Lessons Learned Reviewing Monitoring data

- Crossrail Excavation Case History Monitoring Data

Monitoring Group Presentation – 15 July 2025

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Outline

- Peck's Rankine Lecture - Monitoring Requirements for OM
- Monitoring Data Review Guidance
- Crossrail Data from Excavation Case Histories
  - ➢ Inclinometer (e.g. IM / IPI/ Shape-Accel-Array)
  - ➢ Piezometer
  - ➢ Extensometer
- Crossrail TCR-WTH temporary prop monitoring – strain gauge
- Summary & Discussion

Peck’s Rankine Lecture (1969)

“The results of the observations must be reliable [1]. If we have adopted the observational method as the final basis for the design and if the observations fail, our plight may well be desperate. Regrettably, far less thought is usually put into the planning of the observations than is needed. Far too much dependence is placed on reports of the successful performance of instruments [2] that are in reality almost untried under field conditions or have actually failed or given erroneous results in most installations.

To a large extent this unfortunate situation arises because those who see the need [3] for the measurements and who plan the programme are not themselves personally experienced in installing, observing and maintaining various types of instruments under a variety of conditions and for a number of years. Whoever plans an installation of any complexity will need all the skills that can be developed only by years of experience in actually installing and observing field measuring equipment.

The repots containing the results should be regarded as working documents, issued whenever the information needs to be brought up to date [4]. Unfortunately, there is a tendency to accumulate data until an elaborate, fully documented final report can be prepared. Not infrequently less thought goes into the significance of the data [5] will respect to design and behaviour than into the mechanics of production of the document, and observations are made to fill gaps in a table rather than to provide understanding when significant events occur……”

Monitoring Data Review Tips

- Empirical correlations - a general guide to check data

  e.g. Max $\delta_{displacement}/H_{excavation}$ = ~ *0.05% to 0.4%*

- Reliable Observations – dependent on good understanding of instruments and data

  e.g. Installation issues / potential errors in data.

- Imperfection of data

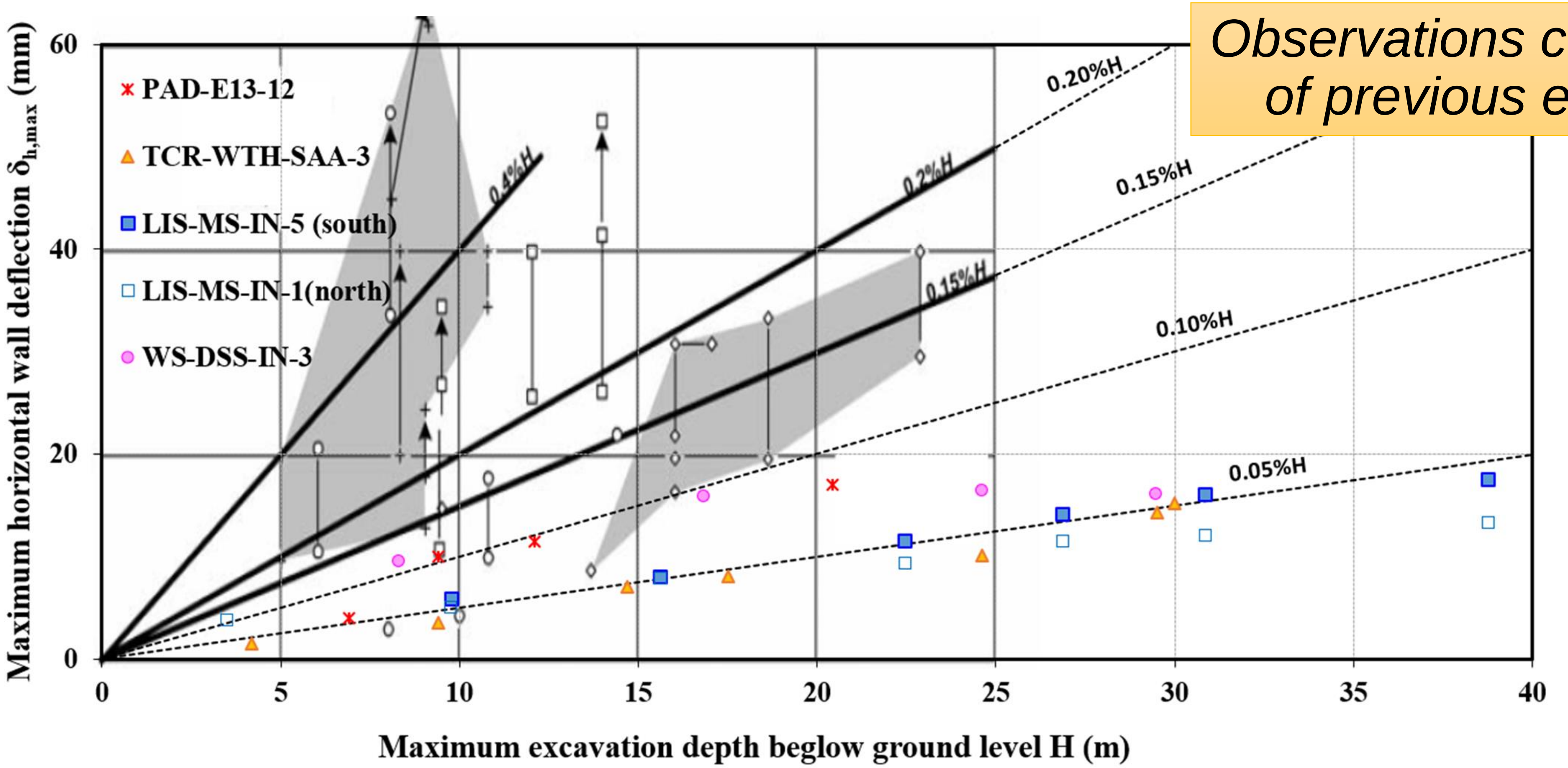
  Observation error diagnose, take account errors in the back analysis.

Empirical Correlations - London Clay

- London Clay Stiffness E_u/c_u = *750 ~ 1000 (Ciria 760)*
- Wall installation Max δ_z *(Ciria 760)*
- Wall deflection Max δ_H/H_e = *0.05% ~ 0.10 % (Crossrail / Hugh St. John)*
- Ground surface settlement Max $\delta_z/H_e \leq$ *0.2% (Crossrail)*
- Strut force envelope *(Twine & Roscoe / Peck)*
- Piezometer response - undrained behaviour
  - $\Delta u/\Delta\sigma_v \approx 0.4 \sim 0.6$ *(B bar)*

Wall Deflection / Excavation Depth

Observations can be outside of previous experience !



Note: 1. Paddington (PAD) station box inclinometer E13-12 data was reviewed by the monitoring contractor; 2. Whitechapel station – Durward Street shaft (WS-DSS) inclinometer IN-3 data refer to Mills (2016).

Reliable Observations

How different systems work:

- Inclinometers (IM / I-P-I / SAA)
- Strain gauges / load cells
- Piezometers
- Extensometers
- Levelling studs
- 2D/3D prisms/ station survey

(accuracy, reliability, frequency and installation & calibration)

Lessons learnt:

- Don’t accept face value – but review needs skilled monitoring engineer;
- Hard to validate/confirm after the construction completion – Real Time data is preferred.

Inclinometer – measure wall displacements

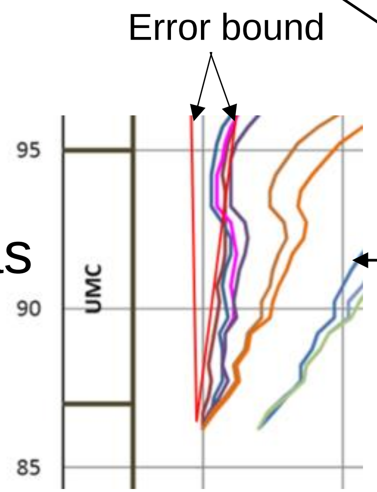
- Error embedded in data
  - Attempt to correct with prism data - less success (prism accuracy > +/- 2mm);

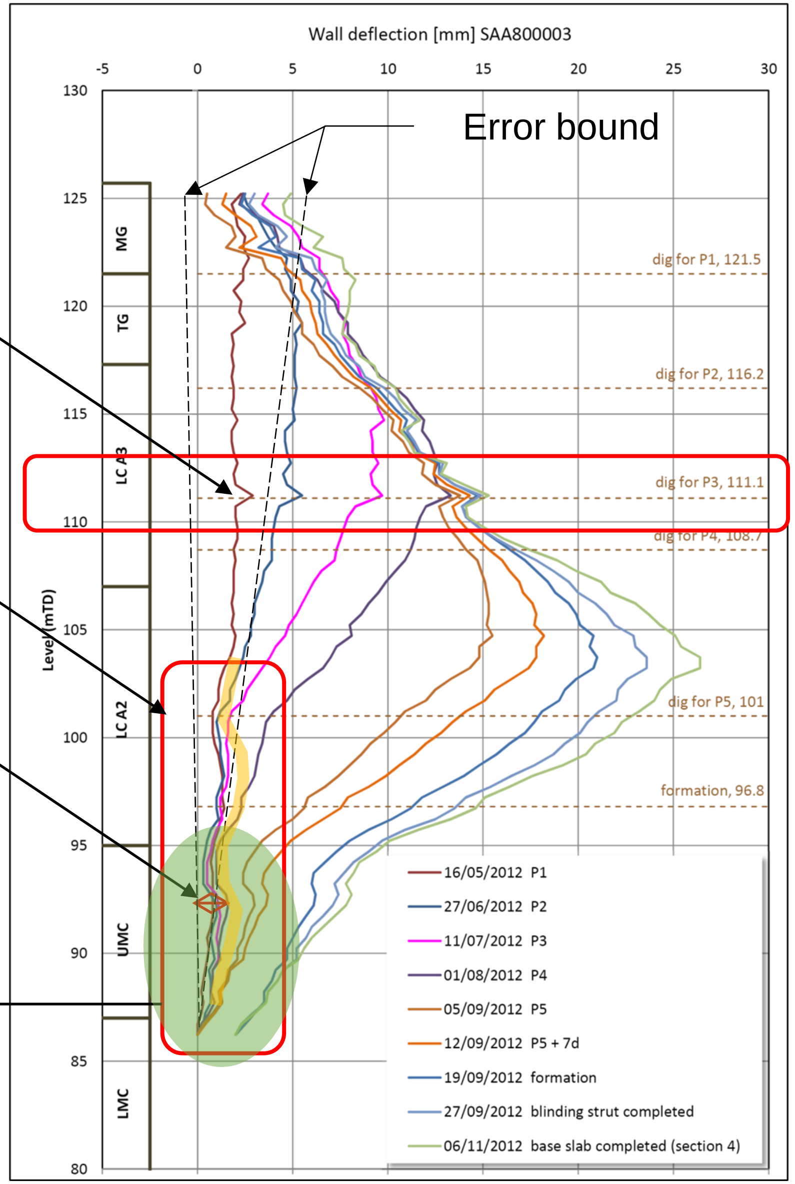
- Common errors:
  - Installation issue – short, alignment, casing curvature etc.;
  - Baseline reading establishment;
  - Rotational error.

- Diagnosis of data errors, and correction often occurred at post-construction stage – too late to make significant change to construction.

Crossrail Case 1 -TCR

- Anomalous displacements at +111mATD;
- Potential rotation error in the data between +90 and +100 mATD;
- >2mm displacements at +92.5mATD at early excavation stages;
- Bottom 10m measurements have exceeded the SAA random error bound as ±0.19 √N;

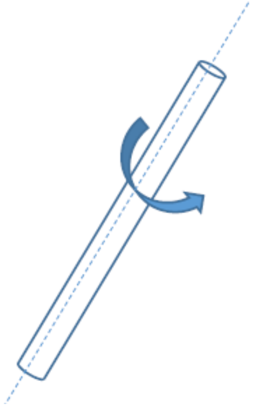




TCR – SAA80003 data corrected with prism data

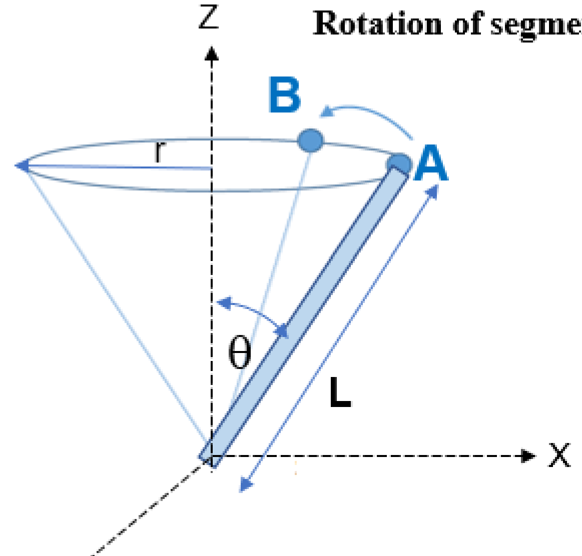
Rotational Error in Shape Accel Array

Rotation of segments



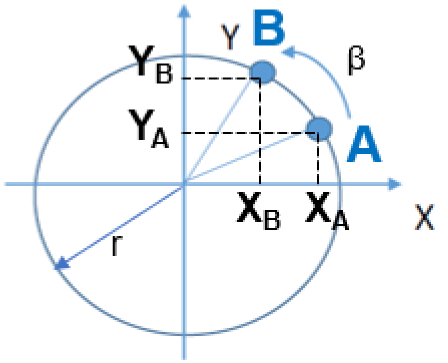
No change in tilt

Rotation of segments



No change in tilt

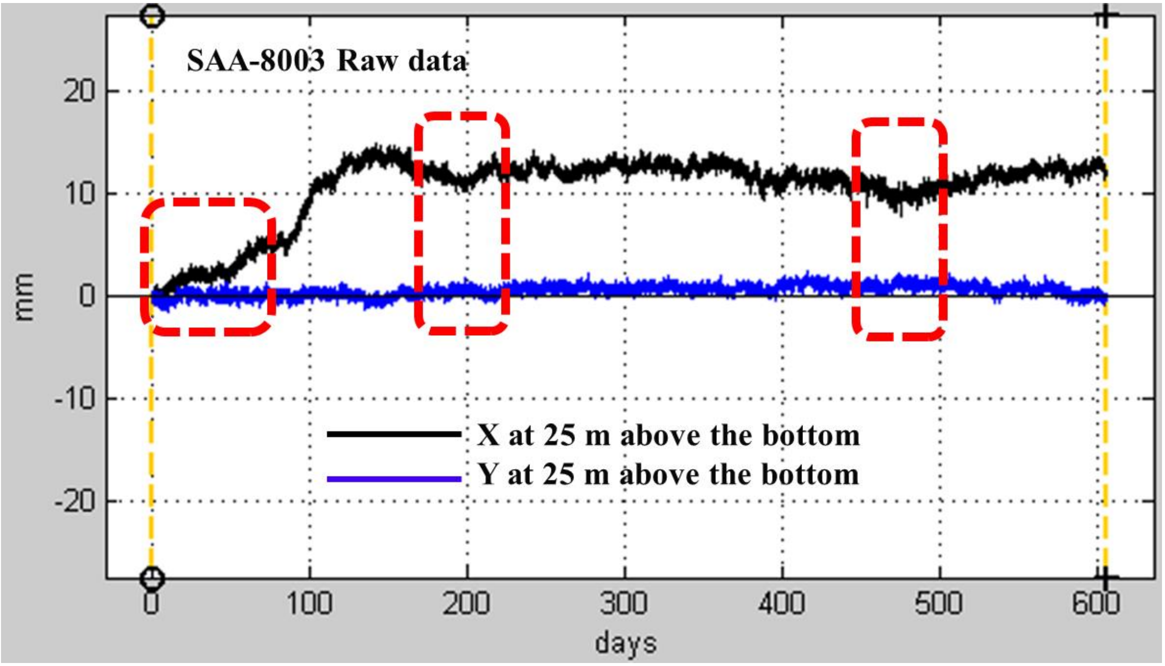
$$\tan\beta = \frac{Y_B - Y_A}{X_B - X_A}$$

