based design, “field” parameters)
	Digital Twins

I + M Procurement – Lessons Learnt

(O.M. not implemented)

One procedure that is **not** recommended is for I & M to be billed as individual items for the main contractor to price (on lowest bid basis)

A switch to Construction Manager controlled monitoring was made and there was a marked upturn in the effectiveness of the I&M

Our experience with the (low bid) arrangement is that regardless of the contract requirements, the quality and performance of the I&M is often low on the list of main contractor concerns

Owner chose a low bid specification with Main Contractor …it would have been better to have most aspects of the I & M under the control of a single entity answering directly to the Owner

I & M specialist (employed by Client) not interested in responding to our (D&B designer) queries

In reality the site team will not stop construction because of this

I & M and contracts

Key problems

Why?

instrumentation needed – **KEY QUESTIONS** that need answering

Who?

is **RESPONSIBLE** for **QUALITY** of instrumentation (competence + authority)

Who?

is under **CONTRACT** with who (no panacea):

- I&M employed by Client
- I&M employed by Main Contractor

When?

will I&M be installed (need background / enviro effects, **BEFORE** construction)

Detail

what + how – **AVOID "CUT + PASTE"** (specialist input on latest technology)!!

- I&M often viewed as trade activity
- Geo-professionals – lost interest in Procurement and Contracts? Fragmentation of roles + gaps!!
- Motivation for Main Contractor??

Specifications

Traditional Specifications – inadequate.
Move to OUTCOME / PURPOSE DRIVEN Specifications

Technology – matures like "fish"

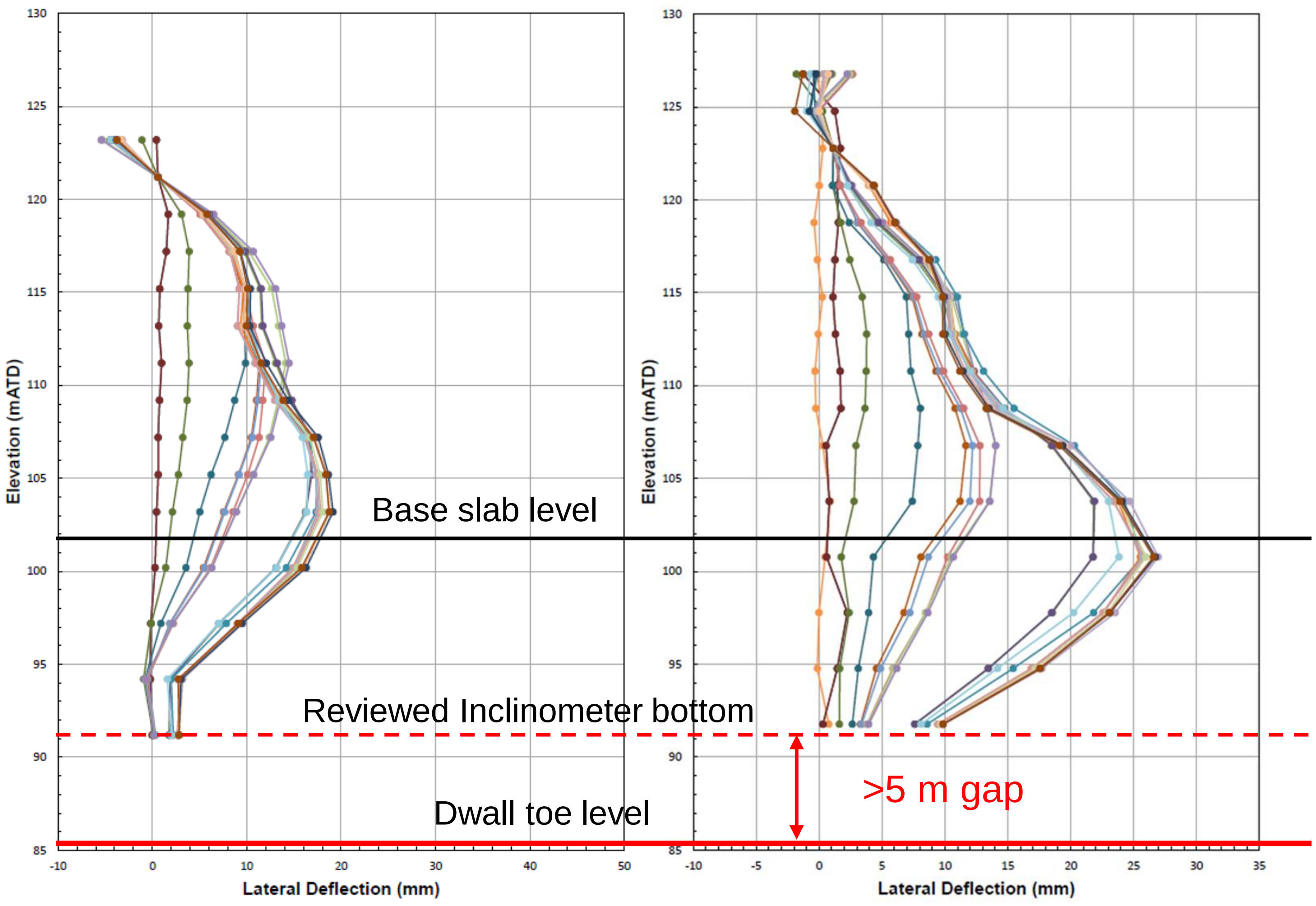
Information – matures like "fine wine"

Technology is changing quickly – Industry needs to move away from "nuts + bolts" specifications !

Bad practice – why does this still happen?

Get basics right – right place/ right depth?

- Many Inclinometers installed (dozens)
  - Initially Manual Inclinometers
  - Changed Inclinometer probes
  - THEN replaced by In-Place-Inclinometer
- All above, during construction
- Baseline of inclinometer data – lost trace of data history
- Wall fixity at toe level? – Major uncertainty
- Outcome – All I&M useless, BIN!!!

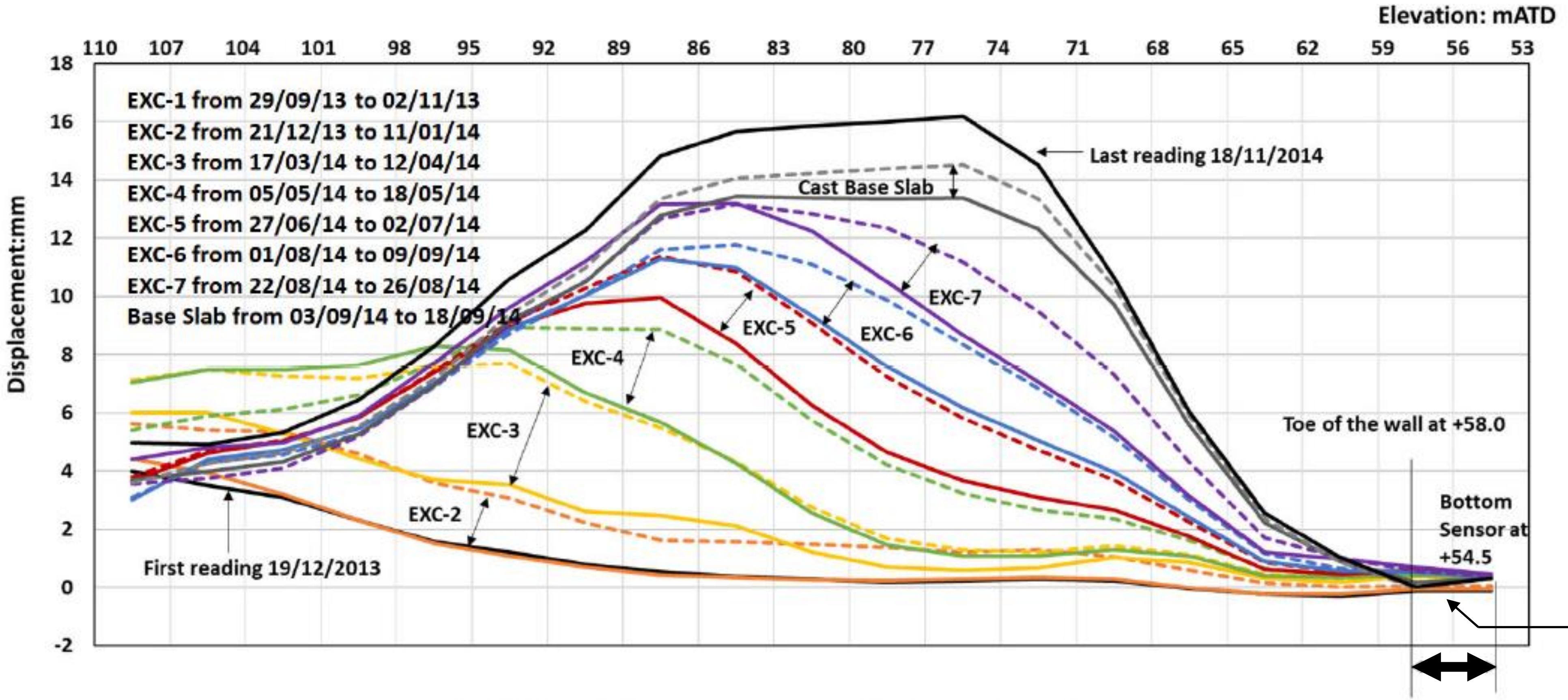


Inclinometer data

Good practice – we can do this, why not all the time?

Get Basics Right – right place/right depth?

- Inclinometer was installed a few metres below the wall toe – ensure fixity at bottom of inclinometer

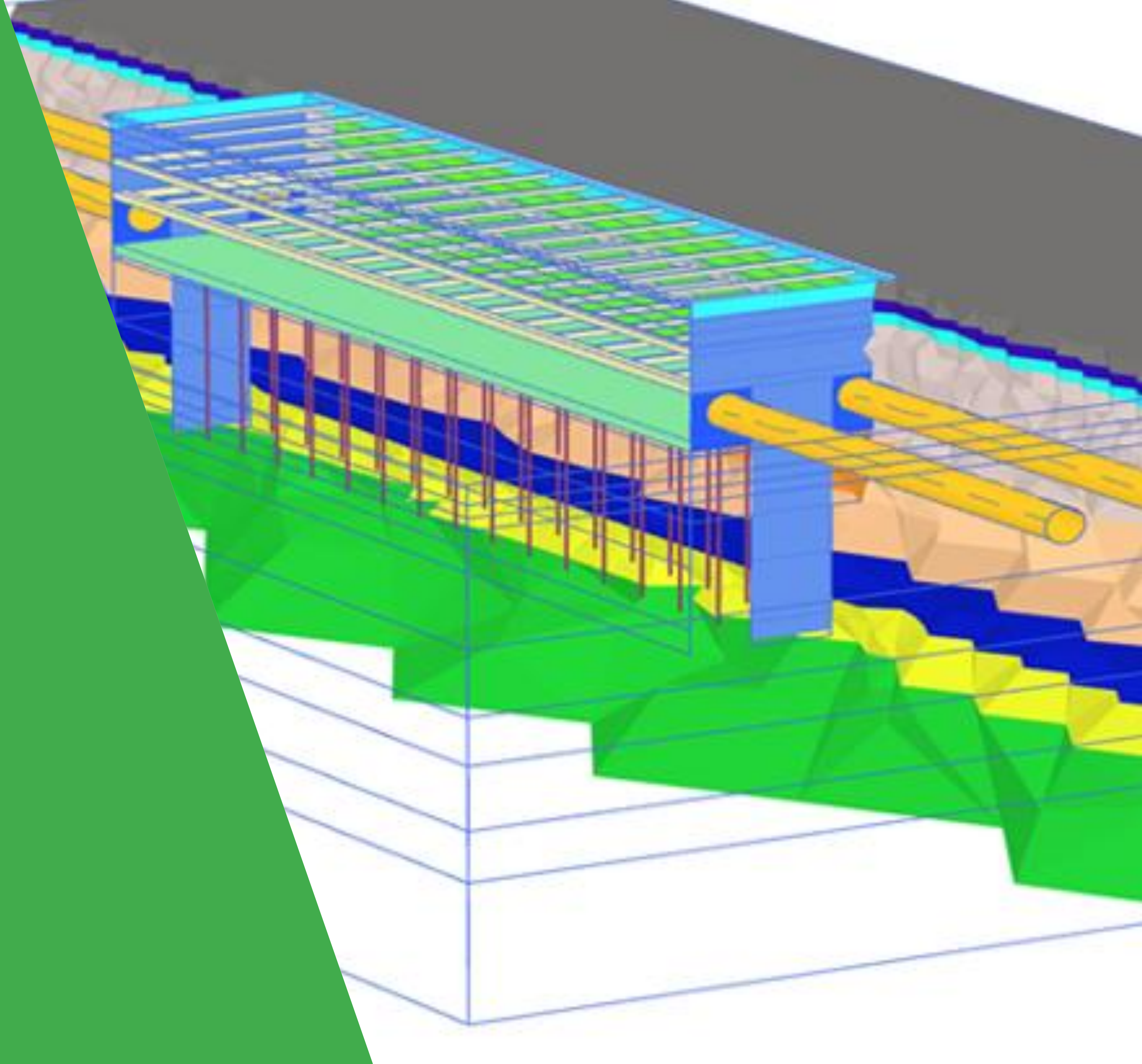


repeatable reading: ≤ 1mm.

Inclinometer toe is 3.5m below Dwall toe;

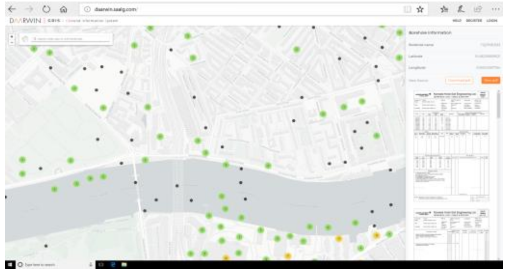
Looking to the future

Real-Time Back-Analysis (R.T.B.A.)