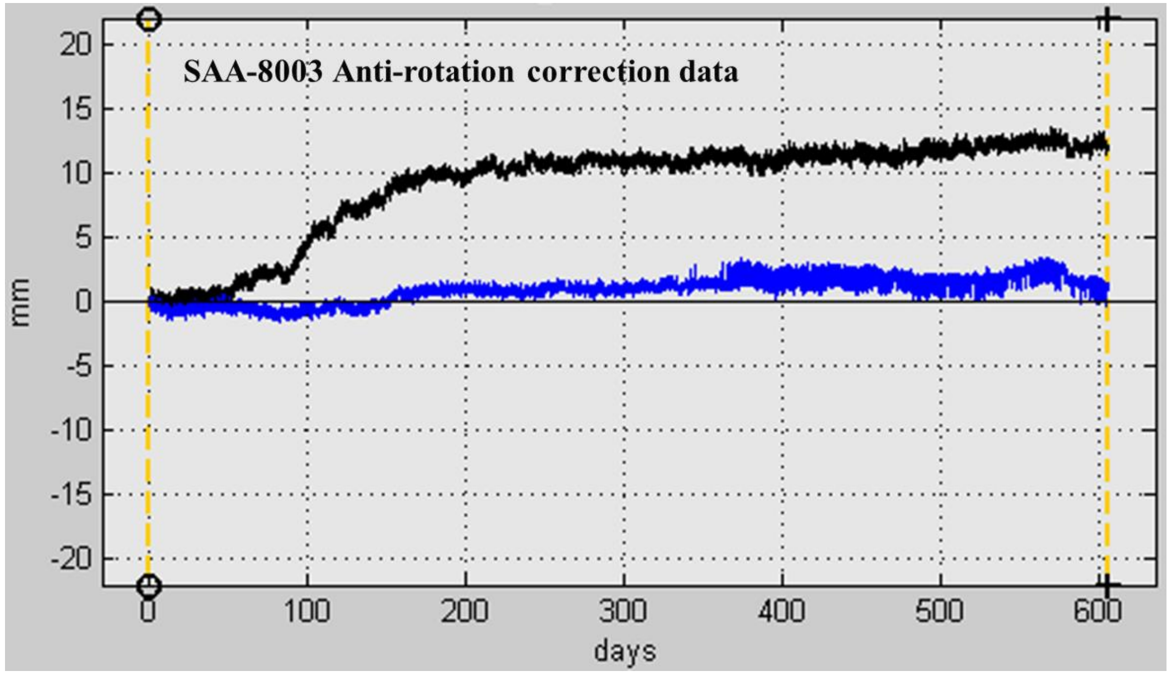


Looking down on the virtual cone

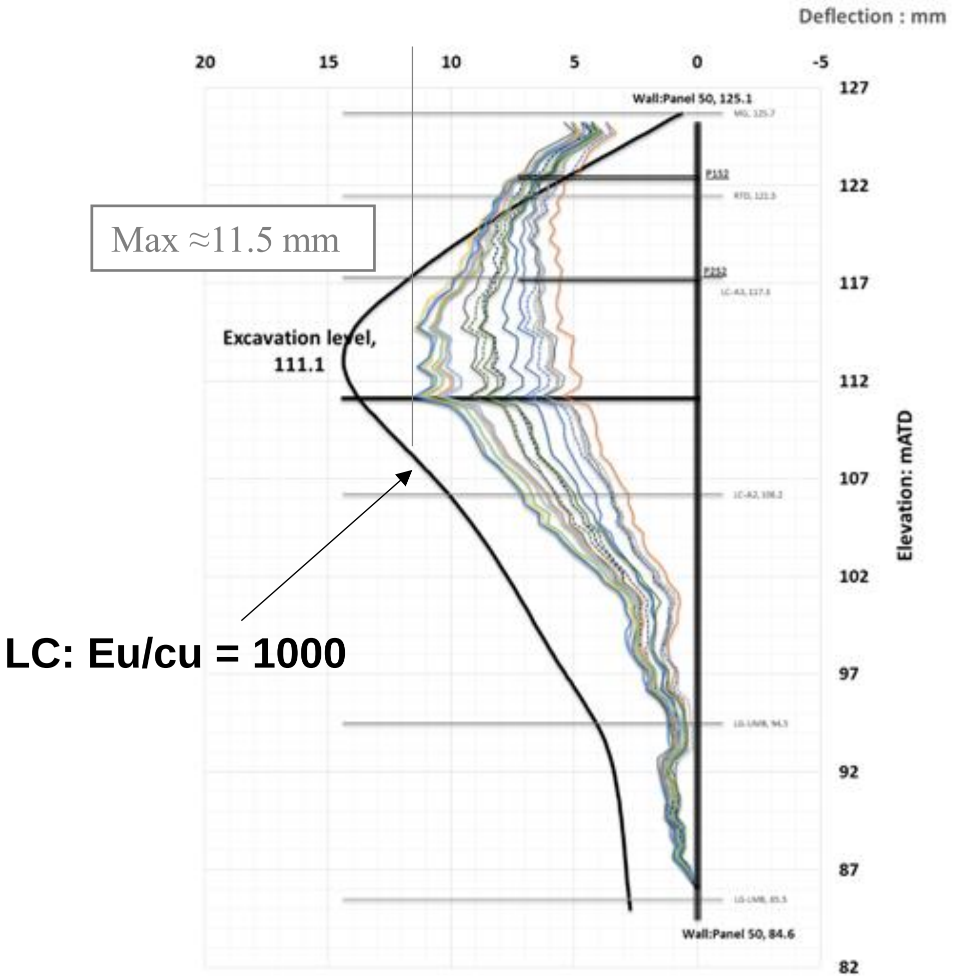
Rotational Error Correction for SAA

- Crossrail Case 1 –TCR: SAA80003 data

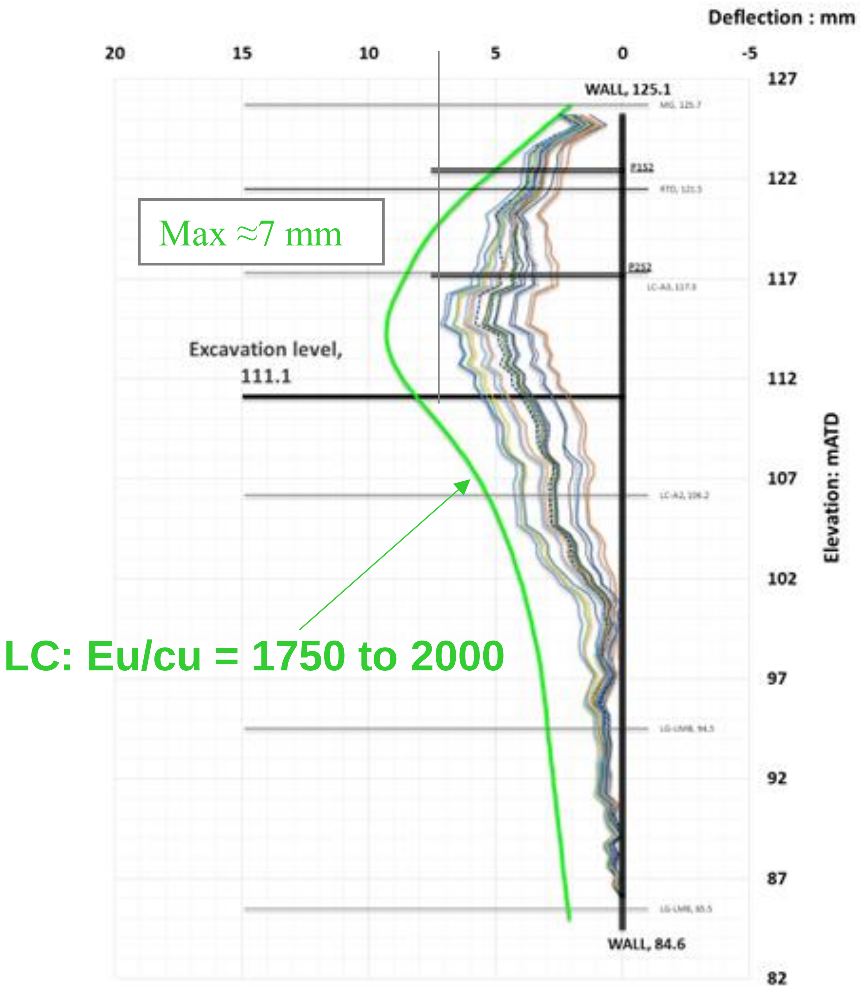




Crossrail Case 1 –TCR back analysis



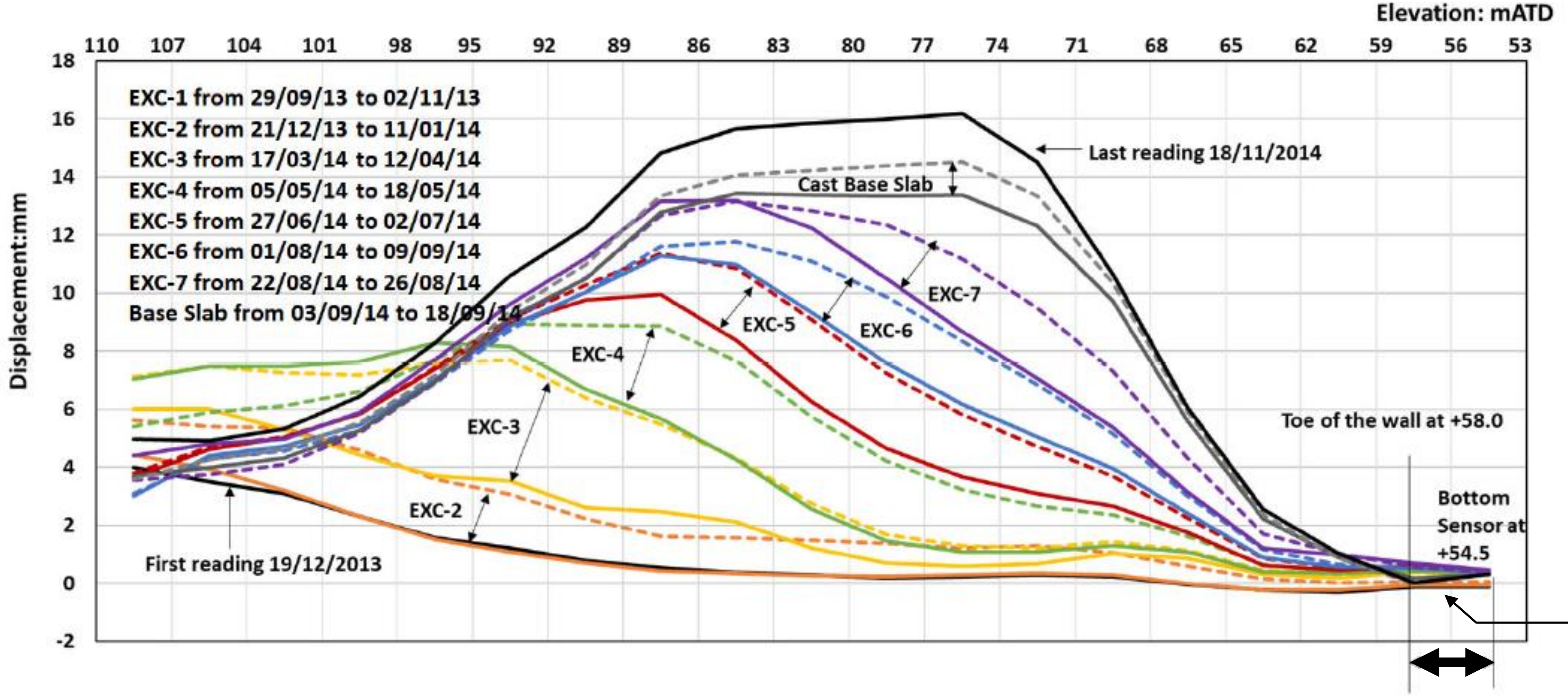
Back-analysis based on raw SAA data – As-built



Back-analysis based on 'reviewed and corrected' SAA data

Good Practice: Case 2 - LIS-MS

IE01 was installed a few meter below the wall toe level – fixity of wall;



repeatable reading: ≤ 1mm.

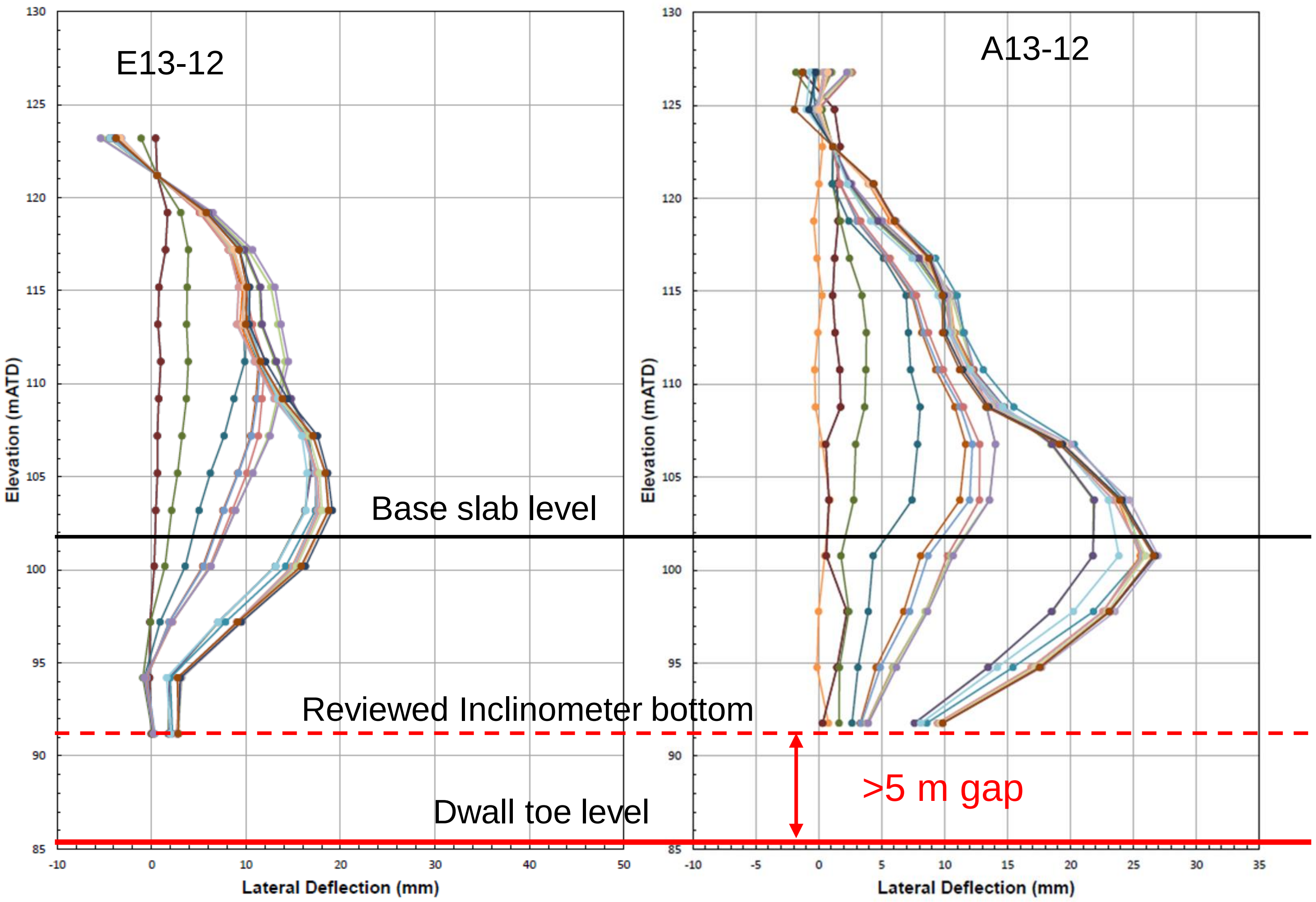
LIV-MS – IE01 data – X axis

Inclinometer toe is 3.5m below Dwall toe;

Poor Practice

Case 3 - PAD

- 42 Inclinometers installed for PAD;
    1) Initially Manual Inclinometers
    2) changed Inclinometer probes
    3) 21 nos replaced by In-Place-Inclinometer;
- Baseline of inclinometer data recalculated for each change – lost trace of data history;
- Correction introduced uncertainty in the wall fixity at toe level;



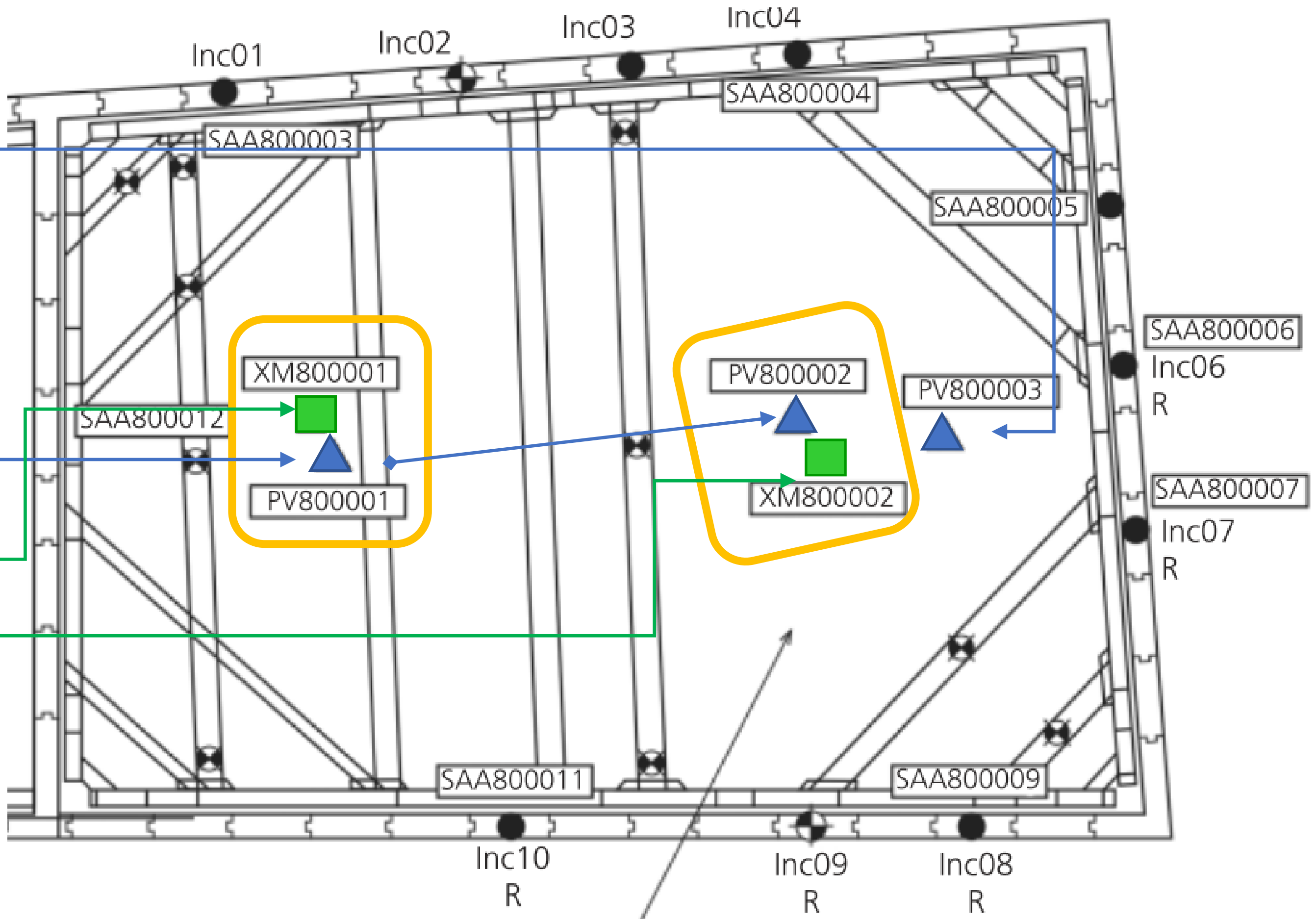
PAD inclinometer data: E13-12 vs A13-12 (Inclinometer close-out report)