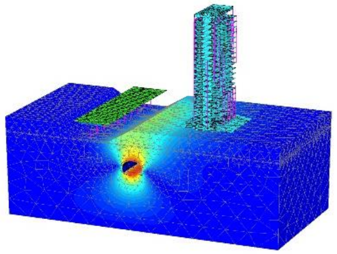


R.T.B.A. – SAALG's DAARWIN (Practical Use of Machine Learning)

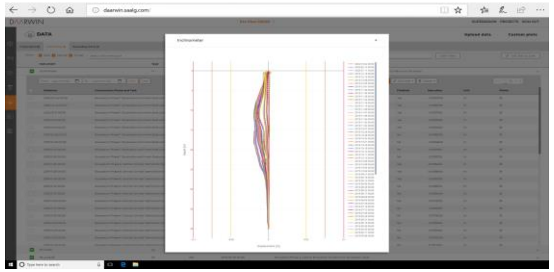
Centralise + Connect all key information



HISTORICAL INFORMATION

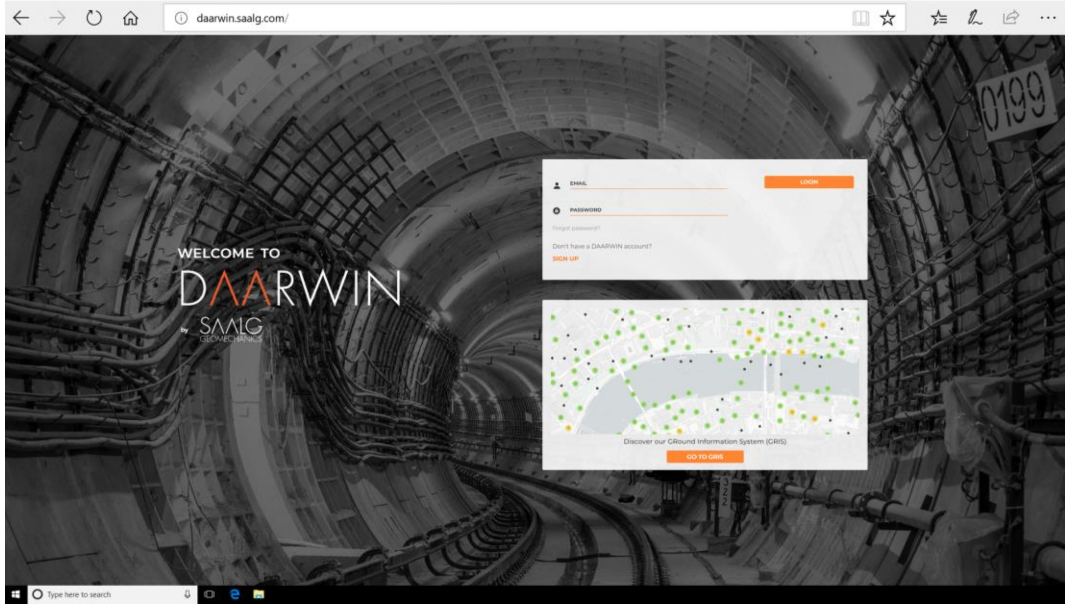


NUMERICAL MODELS



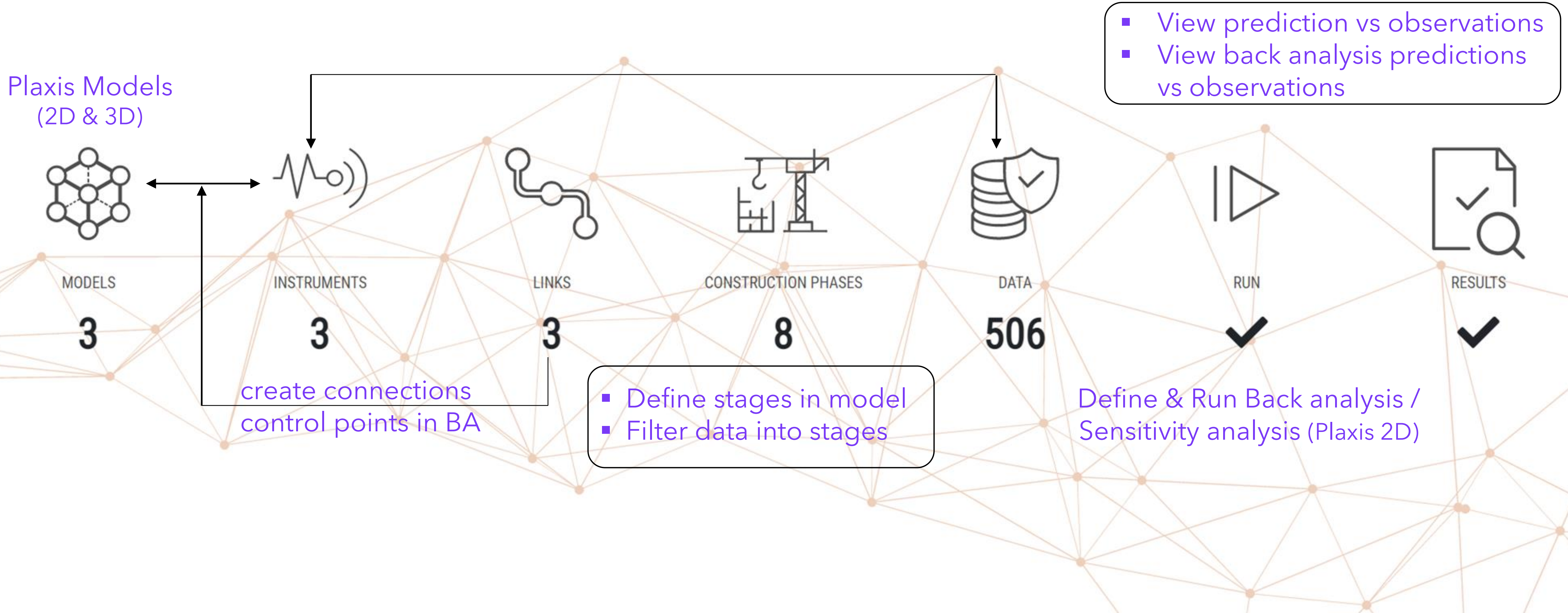
MONITORING DATA

CONSTRUCTION PROGRESS



R.T.B.A. – SAALG's DAARWIN

Numerical analyses linked to I&M + construction data: sensitivity plus full back-analyses



R.T.B.A - SAALG’s DAARWIN

Back analysis – Genetic Algorithm driven machine learning

- Back-analysis computation run within 48 hours
- 4920 combinations created
- Statistical Optimal value based on 4286 successfully analysed combinations
- NB – a mathematical best-fit created

BACKANALYSIS RESULTS

Backanalysis Plot

Run Name	Back Analysis Dig to +77mOD	Search space size (# possible individuals)	96,381,722,112	# total individuals evaluated	4,920