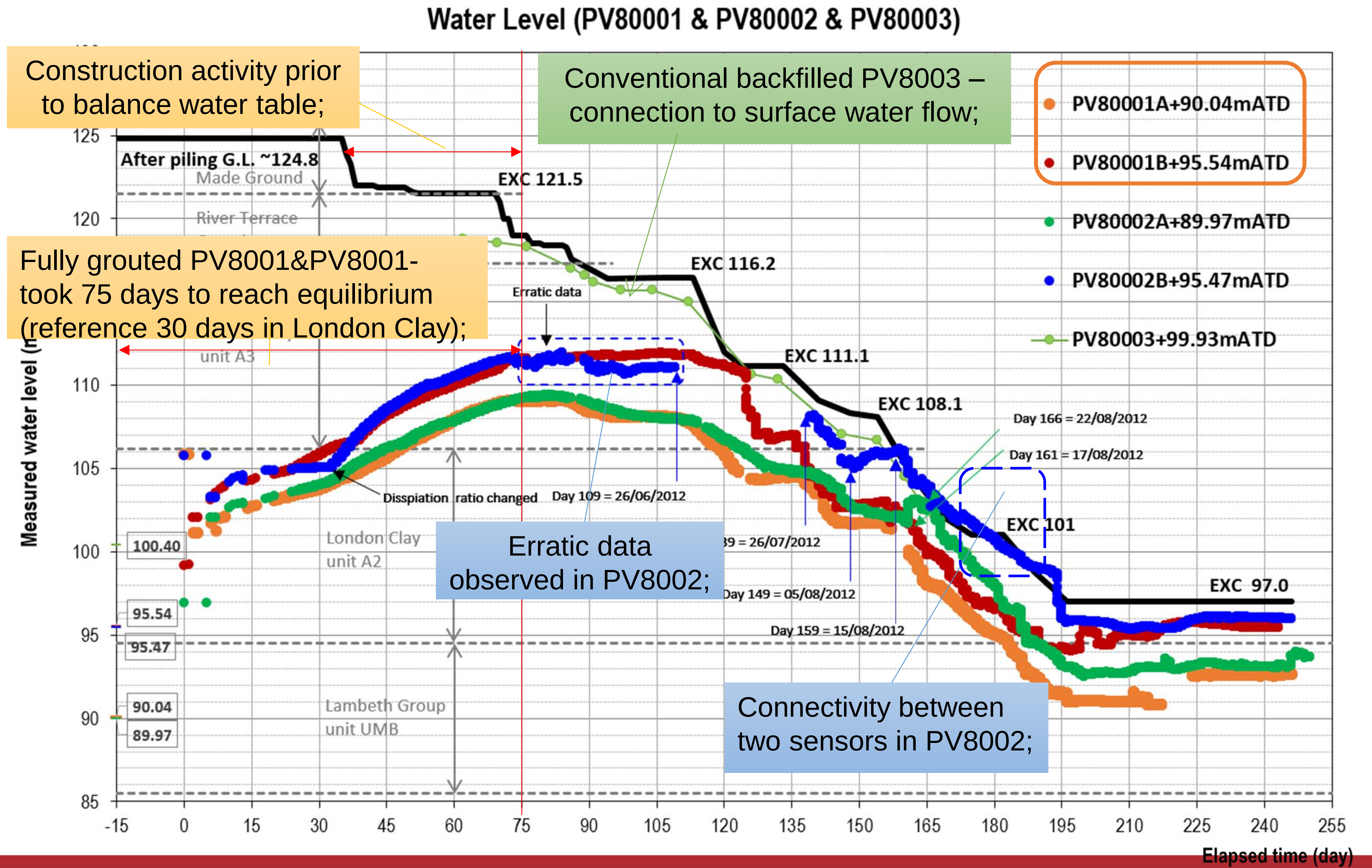
Inclinometer – Lessons Learnt

- Important to ensure the fixity of the wall, e.g. extended inclinometer below the wall toe if available.
- Have the cross-checking system, e.g., 2D/3D survey prisms, though different instruments, their data accuracy may be insufficient to validate inclinometer data.
- Installation needs trained technicians
- Plan the sufficient time for baseline reading, e.g., weeks ahead of any construction activity, subjected to contractual agreements.
- Real-Time data review is preferred.

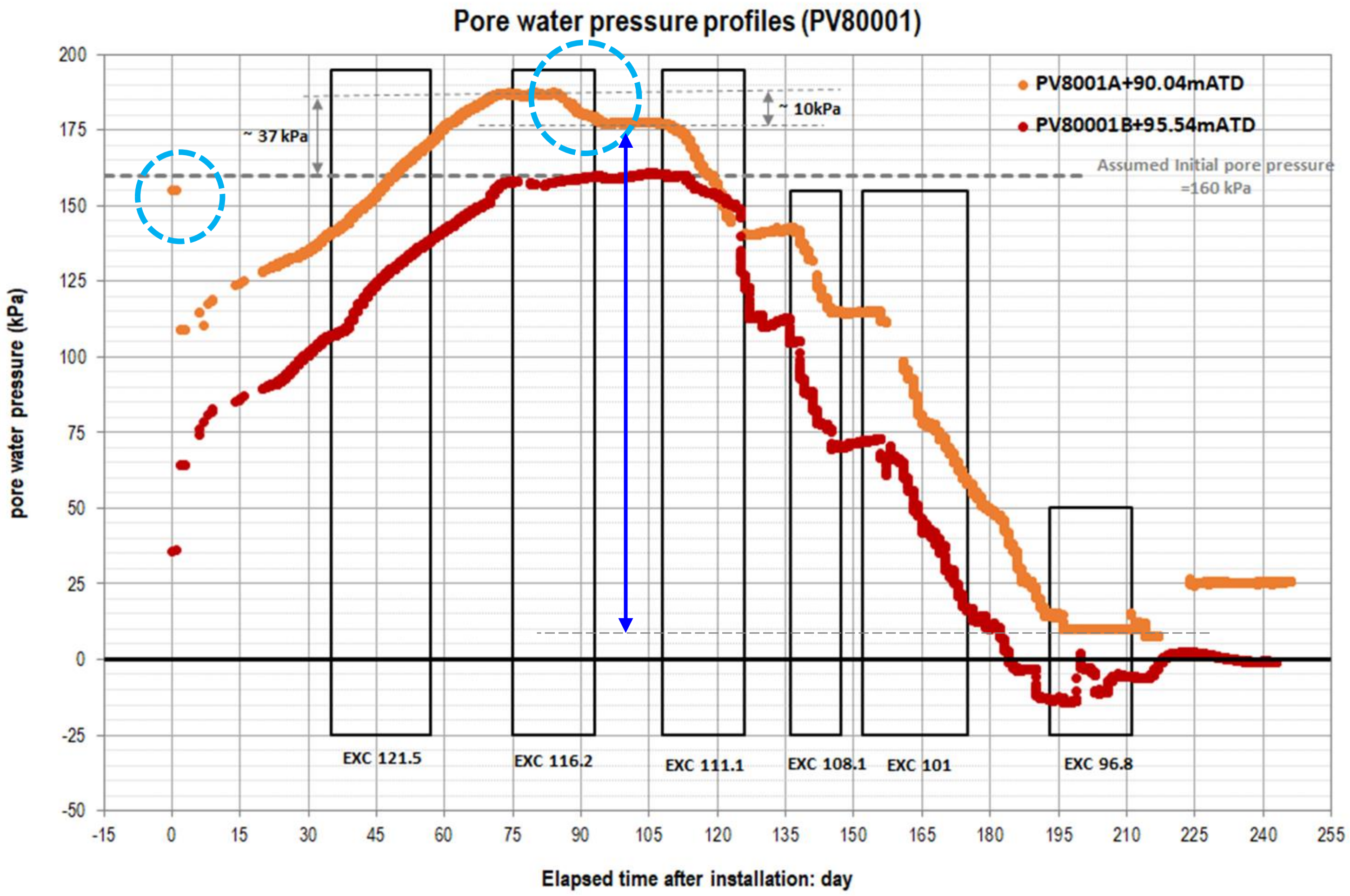
Piezometer: Case 1 - TCR

- Conventional installed piezometer
  PV80003
- Grouted multiple piezometers
  PV80001 & PV80002
- Extensometers (grouted)
  XM80001 pared with PV80001
  XM8002 pared with PV80002




Water Level (PV80001 & PV80002 & PV80003)
Construction activity prior to balance water table;
Conventional backfilled PV8003 – connection to surface water flow;
PV80001A+90.04mATD
PV80001B+95.54mATD
PV80002A+89.97mATD
PV80002B+95.47mATD
PV80003+99.93mATD
After piling G.L. ~124.8
Made Ground
River Terrace
EXC 121.5
EXC 116.2
EXC 111.1
EXC 108.1
EXC 101
EXC 97.0
Fully grouted PV8001&PV8001-took 75 days to reach equilibrium (reference 30 days in London Clay);
Erratic data
unit A3
Measured water level
Dissipation ratio changed
Day 109 = 26/06/2012
Day 166 = 22/08/2012
Day 161 = 17/08/2012
Day 149 = 05/08/2012
Day 159 = 15/08/2012
London Clay
unit A2
Erratic data observed in PV8002;
Lambeth Group
unit UMB
Connectivity between two sensors in PV8002;
100.40
95.54
95.47
90.04
89.97
Elapsed time (day)

PV8001 – Water pressure



TCR – PV80001 water pressure

- Calculate water level from strain value;
- Calculate water pressure by

  9.81* (WL-sensor level)

- Undrained behaviour, B bar example:

  $\Delta u/\Delta\sigma_v$= (175-10)/[20*(111.1-96.8)] = 0.58

  (ref. B bar as 0.4 – 0.6)

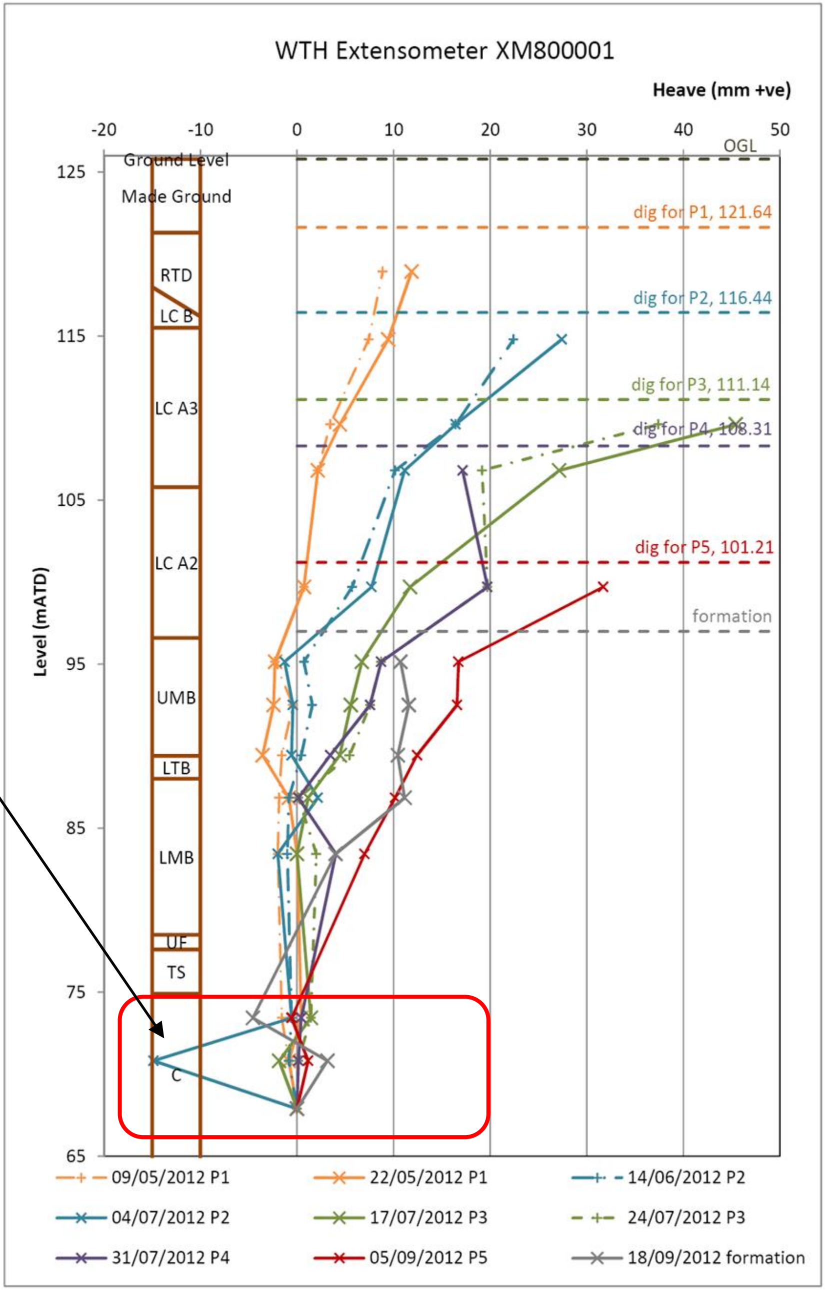
Piezometer – Lessons Learnt

- Careful sensor preparation and calibration is required.
- Installation: grouting or conventional backfill, no water path connectivity between sensors;
- Sufficient equilibrium period: allowing the water pressure to reach balance before the excavation and other field activity;
- Data interpretation is not easy.

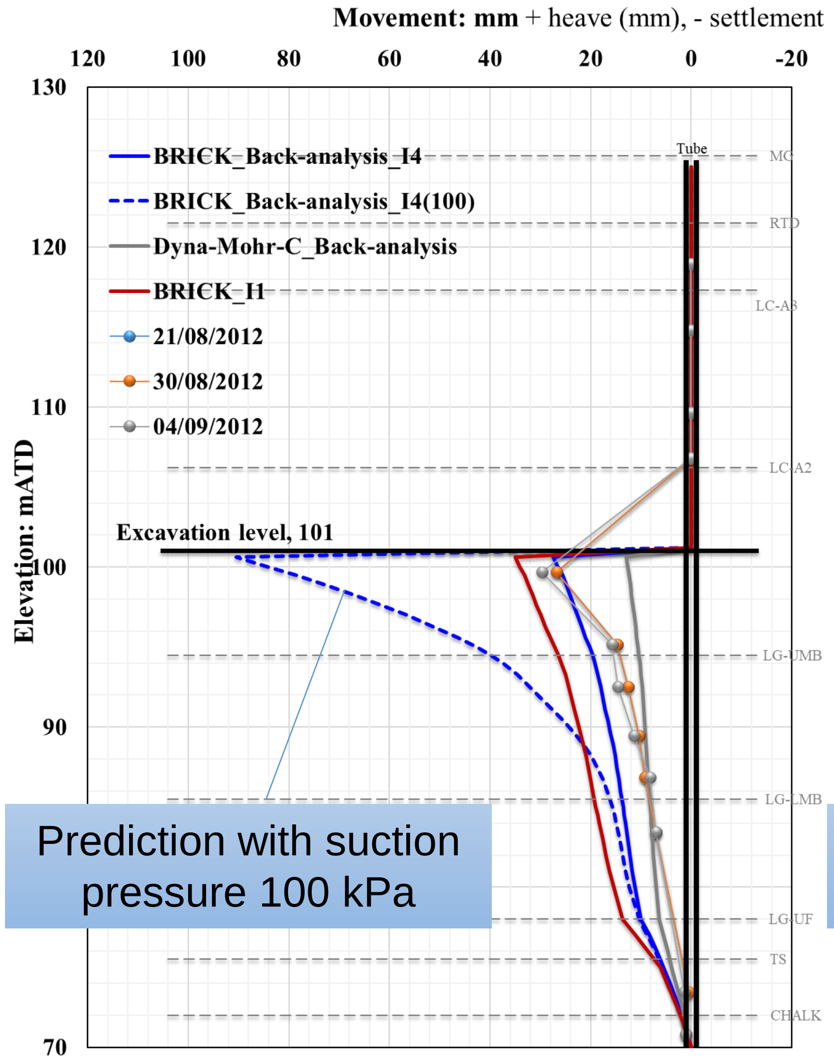
Extensometer

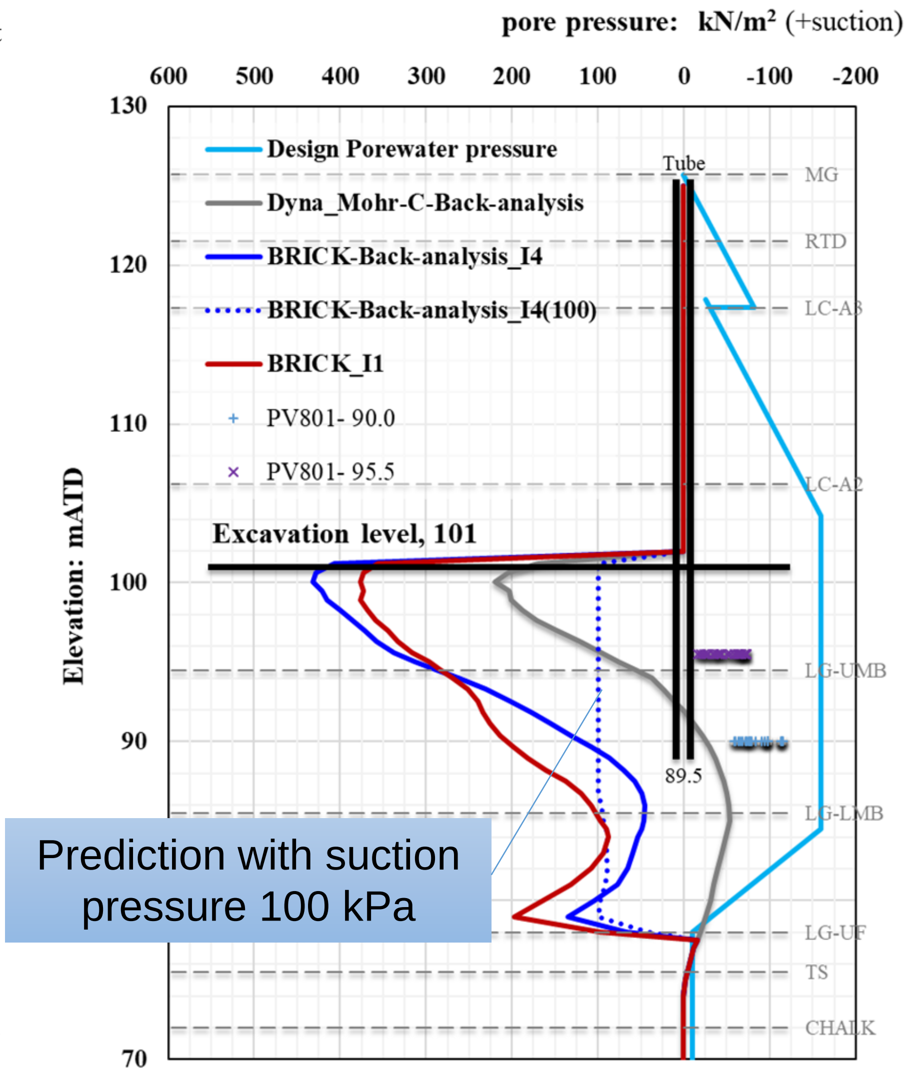
Case 1 -TCR

- Fixity of lower magnets in Chalk – cannot be moving?
- Varied measuring frequency – not capture when excavation occurred;
- Accuracy of data ?
- No validation reference data, e.g. survey trimmed casing;
- Data correction is not possible.



XM 8001 & PV8001 in back analysis (3D model)





Undrained behaviour - measurements Vs predictions

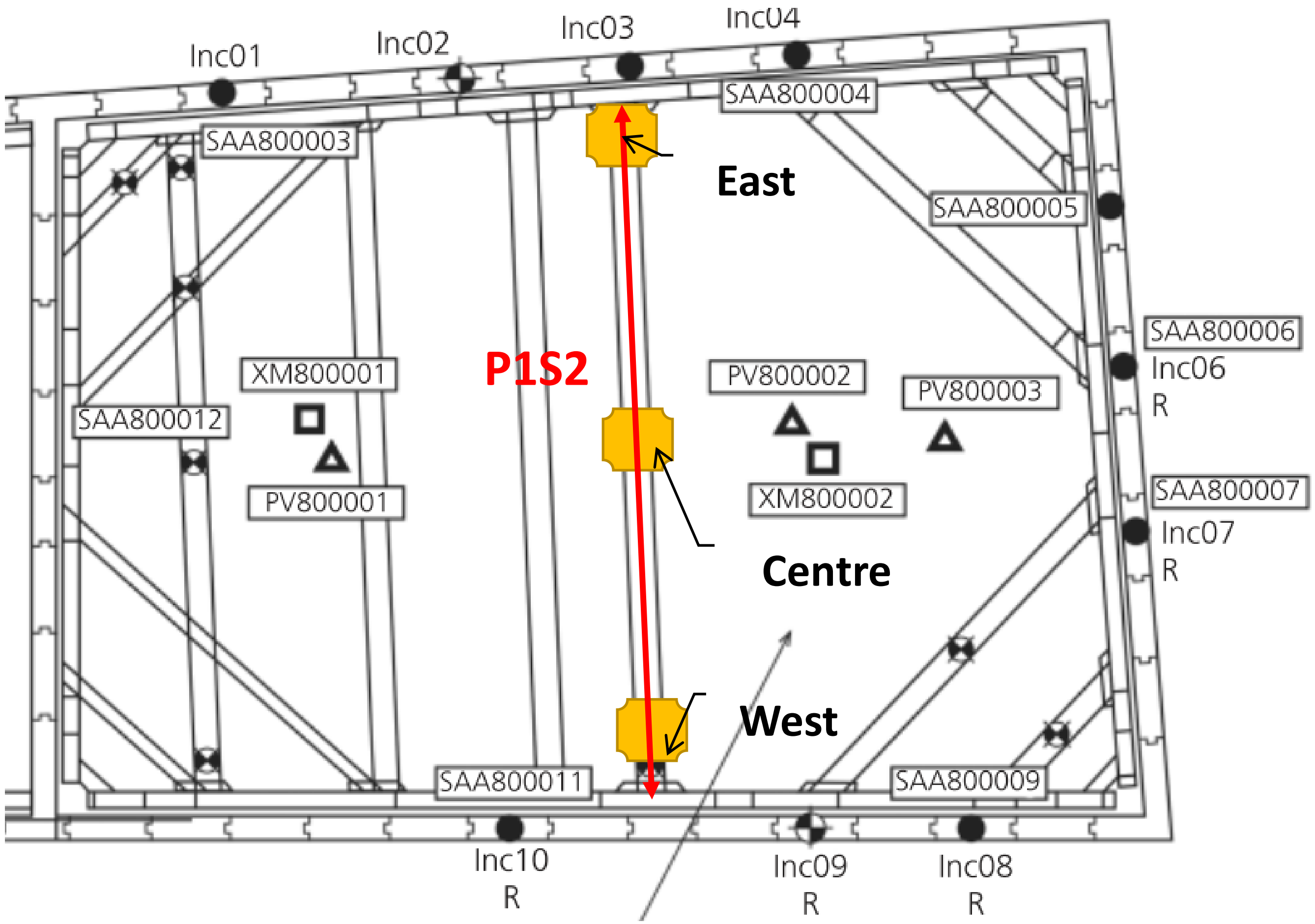
- Predicted heaves compares well with measurements by Extensometer.
- Predicted high suction pressures - not captured by Piezometer!

Extensometer – Lessons Learnt

- Installation in field
  - ➢ Grouting material stiffness in relation to the ground stiffness;

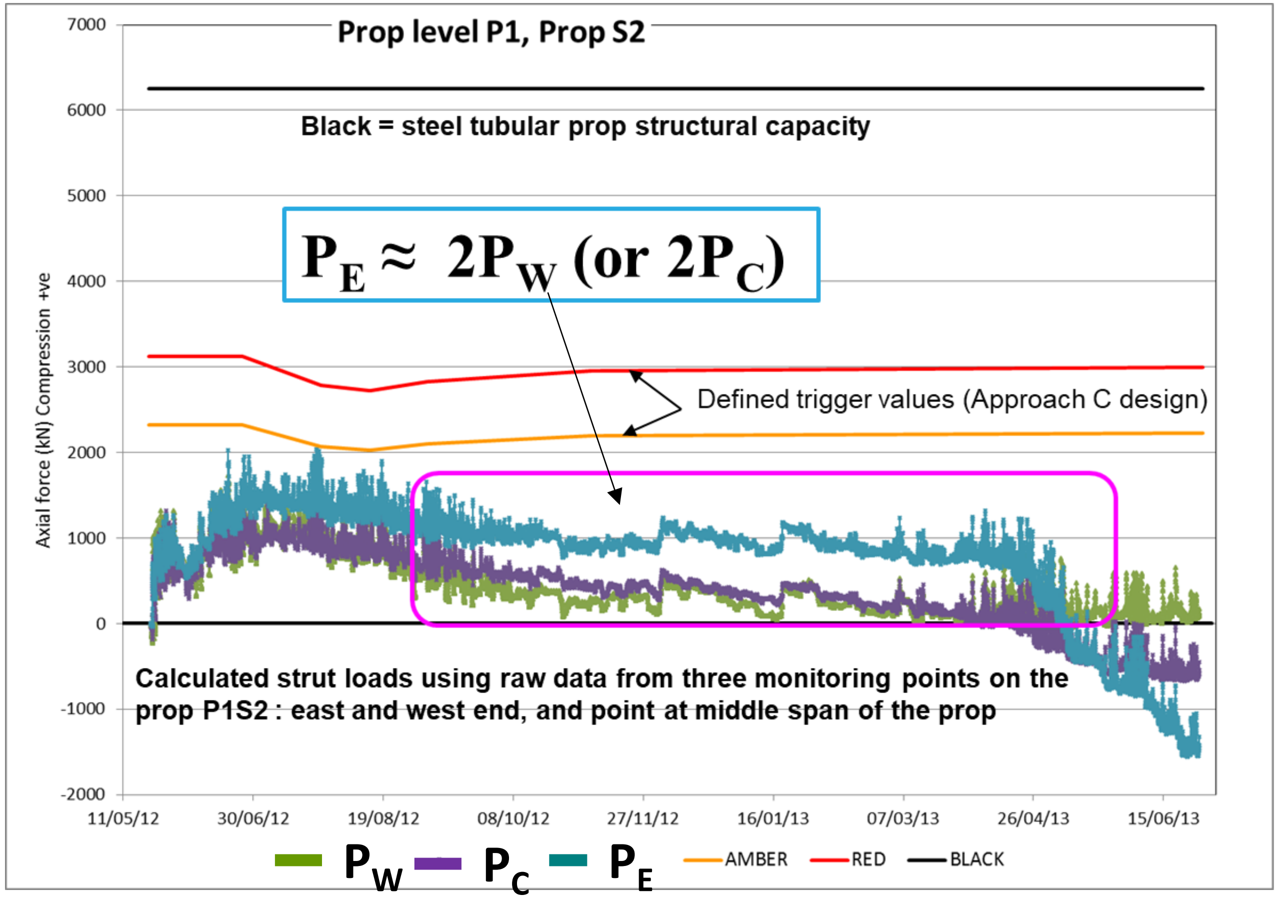
- Interpretation of data
  - ➢ Baseline reading establishment;
  - ➢ Continuing validation (e.g. survey the top of casing) to confirm the reference point level.

Strain Gauges: Case 1- TCR

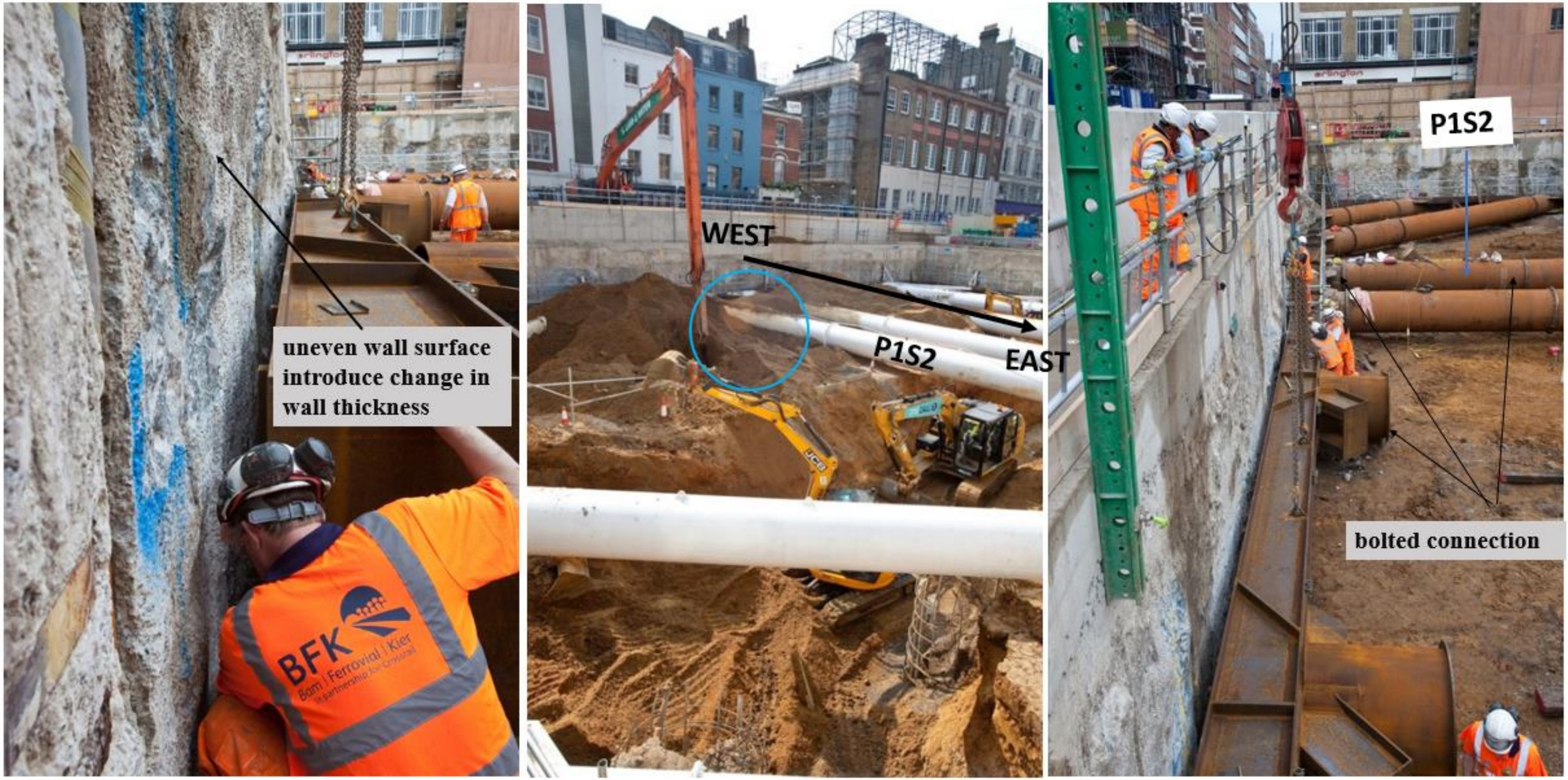


P1S2 Prop Force

- Prop force $P = EA\frac{(\varepsilon_1+\varepsilon_2+\varepsilon_3+\varepsilon_4)}{4}$ - no bending stress considered?
- Prop force measured from three monitoring points: $P_E \neq P_W \neq P_C$?
- Additional force locked-in during baseline reading establishment?
- Monitoring points close to the bolt or welding connection?



TCR Prop - P1S2 data


uneven wall surface
introduce change in
wall thickness
BFK
Bam | Ferrovial | Kier
WEST
EAST
P1S2
P1S2
bolted connection

(a) (b) (c)

Strain Gauges - Lessons Learnt

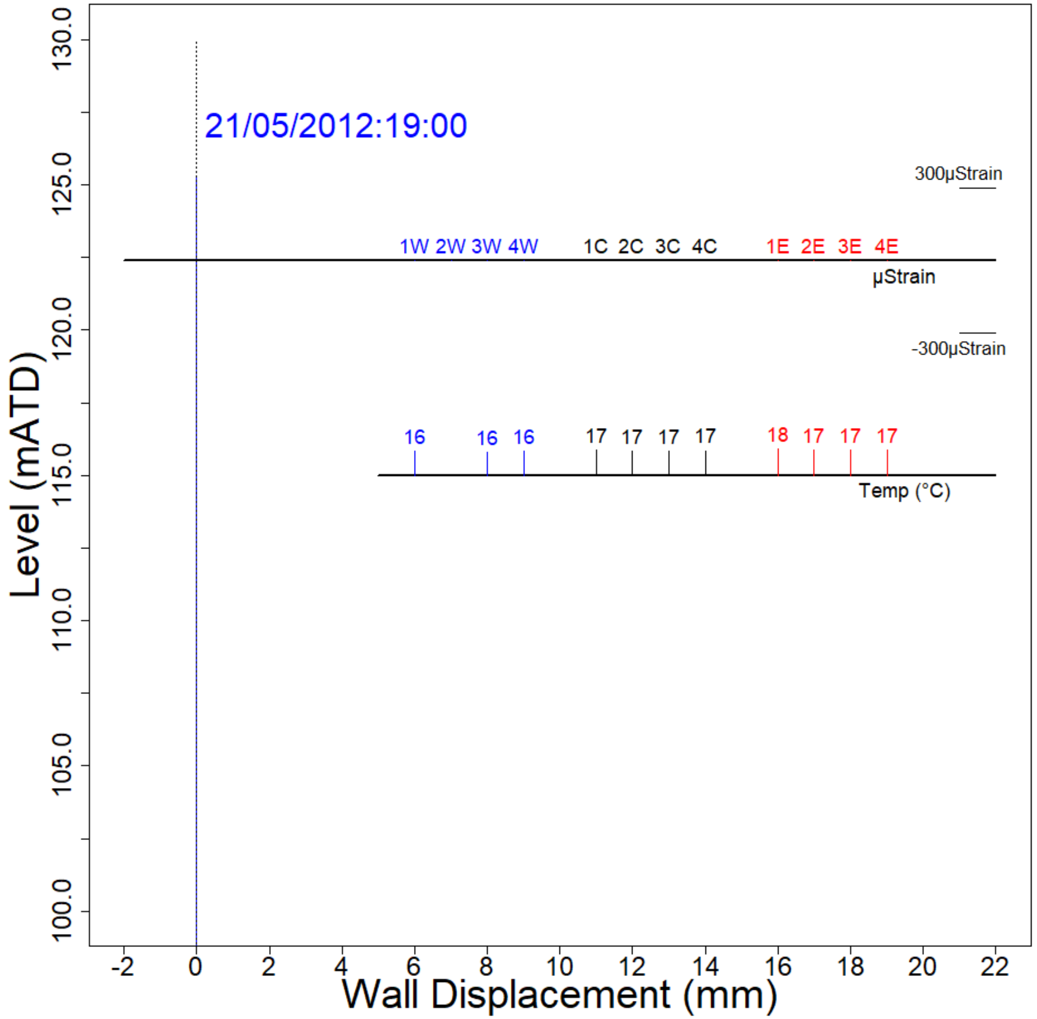
- Errors in relation to Installation:
  - Gauge numbers, position on the surface of prop;
  - Monitoring Points along a prop, and position should avoid too close to joints.