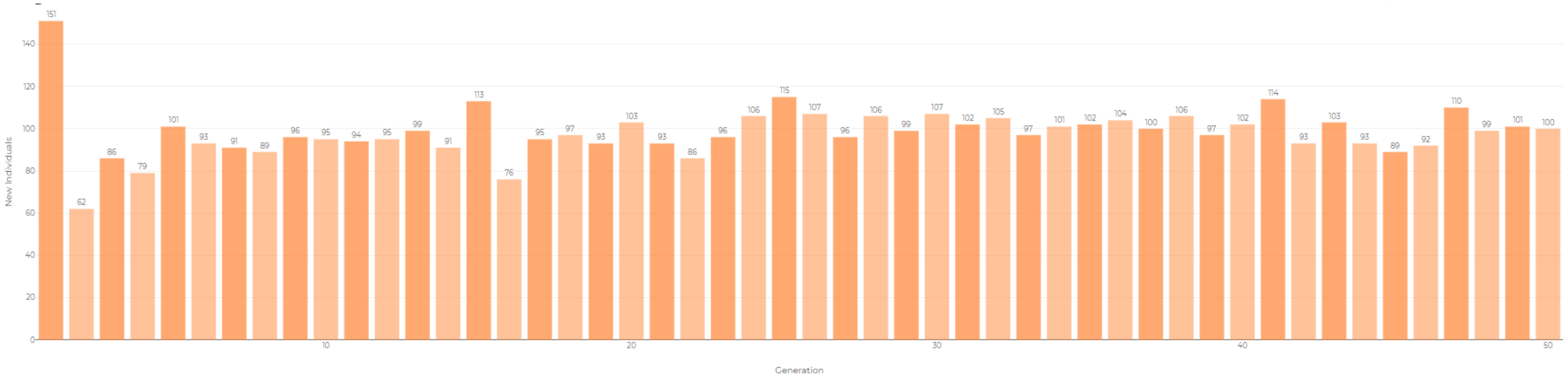
Run definition

Raw data results

Table based on the best individual and **4286** good individuals out of a population of **4920** individuals

Material	Parameter	Unit	Type	Design Value	Optimal Value	±	Standard Deviation	Best Individual
04 Mercia_Mudstone_I_active	E	kN/m^2	Reference parameter	475,000.00	603,687.59	±	83,363.64	710,000.00
	E_inc	$kN/m^2/m$	Reference parameter	55,000.00	77,355.34	±	25,604.21	80,000.00
03 Mercia_Mudstone_II_active	E	kN/m^2	Reference parameter	420,000.00	334,094.73	±	46,018.54	335,000.00
	E_inc	$kN/m^2/m$	Reference parameter	30,000.00	36,387.07	±	31,371.21	10,000.00
03 Mercia_Mudstone_III	E	kN/m^2	Reference parameter	245,000.00	251,866.54	±	36,831.04	270,000.00
	E_inc	$kN/m^2/m$	Reference parameter	72,500.00	166,394.07	±	11,859.30	195,000.00
02 Mercia_Mudstone_IV	E	kN/m^2	Reference parameter	100,000.00	128,756.42	±	57,175.96	75,000.00
	E_inc	$kN/m^2/m$	Reference parameter	47,700.00	52,465.00	±	34,499.56	20,000.00
04 Mercia_Mudstone_I_passive	E	kN/m^2	Bonded parameter	328,000.00	416,544.44	±	57,520.91	489,900.00
	E_inc	$kN/m^2/m$	Bonded parameter	38,000.00	53,375.19	±	17,666.91	55,200.00
03 Mercia_Mudstone_II_passive	E	kN/m^2	Bonded parameter	301,000.00	239,545.92	±	32,995.29	240,195.00
	E_inc	$kN/m^2/m$	Bonded parameter	21,500.00	26,089.53	±	22,493.16	7,170.00

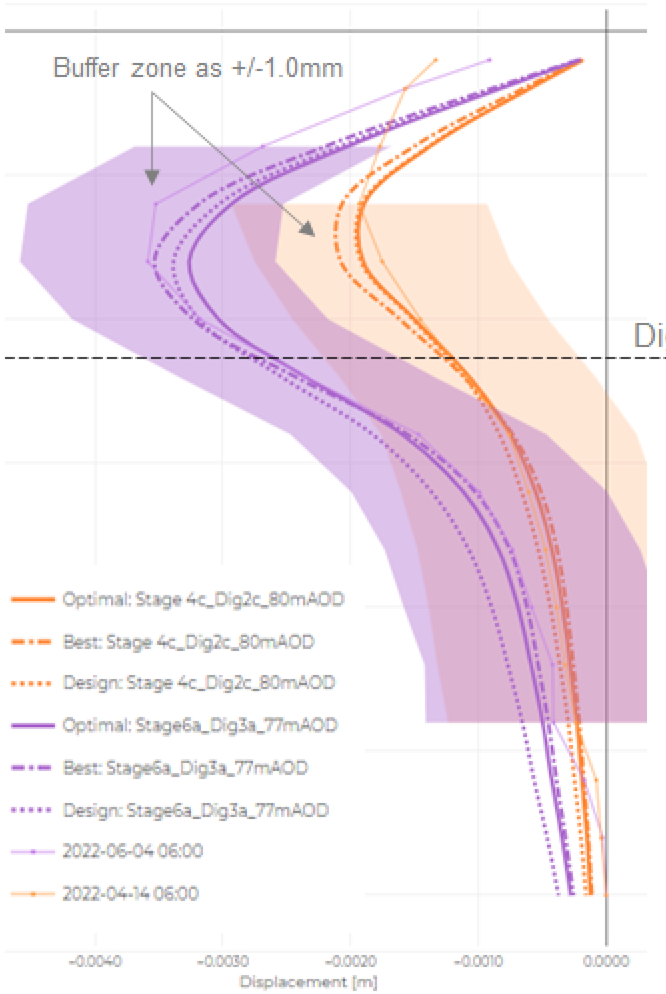
New Individuals by Generation Plot



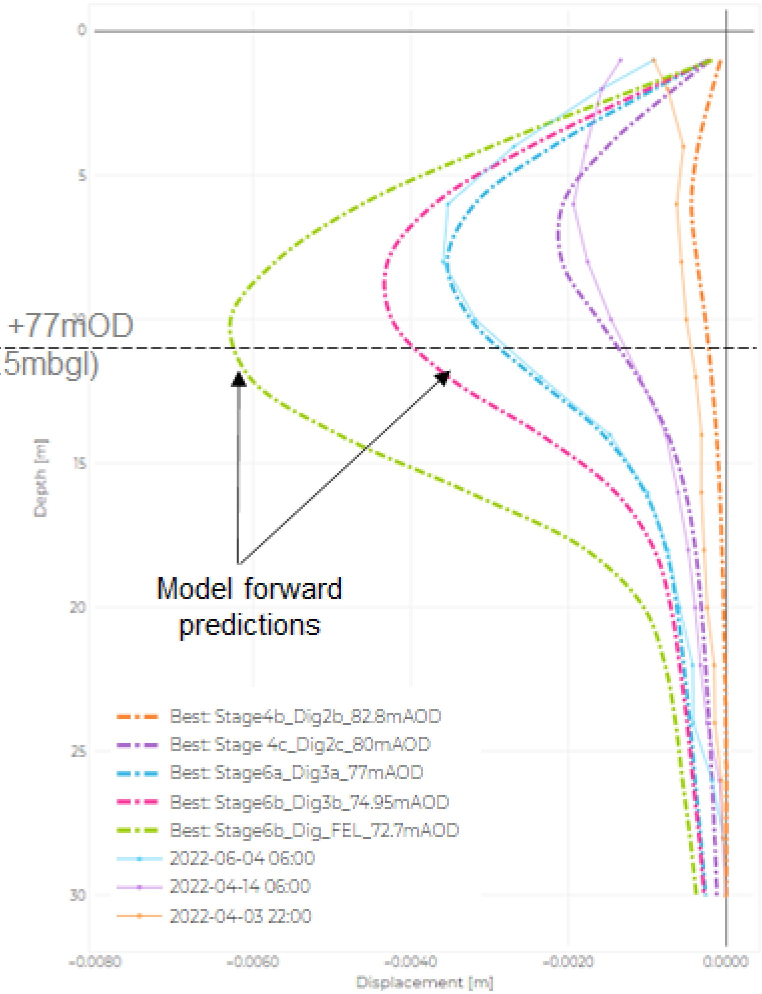
R.T.B.A. – SAALG's DAARWIN – Back analysis results