- Errors in relation to data interpretation
  - Baseline reading establishment;
  - prop can bend in vertical and horizontal plane;
  - Thermal effect, daily and seasonally temperature changes reflected in data (how to eliminate the thermal load from main prop force induced from excavation?

- Data continuity & Data processing

Temperature Effects on Props

Multi-propped retaining structure



Current Practice

$$Q_{\mathrm{k,temp}} = \alpha . \Delta t . E . A . (\frac{\beta}{100})$$ (CIRIA C760 Eqn 8.10)

where

$Q_{\mathrm{k,temp}}$ = additional load generated in prop that is restricted or prevented from expanding freely

Δt = change in prop temperature from installation temperature

α = thermal coefficient of expansion for the prop material

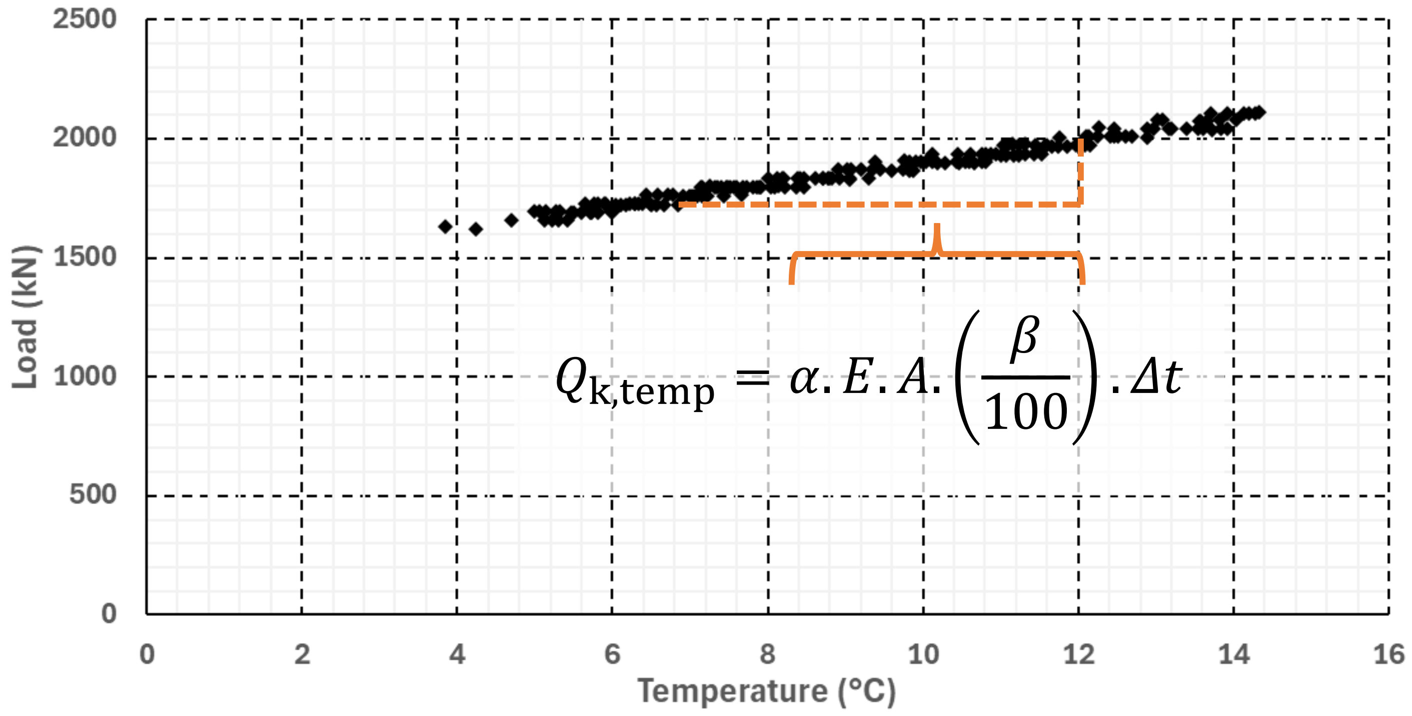
E = Young’s modulus of the prop material

A = cross-sectional area of the prop

β = percentage degree of restraint of the prop

Current Practice

Back analysis of β - example



$$Q_{k,temp} = \alpha . E . A . \left(\frac{\beta}{100}\right) . \Delta t$$

Richards *et al.* (1992)

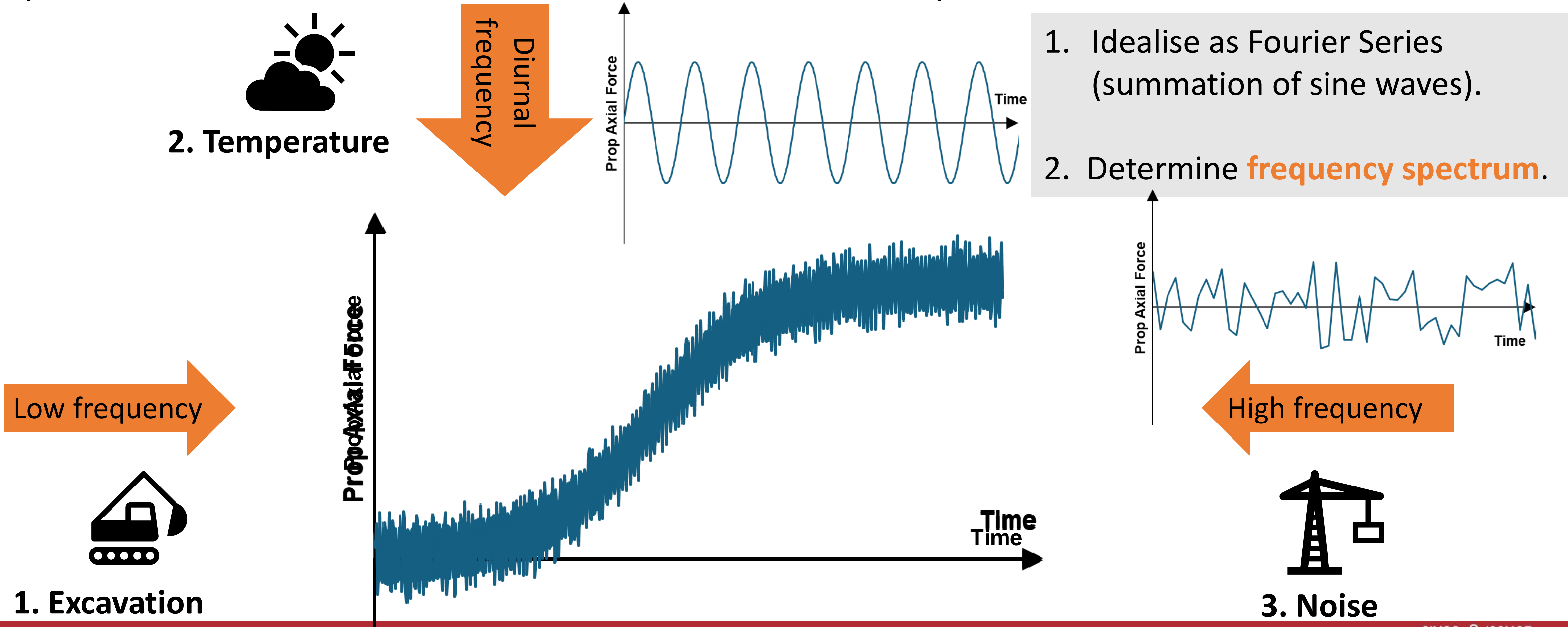
- Data recorded over a two-week quiet period.
- Construction activities will lead to wider scatter in data.
- Determination of β may not be straightforward.
- Also varies with depth.

New Approach

A conceptual model

Prop force can be viewed as a summation of several components:

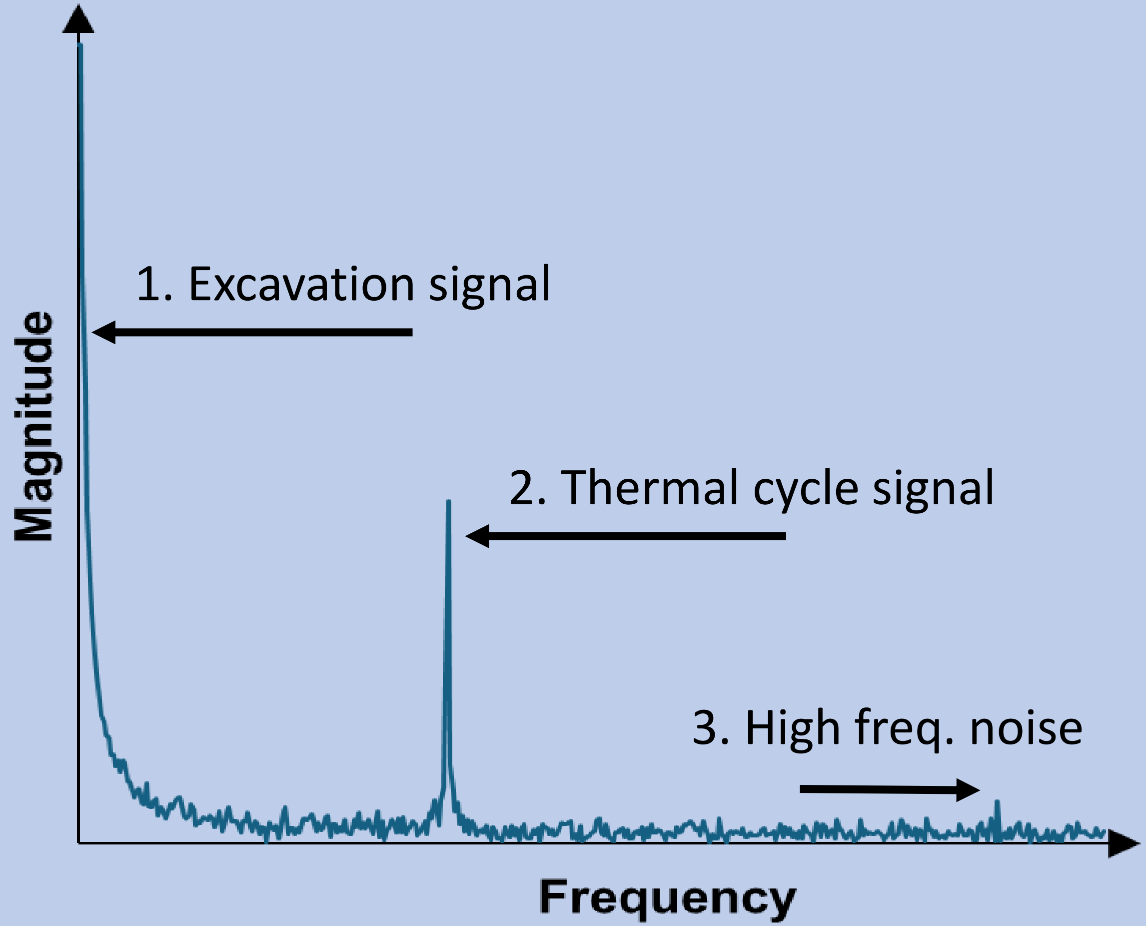
1. Idealise as Fourier Series (summation of sine waves).
2. Determine **frequency spectrum**.



New Approach

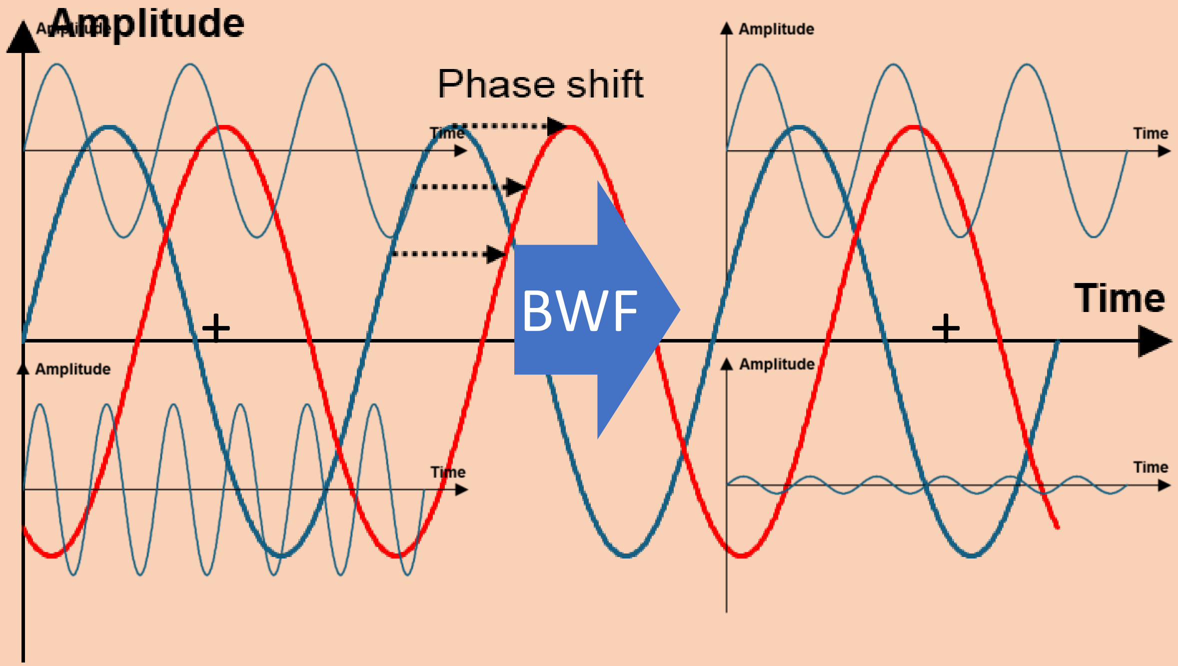
Frequency spectrum and application of Butterworth filter

Frequency spectrum



Butterworth filter selected based on two key criteria:

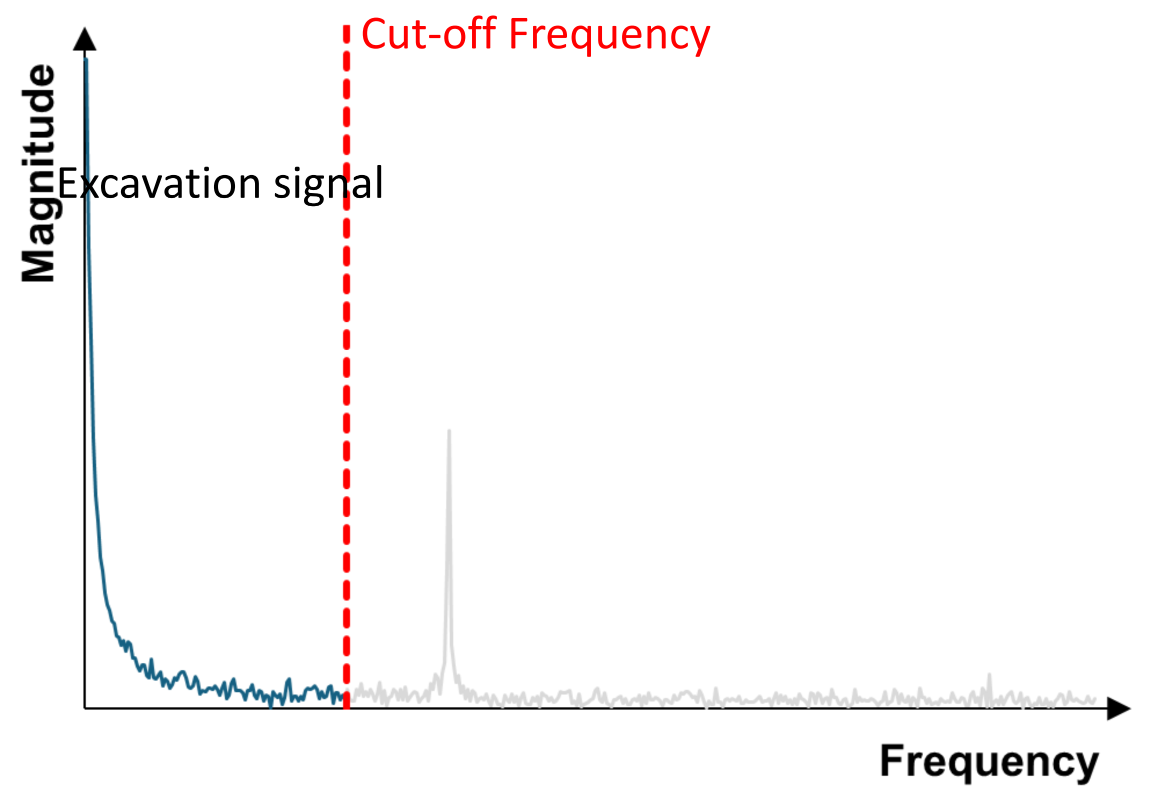
1. Attenuation of unwanted frequencies.
2. Minimising phase shifts in signal.



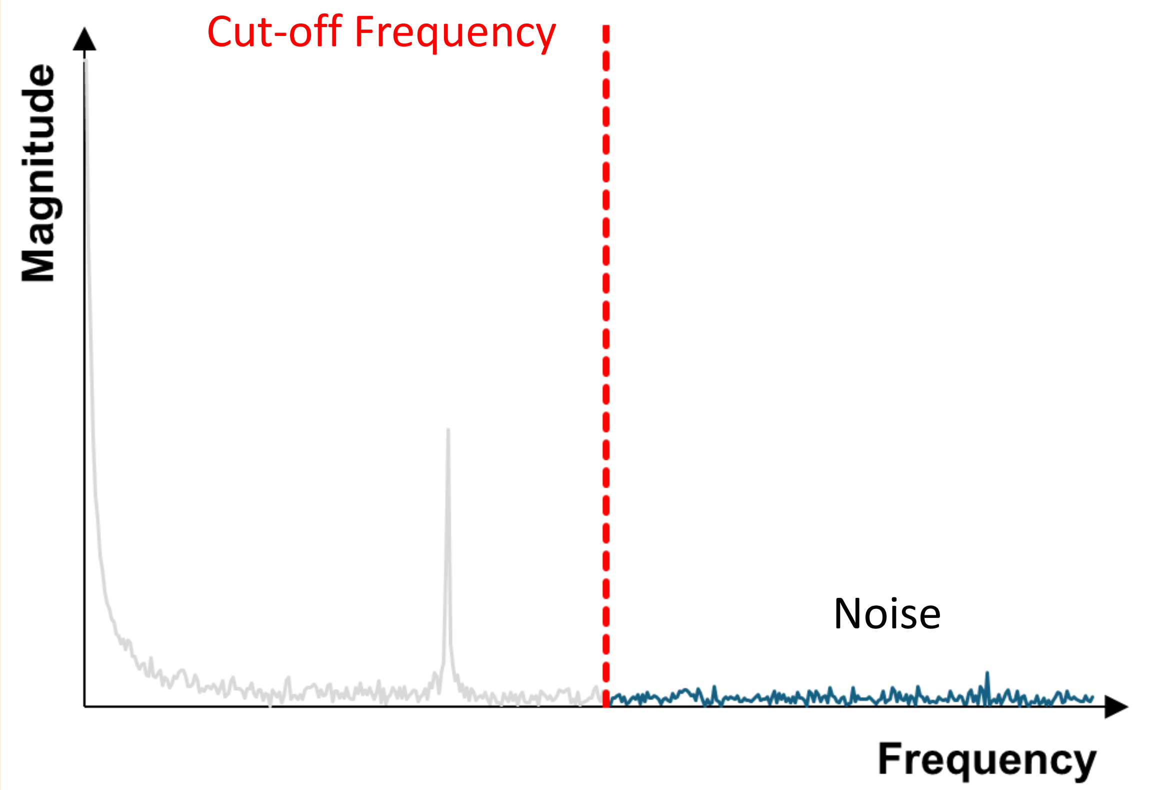
New Approach

Butterworth digital filter – low pass and high pass

Low pass filter

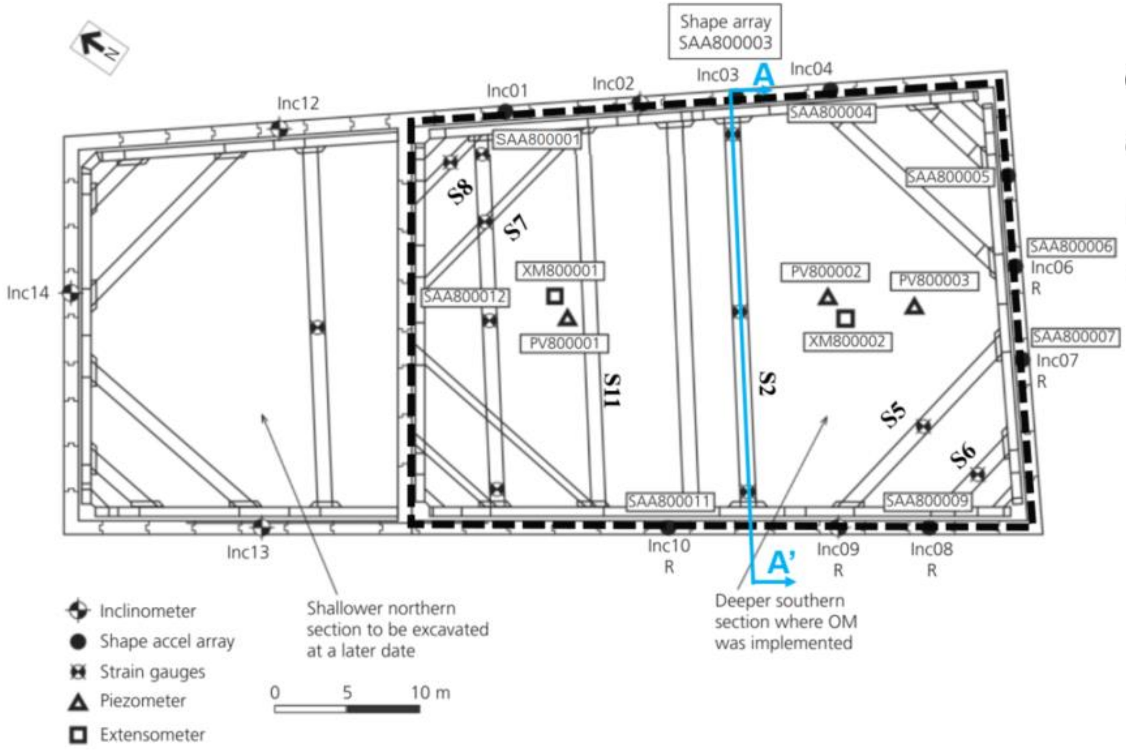


High pass filter

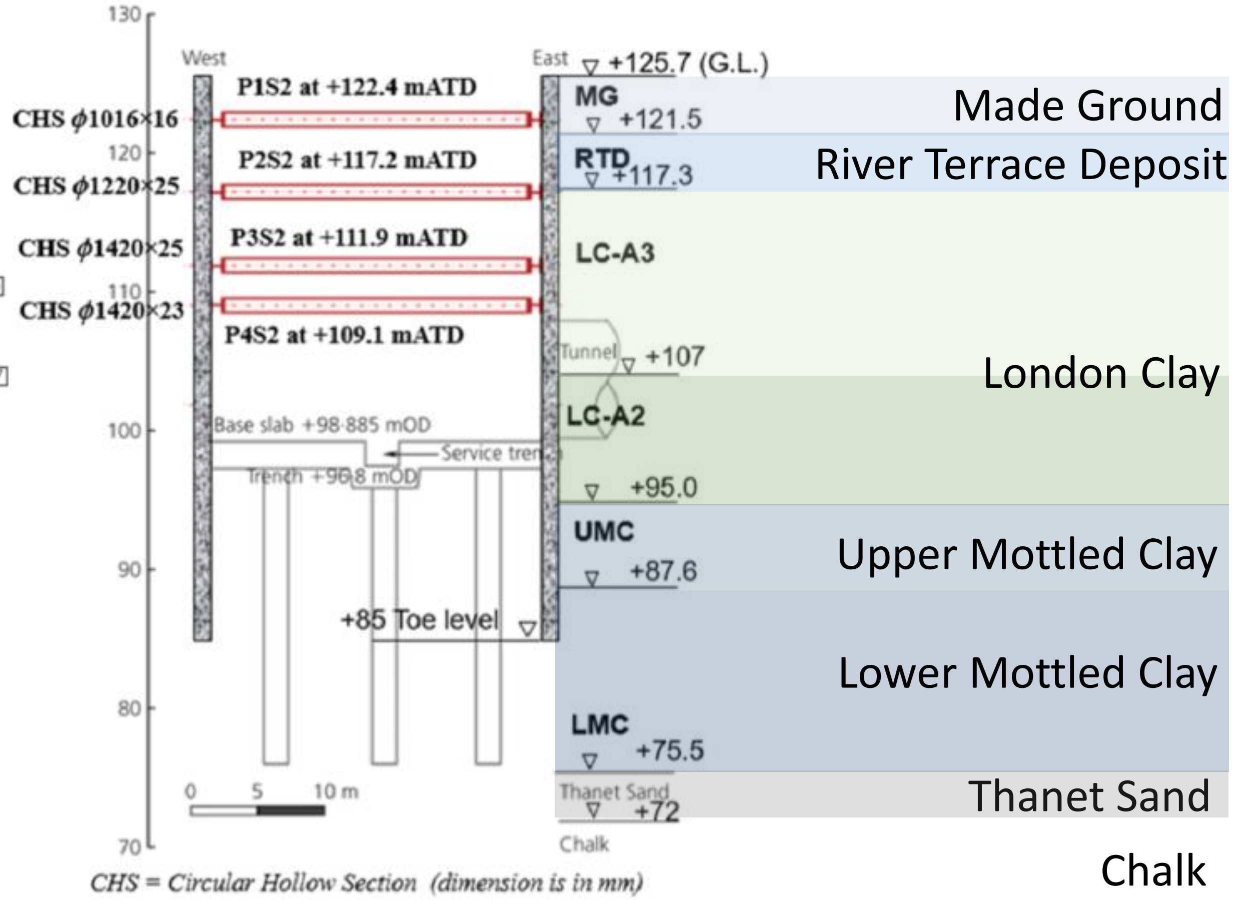


Case Study

Crossrail Tottenham Court Road Western Ticket Hall

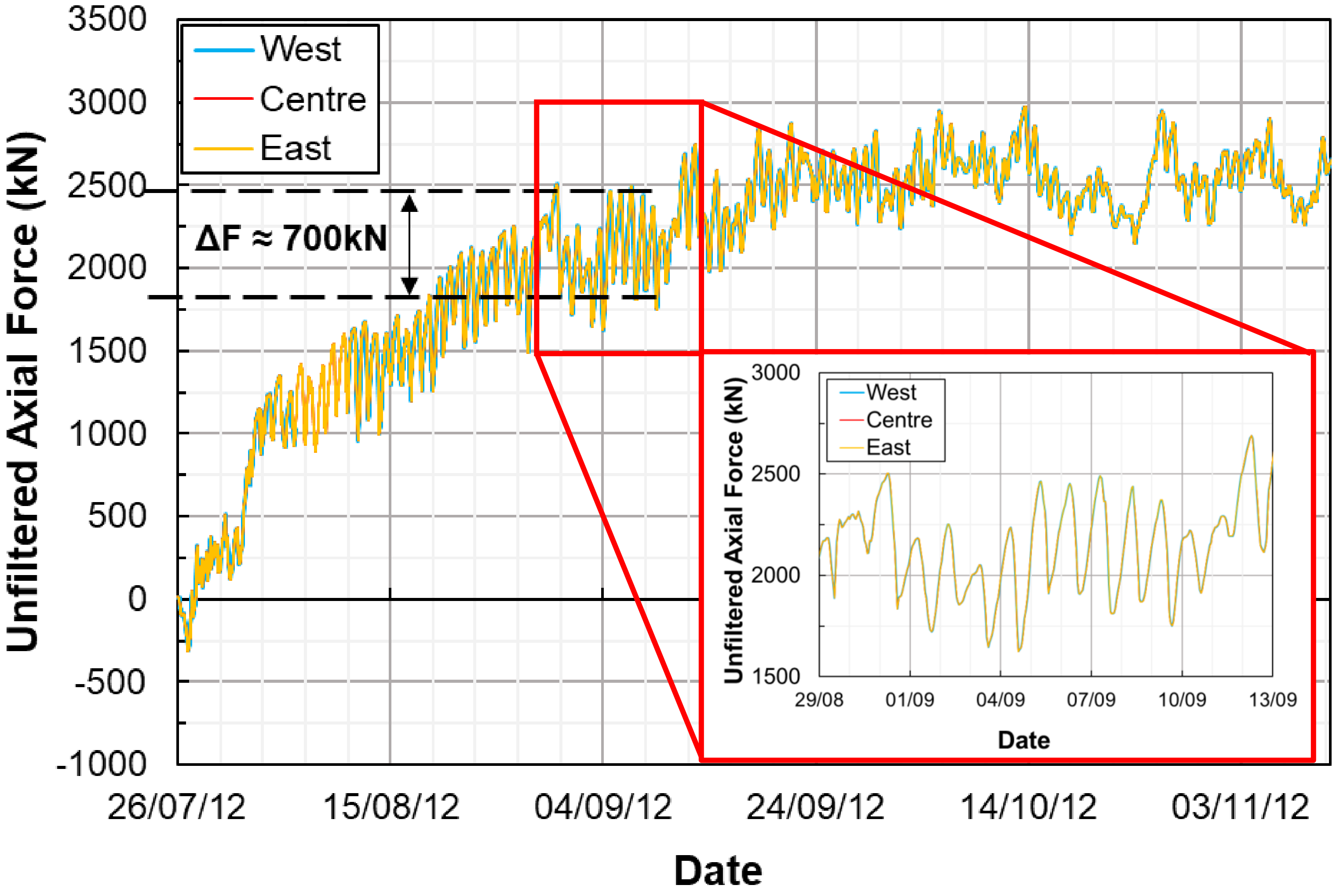


Yeow *et al.* (2014)