Quantifying uncertainty – I&M data + analysis inputs

Predicted range



An example of individual prediction

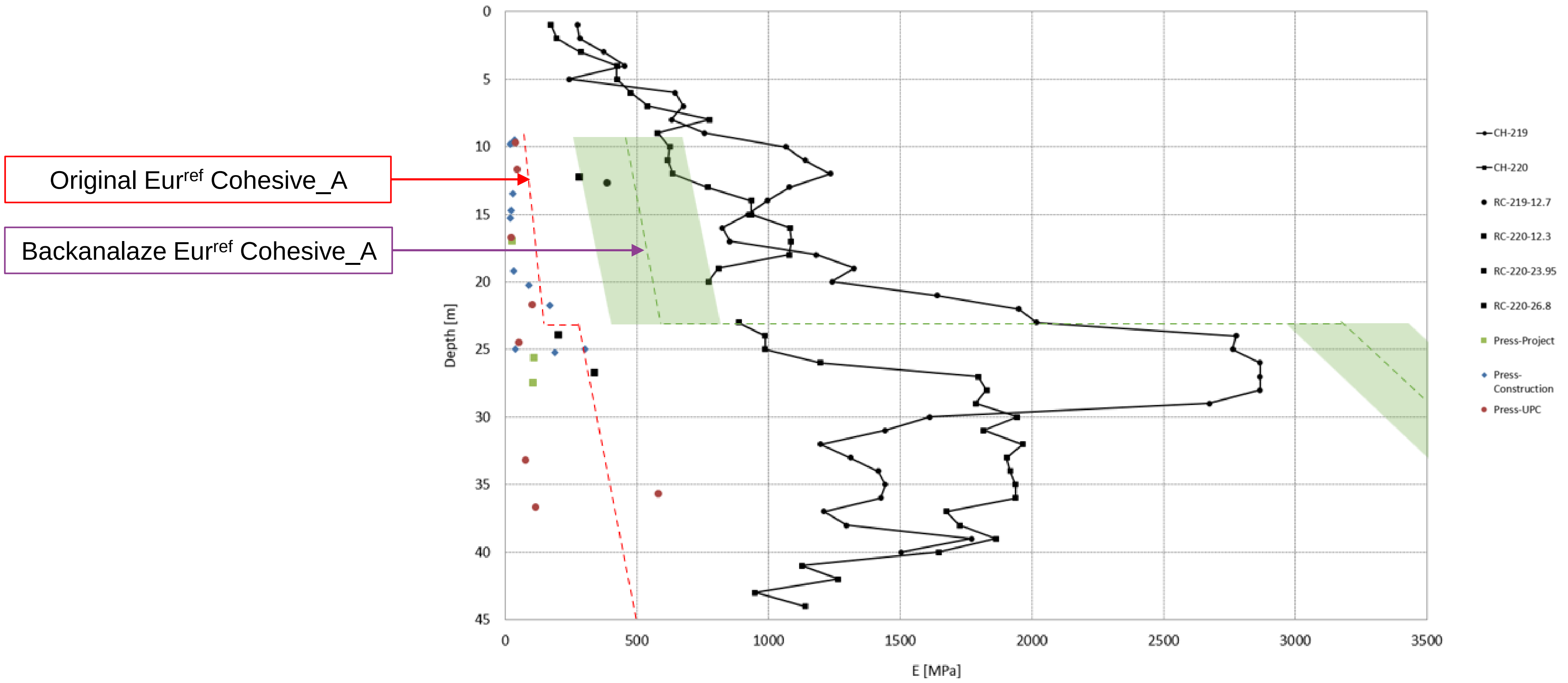


- Back analysis aim to match monitoring data at two dig stages
- Buffer zones indicate the possible monitoring data error – predictions from successful combinations within buffer zones
- Good match is obtained from back analysis
- Statistical optimal values ± standard deviation presents the possible range of 'best estimated' parameter values

R.T.B.A. – SAALG's DAARWIN

Comparison of Geo Parameters – original vs back-analysis vs G.I. data

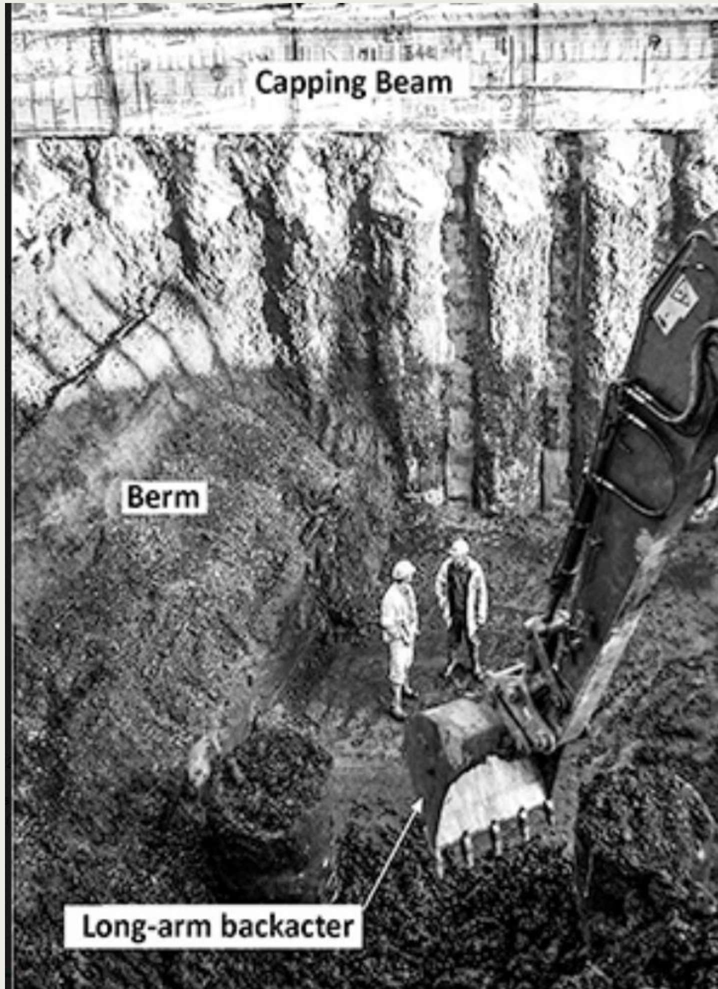
The back-analysed stiffness (Eur^{ref}) is closer to the values obtained from the Cross-Hole tests