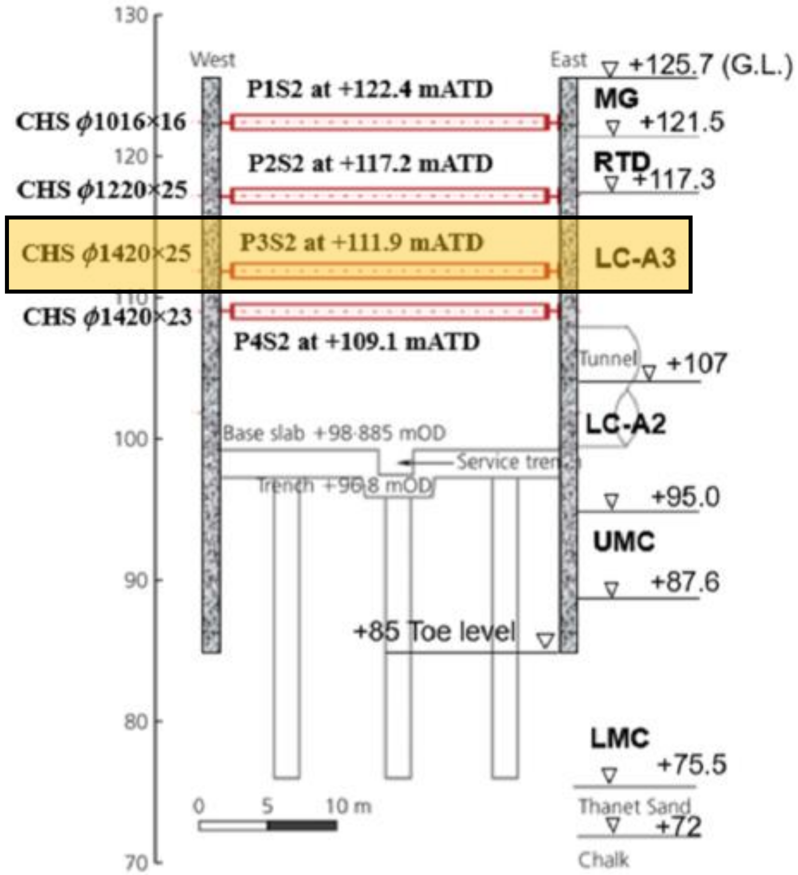


Case Study

Plot of P3S2 Axial Force time series - unfiltered

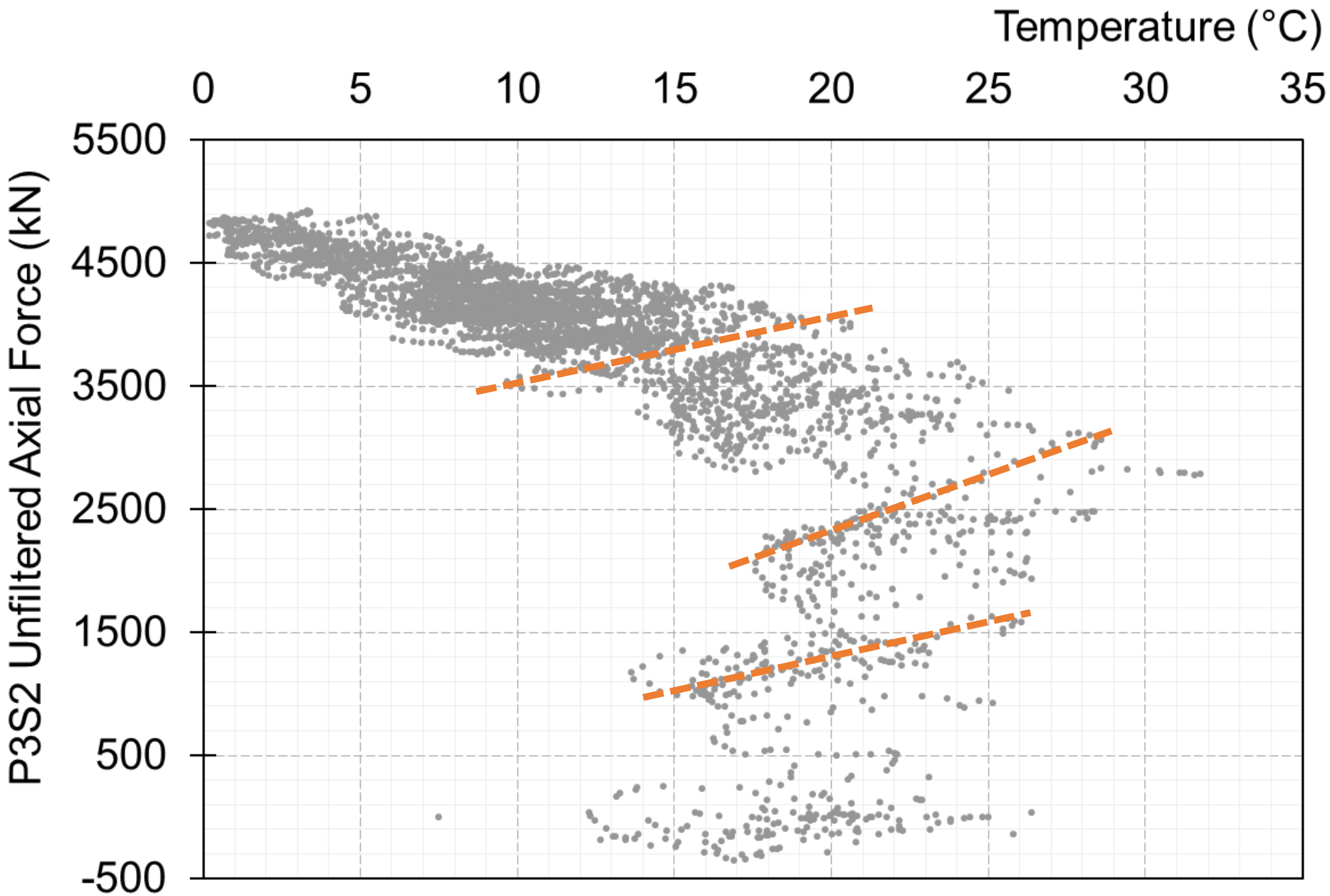


Sample rate is 1 per hour



Case Study

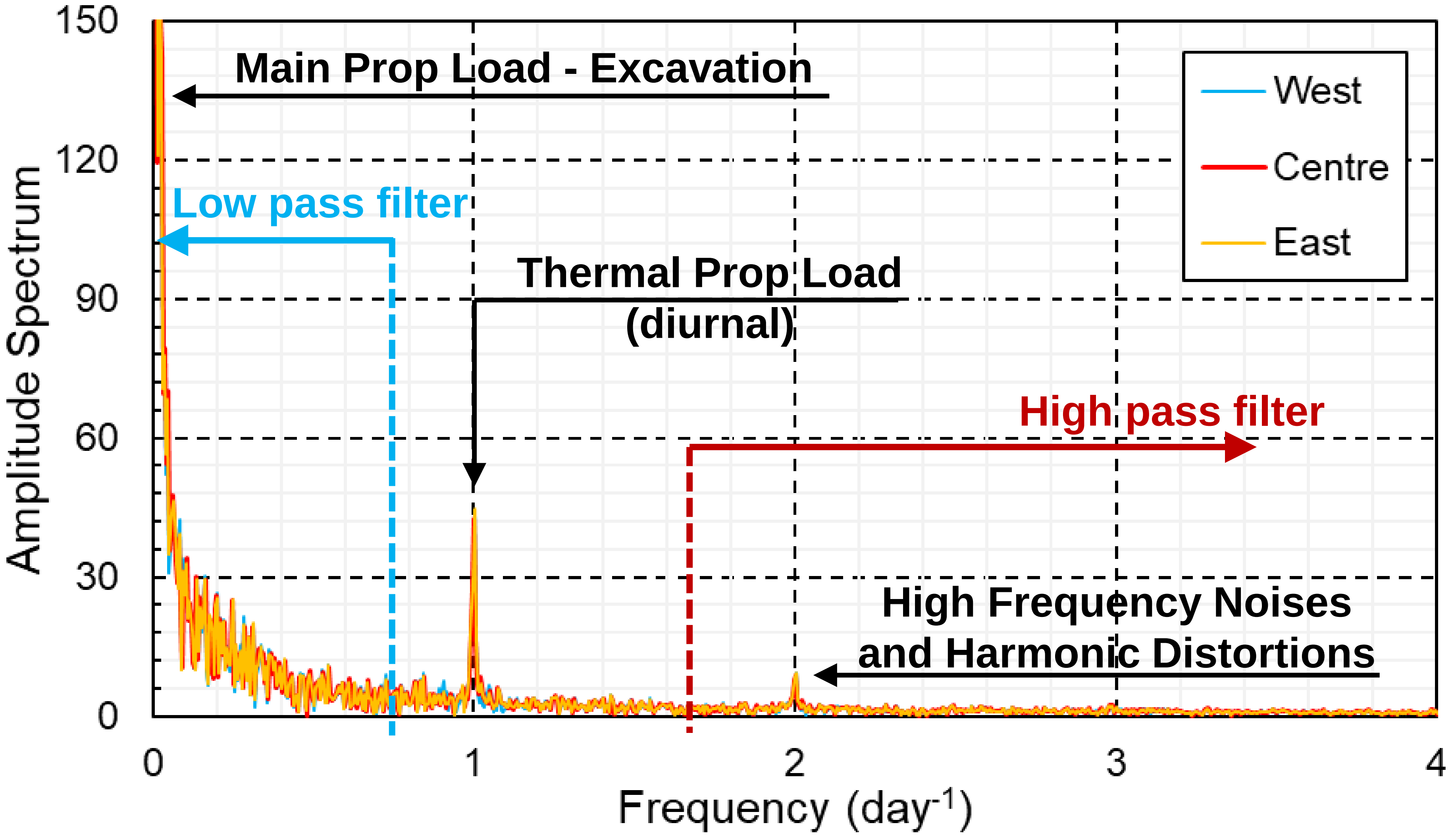
Plot of P3S2 Axial Force versus Temperature - unfiltered



- Difficult to isolate temperature behaviour when excavation is continuously ongoing.
- Limited insights and manual effort to determine β.
- Utilise low and high pass Butterworth Filters to decompose signal.

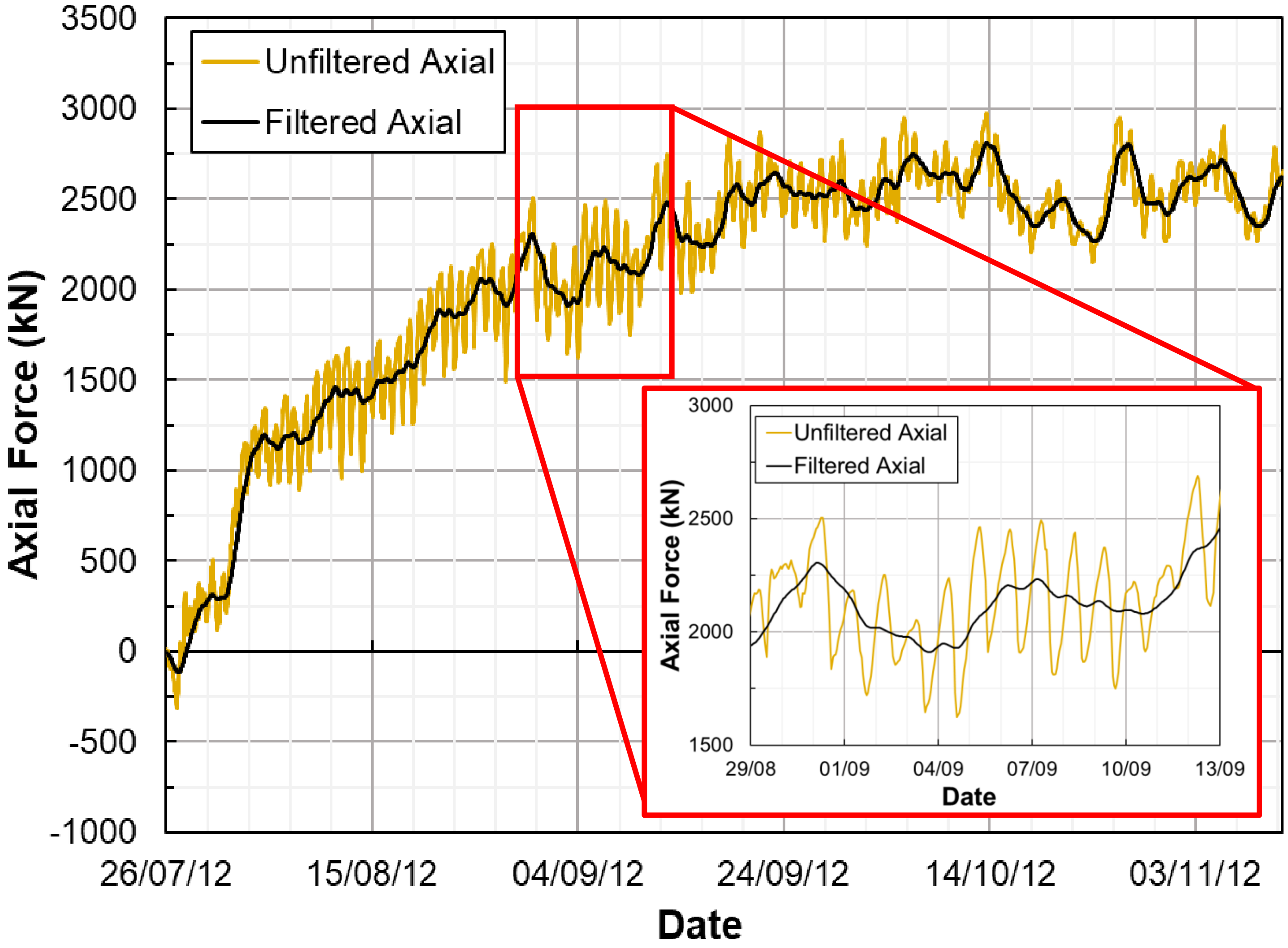
Case Study

P3S2 Axial Force Frequency spectrum

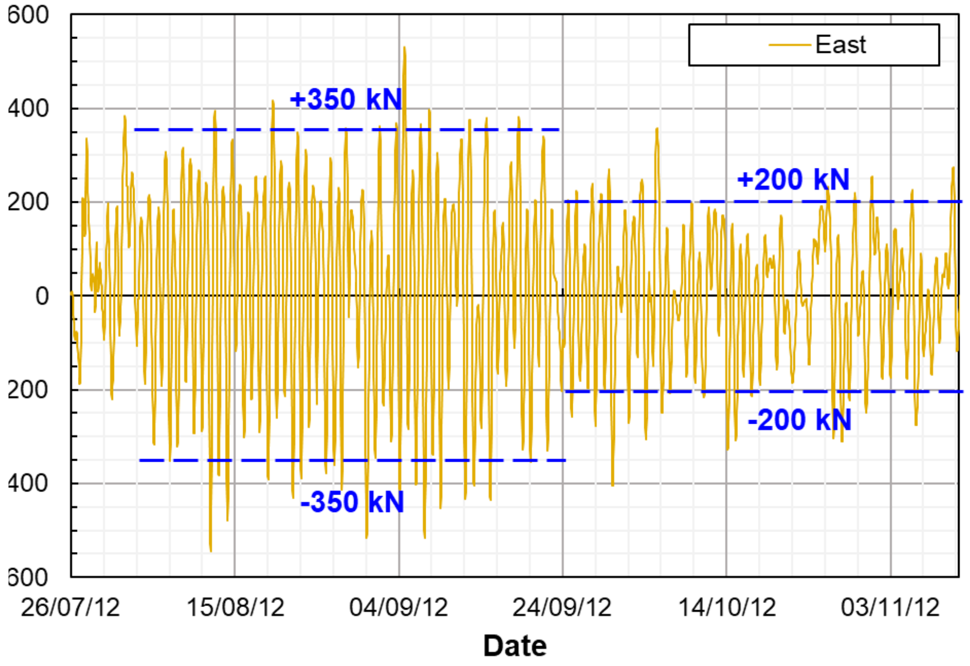


Case Study

P3S2 East Filtered Axial Forces

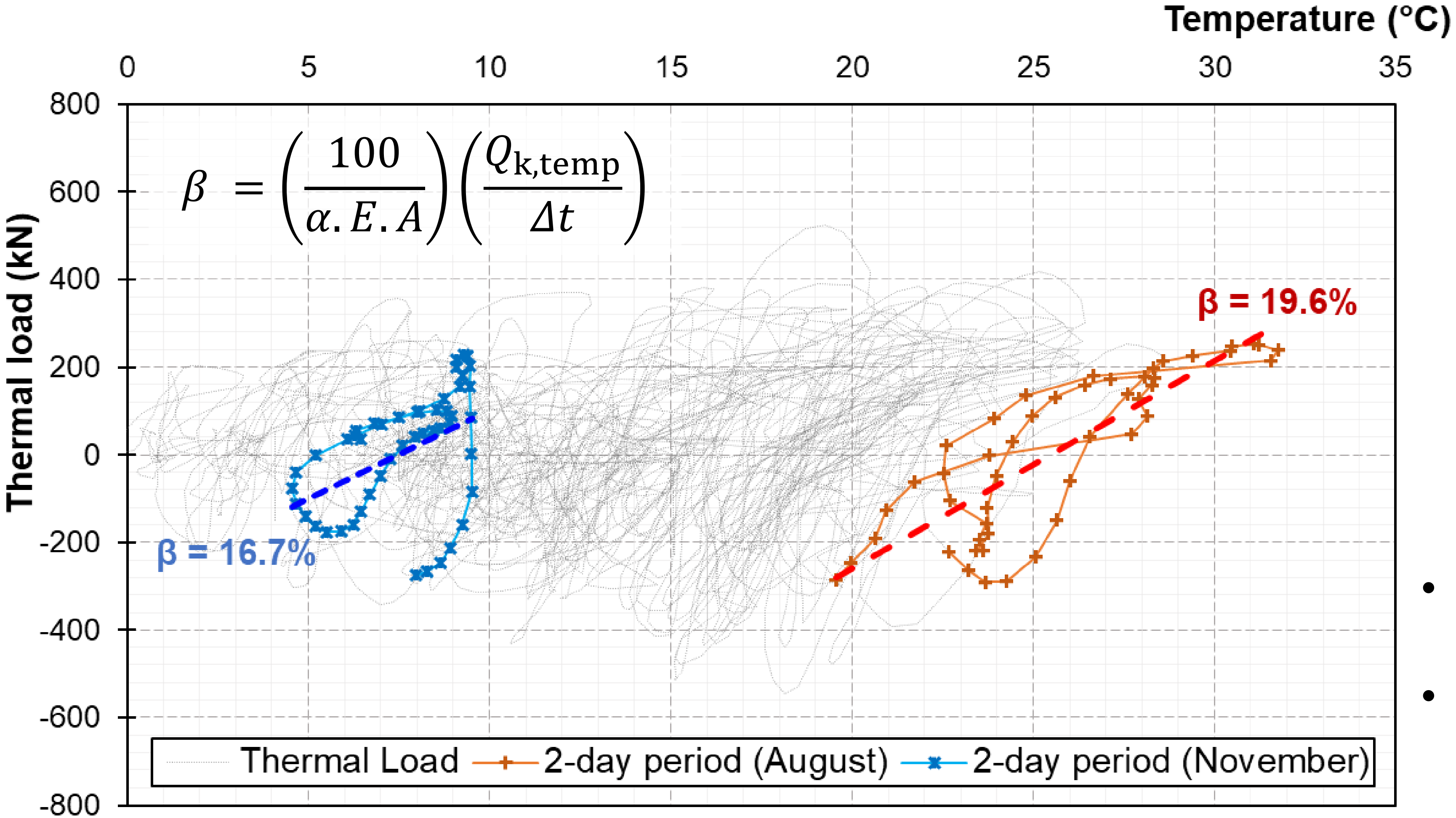


- Thermal loads and noise successfully separated from main excavation response.