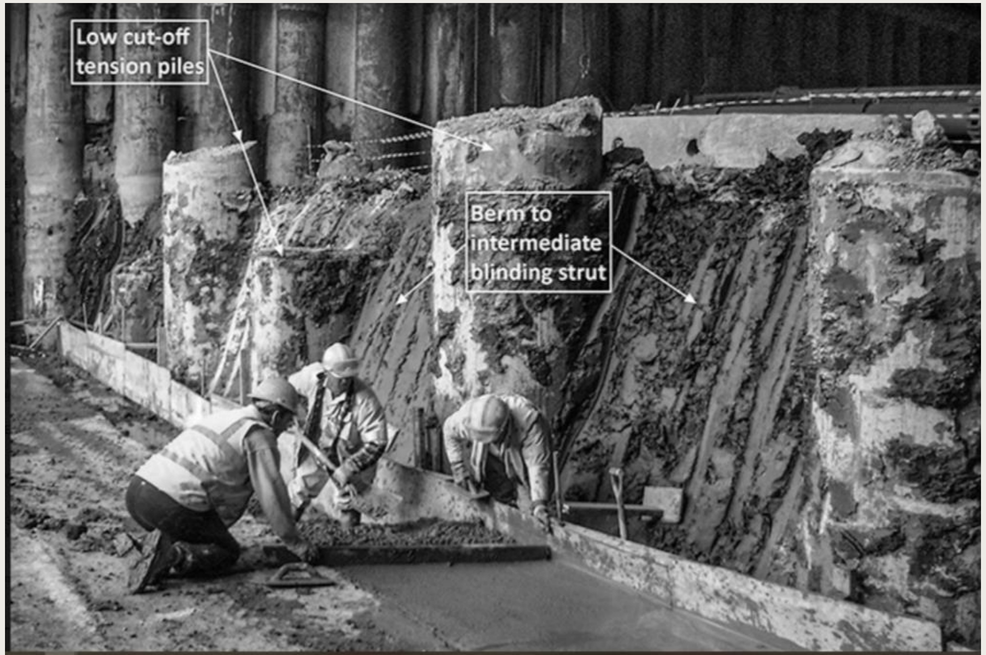
R.T.B.A - Some influential factors

3D vs 2D

- Construction – typically highly 3D, eg longitudinal berms + short (c 10m long) excavation bays
  - NB – if analysed as 2D this would NOT work!
- Base slab + blinding strut – cast in “previously excavated” bay
- “Future” bay to be excavated – supported by stiff capping beam + unexcavated ground



- 3D geometry varies during construction



R.T.B.A. – Some influential factors

Time, Arching, Non-linearity

TIME effects

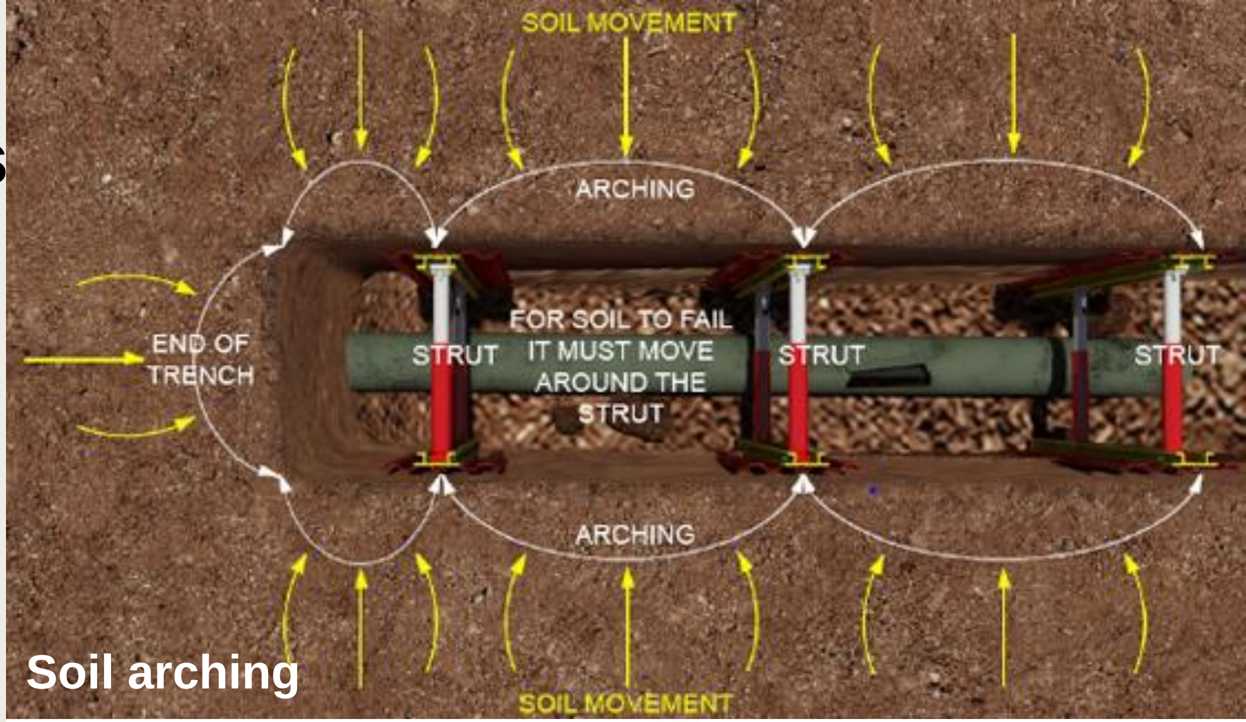
- actual durations for critical stages, may vary days to months. For clays/mudstones – undrained?, sands – drained? Reality affected by partial drainage (fn of permeability, construction rate, boundary conditions) and strain rate

Arching (ground-structure interaction)

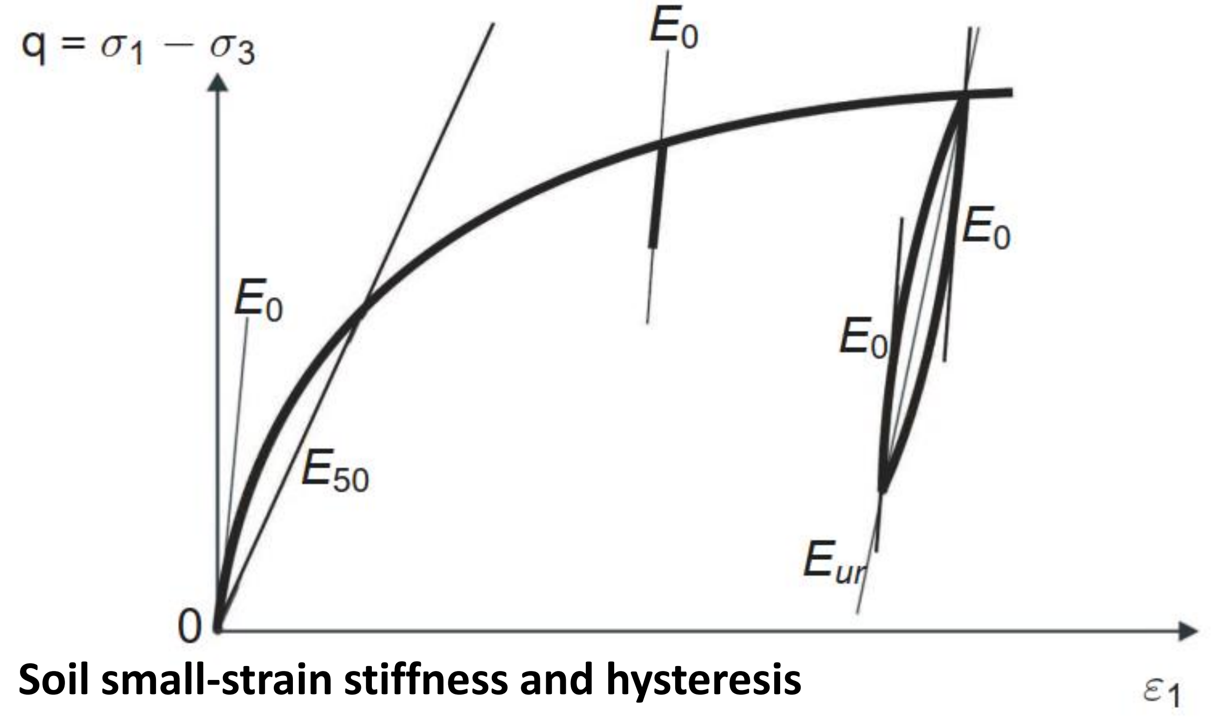
- loads follow stiffest load path, (applied earth pressures lower than assumed), this effect interacts with 3D effects. Ground hysteresis applies during multiple construction stages

Non-linear ground stiffness

- Potential for acceleration in movements as ground becomes more highly stressed. If simple models used for back-analysis, later stages may be under-predicted!



Soil arching



Soil small-strain stiffness and hysteresis

A way forward for creating more opportunity for The O.M.

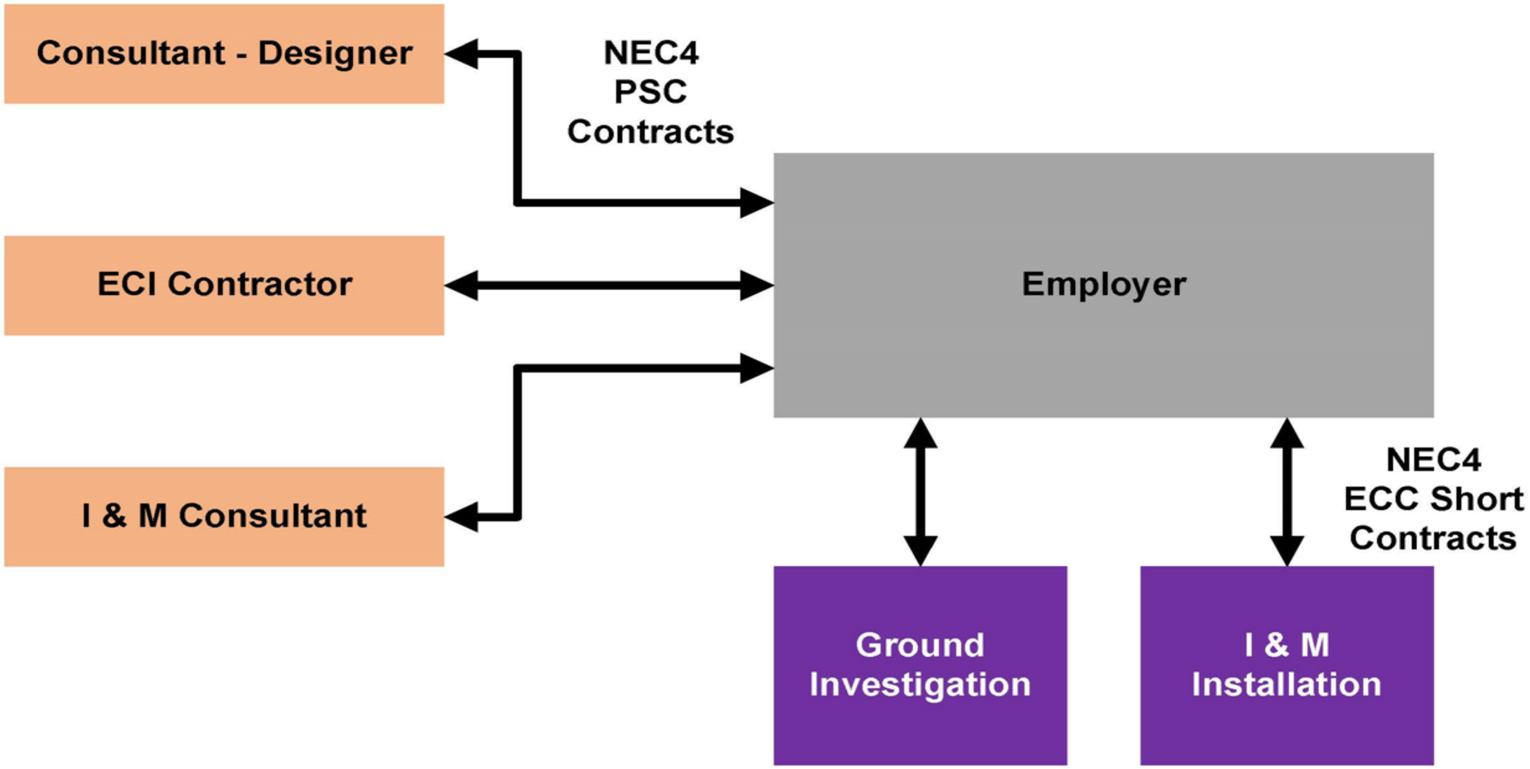
- Contracts- eg NEC4, NEW Cl 16 for Value Engineering + X22 for E.C.I.
- Achieving Agreement to use the OM – needs determined experienced pragmatic advocacy
- Use of Progressive Modification – caters for RISKS + OPPORTUNTIES
- Design Assurance – Verification Process
- Multi-disciplinary inputs (structural + geotechnics)
- Better I&M – technology getting better, real challenges are procurement/organisation/recognising value
- Real-time Back-analysis – combined with modern I&M, potential for step-change in understanding

Early Contractor Involvement (aka Progressive Design/Build), Stage 1

Opportunity – developing OM ideas + early I&M installation (eg existing infrastructure)

- **More time than conventional D&B**
- **Develop value engineering ideas (Cl 16), such as OM (better understand benefits, eg time savings)**
- **Develop relationships + trust across the whole project team**
- **Better understand value versus cost**
- **Stage 1 outcome = agreed scope, risk allocation, time + price for stage 2**

NEC 'Design' Contract, ECI Stage 1, possible arrangement

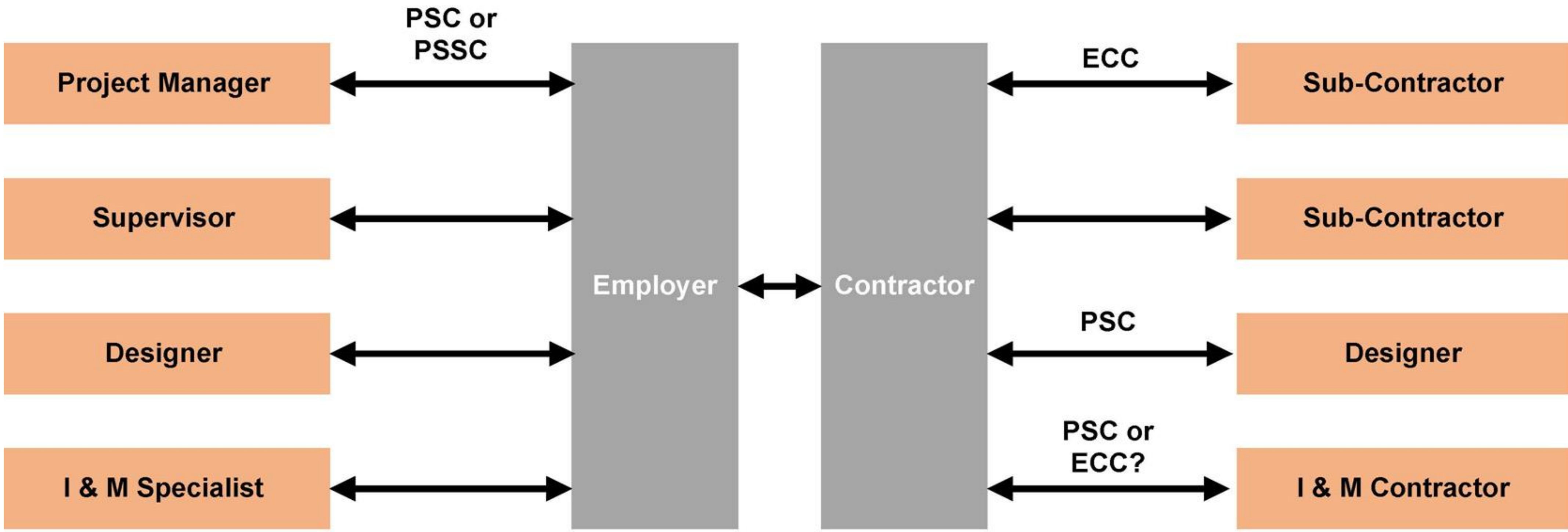


Early Contractor Involvement (aka Progressive Design Build), Stage 2

Stage 2 - implementation

- **Stage 2 – similar to normal contract**
- **If OM, then designer + contractor form a site-based OM team, develop RACI + method statements**
- **If OM then Checkers need to be aligned on OM + approvals/assurance**
- **Instrumentation – VITAL for OM. I&M data man't system under employer. I&M in field – handover to Contractor (?)**
- **I&M – employed on professional service basis (best value)**

NEC ECC ECI Contract, Stage 2, possible arrangement.



O.M. - Key factors in achieving agreement

Typically - the most difficult aspect of any OM !

If Contract OK, then

- Stakeholders: O.M. needs clear + simple explanation
- Risk perceptions can vary wildly, identify common basis for moving forward (time savings, improved safety)
- Design Assurance, becoming more complex!
- Contingencies: simple, quick, robust

Factor	Issues	Comments
Convincing Business Case	Practical benefits need to be clear and communicated to stakeholders	May include costs, time savings, safety improvement, technical risk reduction. Advantages need to be compared against conventional base case.
Sound Technical Basis	Often OM involves some form of ground-structure interaction, either new build or existing infrastructure, or both.	Both geotechnical and structural aspects need to be understood. Hence, multi-disciplinary input + competence required. Must be evident to stakeholders.
Risk Management	Maintaining + demonstrating an acceptable level of safety is essential. A wide range of risks need consideration, both technical + commercial.	Perceptions of risks can vary across different stakeholders, OM practitioner needs awareness of these and appropriate mitigations.
Trust	Critical for any OM application.	Trust has to be earned + requires time + good interpersonal relationships.

O.M. - Limitations and potential solutions

Time

- a key factor, both in obtaining + interpreting the key observations, AND in implementing contingency measures

Simplicity

- essential to ensure clarity + quick decision making (all parties understand roles/responsibilities)

Progressive Modification

- incremental changes from conservative basis, closely track observed changes in trends (implement beneficial modifications)

Real-time monitoring + back-analysis

- supports implementation, used wisely then deeper insights (but avoid data over-load!)

I&M

- quality **not** quantity

Limitation	Potential solutions	Comments
Inability to reliably obtain critical observation	Modify design solution or construction means/methods	Fundamental issue, OM cannot be used unless resolved.
Inability to implement timely contingency plans	Modify construction sequence, or schedule. Identify rapidly installed contingencies.	Fundamental issue, OM cannot be used unless resolved.
Vulnerable to progressive collapse or sudden failure	Modify structure, ensure potentially vulnerable components are more robust.	Fundamental issue, OM cannot be used unless resolved.
Lack of stakeholder support – existing asset owner and independent checker	Careful explanation of the OM; consider use of progressive modification / verification process. Showcase relevant case histories. Set up Expert Panel, with experienced OM practitioners. Introduce a strong interface manager.	Gaining support can be a major challenge. However, can be resolved with: experienced input; determined advocacy; detailed evaluation of relevant scenarios. Multi-discipline inputs (geotechnical + structural) commonly required.

Why Important – Future, DIGITAL TWINS

Better Outcomes

- Modern Instrumentation + monitoring
- Real-time back-analysis, eg SAALG's DAARWIN;
  eg HS2 technology trials
- POTENTIAL for another step-change in Geotechnics
- Asset Owners – basis for more sustainable future, more intelligent Digital Twin
- Greater use of OM with back-analysis
  - Better understanding of ground-structure interaction,
  - Improved safety
  - Stronger connection design to construction
  - Re-use back-analysis outputs in future designs, reduce over-conservatism in geotechnics

The information value chain: showing the connection between data and better decisions that lead to better outcomes

[The Gemini Papers - DT Hub Community (digitaltwinhub.co.uk)]

Conclusions

I & M

Can deliver huge value, but

Potential rarely delivered, due to:

Commercial alignment + motivation ?

Clarity + purpose ?

Perceived as trade activity

Basic errors (time, depth, location)

The OM can deliver:

Enhanced safety; significant time + cost savings

A wide range of applications, including some of the world's most sensitive structures

But – under-used currently (contracts, culture, design assurance)

Conclusions

The OM and I&M

Contracts – modern standard contracts (NEC4 + FIDIC) include: "Value Engineering clauses", potential game-changer (esp with E.C.I.) for better commercial alignment + use of The OM

Design Assurance – The Verification Process + use of OM through Progressive Modification. RTBA supports use of Verification Process

I&M Procurement – needs to change, pro-active use of high quality I&M can create immense value. Industry guidance is needed.

New technology RTBA, eg SAALG's DAARWIN connects and centralizes key data, facilitates rapid analysis of observed behaviour. Supports OM + knowledge management for geotechnics. Skilled interpretation of outputs still needed.

Technology is available for better project outcomes. Can we effectively advocate for a change in contracts + procurement?

Acknowledgements

Colleagues on ISSMGE TC206, especially Contracts sub-group

MM Colleagues, in particular: Imran Farooq; Hock Liong-Liew; Ying Chen, Echo Ouyang; Rob Talby; Nigel Pye; Ringo Tan.

Thank you

anthony.obrien@mottmac.com