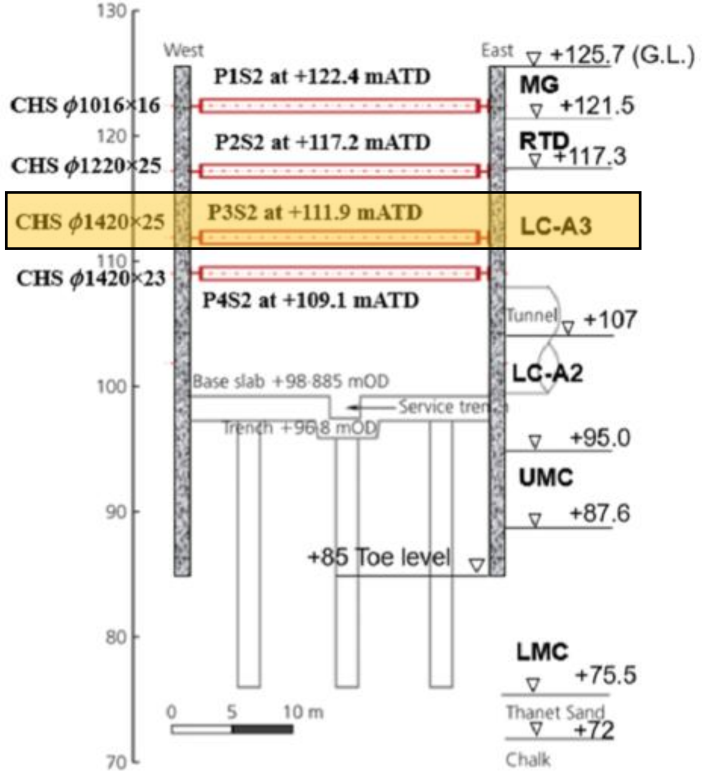


Case Study

P3S2 back analysed β



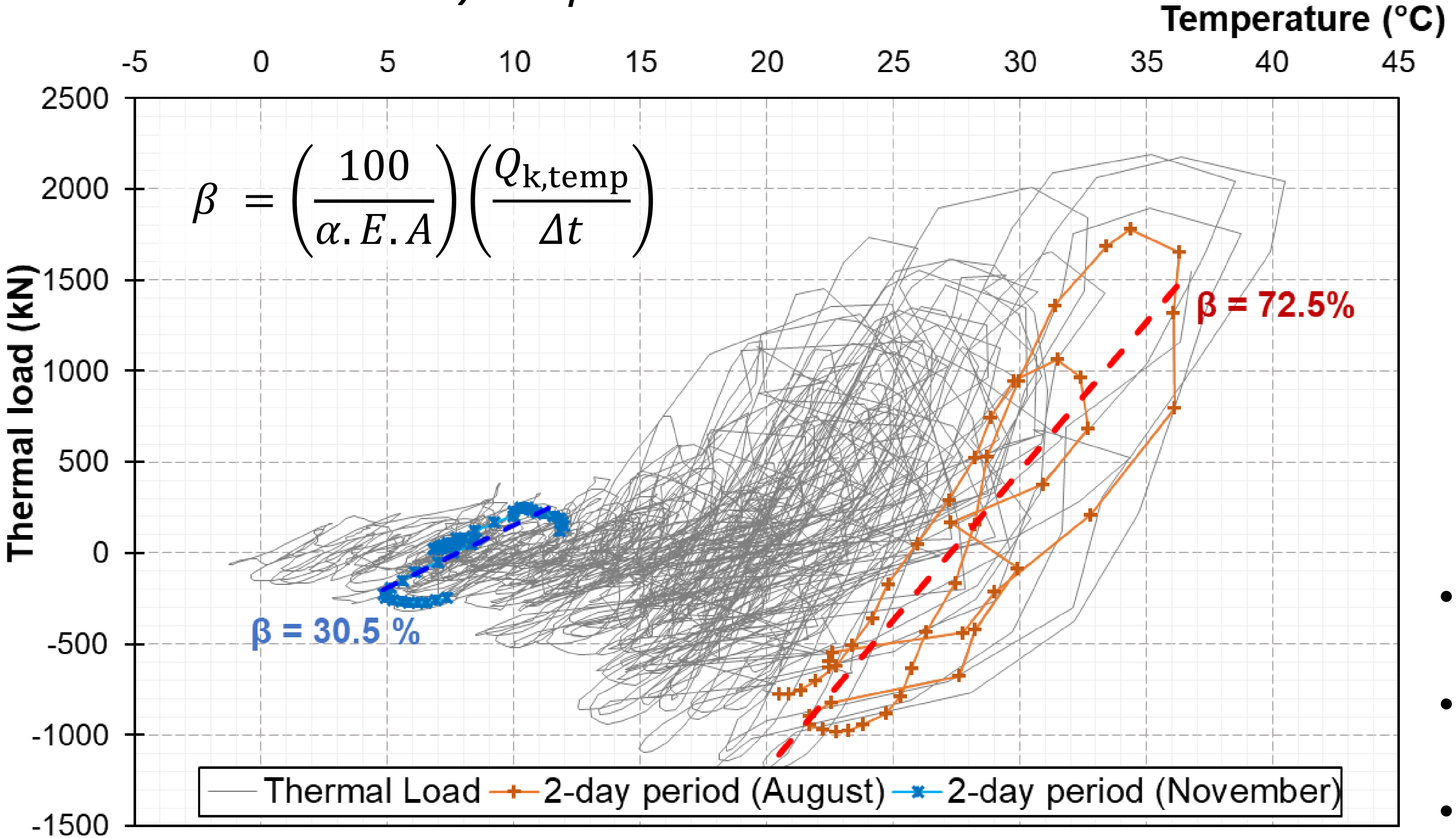
$$\beta = \left(\frac{100}{\alpha.E.A}\right)\left(\frac{Q_{k,temp}}{\Delta t}\right)$$

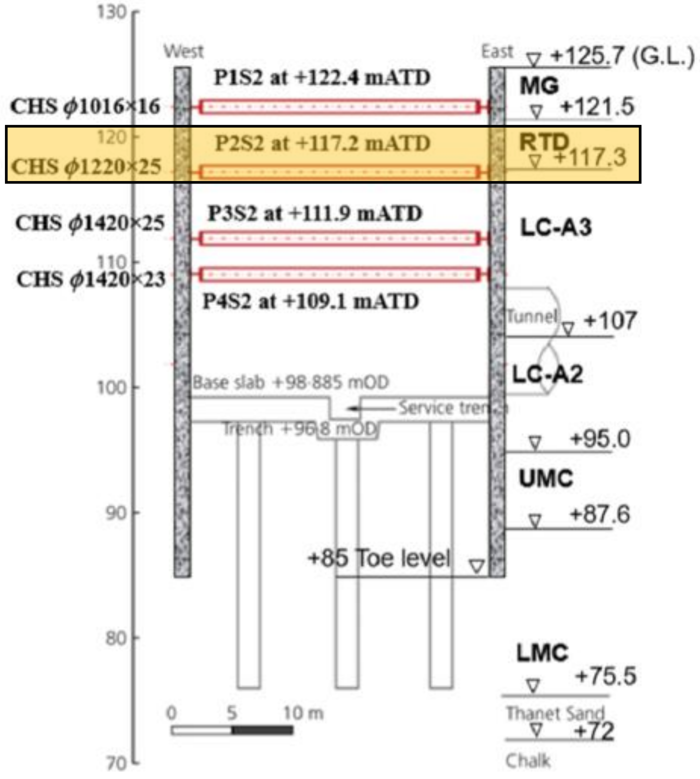


- P3S2 is 13.8m below ground level.
- β relatively constant through the seasons.

Case Study

P2S2 back analysed β

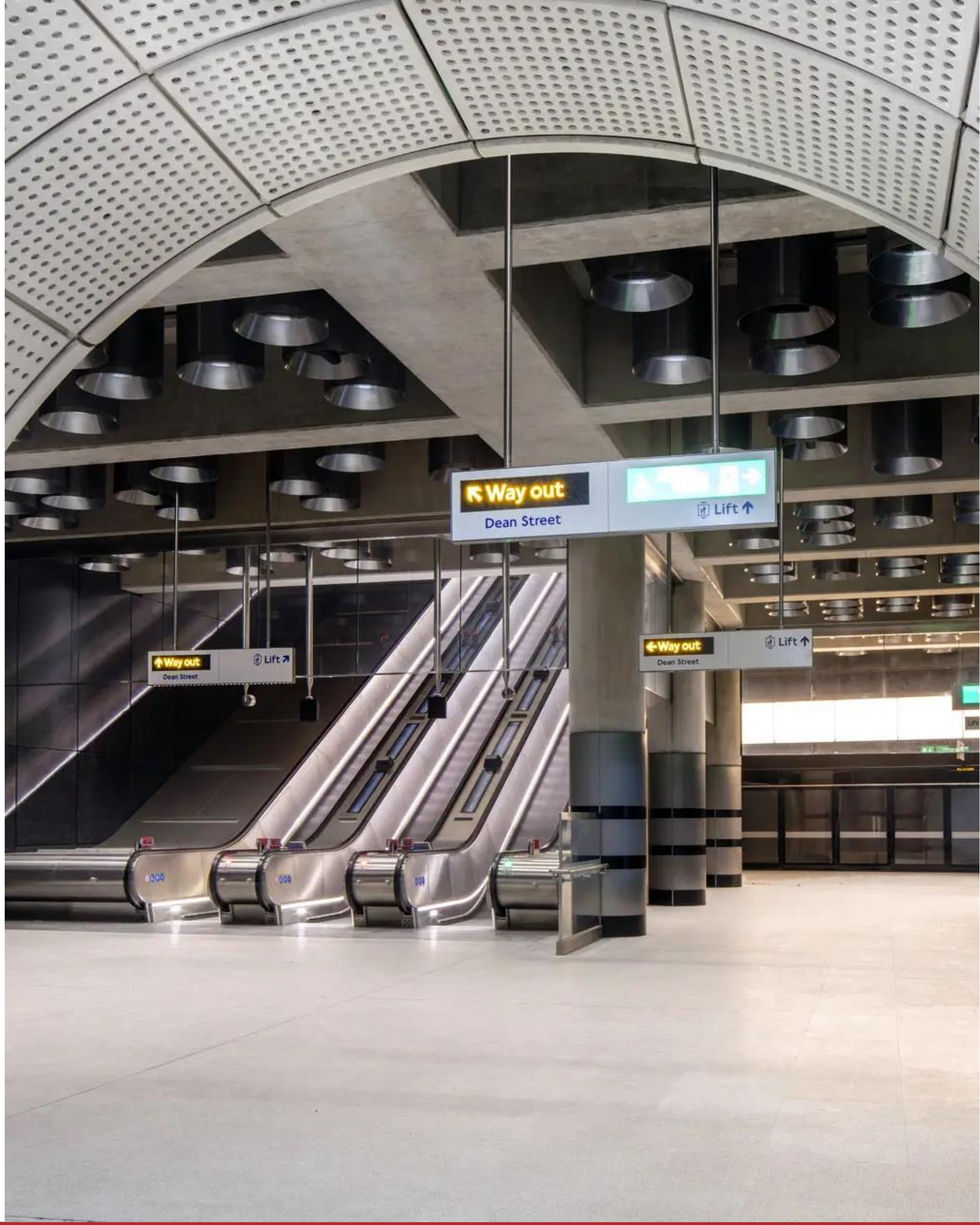




- P2S2 is 8.5m below ground level.
- Decrease in β from August to November.
- Walls are exposed to greater temperature fluctuations.

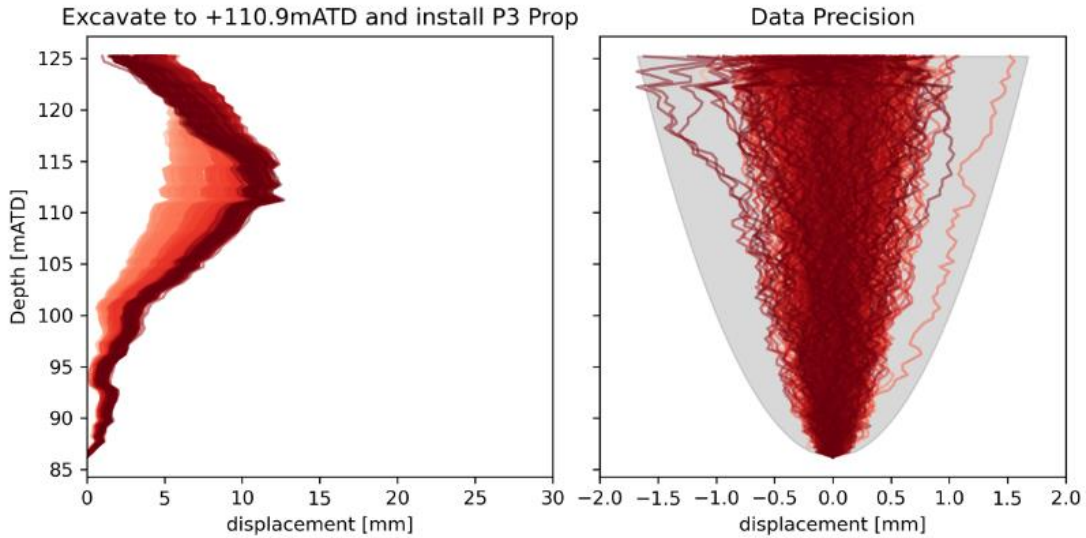
Benefits

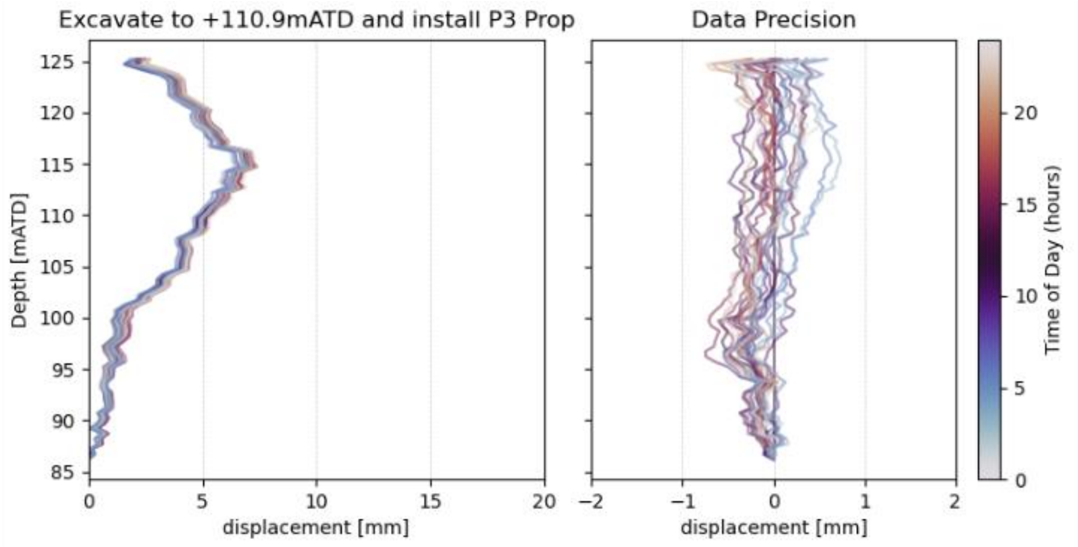
- Introduced a **rigorous approach** to separate components of prop axial force using the **Butterworth filter**.
- β can be assessed at any stage of construction.
- Establish relationship between β and depth (ongoing).
- Readings with **thermal effects** (SAA).
- Back analysis using filtered force due to excavation.
- **Data-driven designs**

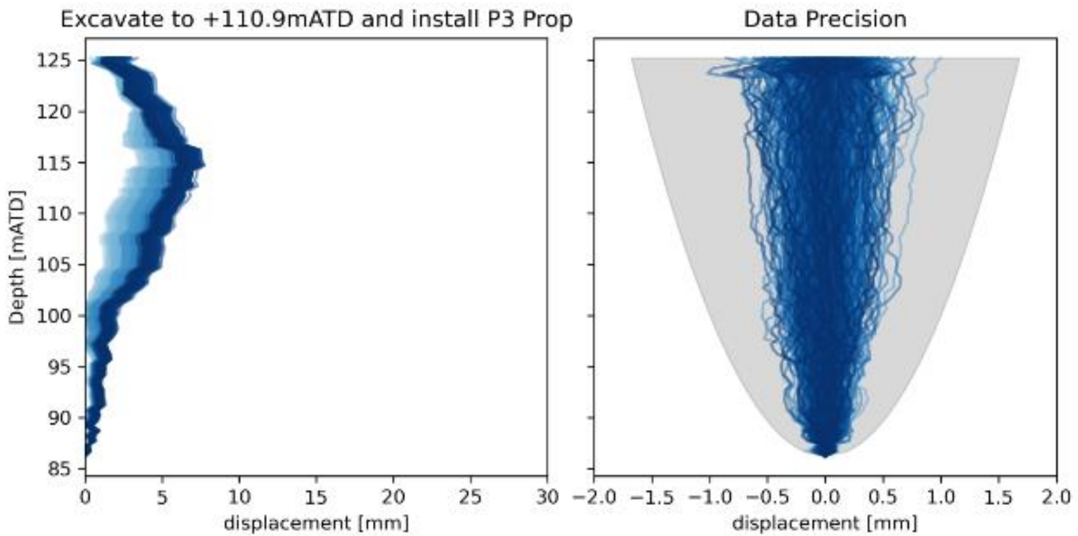


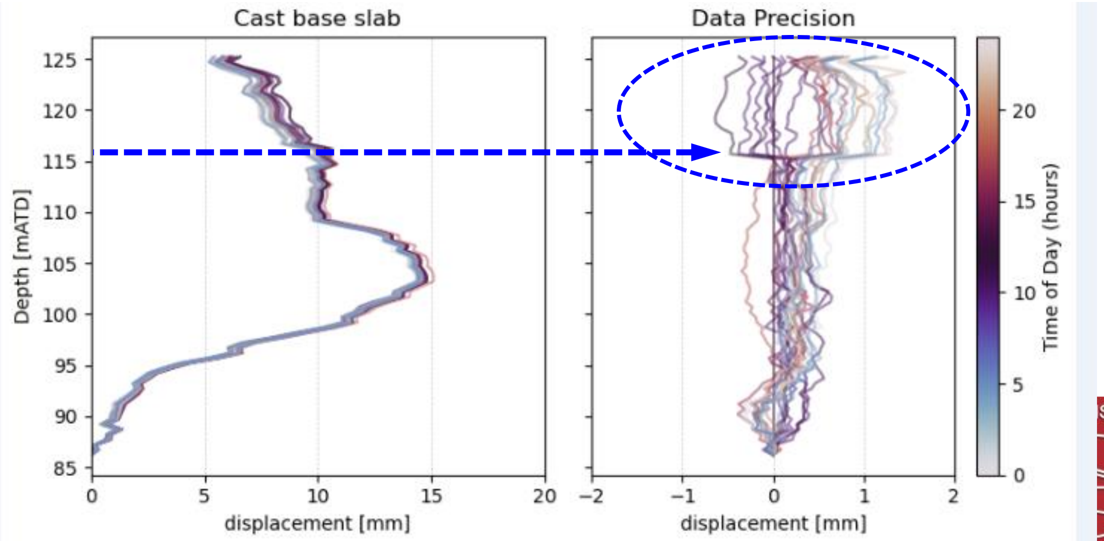
Data-Driven Process – SAA data

Imperial College London, Dr Le Truong K D & PhD Ningxin Yang is working on SAA data using the data-driven approach .









Summary

- Strengthen the specification of I&M and enhance the field practice
  - Installation / Accuracy / Data.
- Use combine behaviour of different instruments /Compare to other sites
  - e.g. piezometers and extensometers; historical data
- Rigorous review of monitoring data prior to application in BA & OM
  - Data assessment: error diagnose and correction;
  - Data-driven processing approach; .
  - Alternative: new instruments with different technology, data-platform for ‘real-time’ data visualisation.
- Contractual role for the monitoring coordinator

Thank you

Discussion - 1

- What are monitoring data criteria for the Real-time back analysis?
- What are different requirements in monitoring data between standard project and OM project?
- Who should be responsible for the monitoring at different stages?

  e.g. Specification, Plan, Installation, Review.

  How can information be transferred from one company to another?
- What qualifications for the contractual role “monitoring coordinator” ?

  – key role in the Construction Review process.

Discussion -2

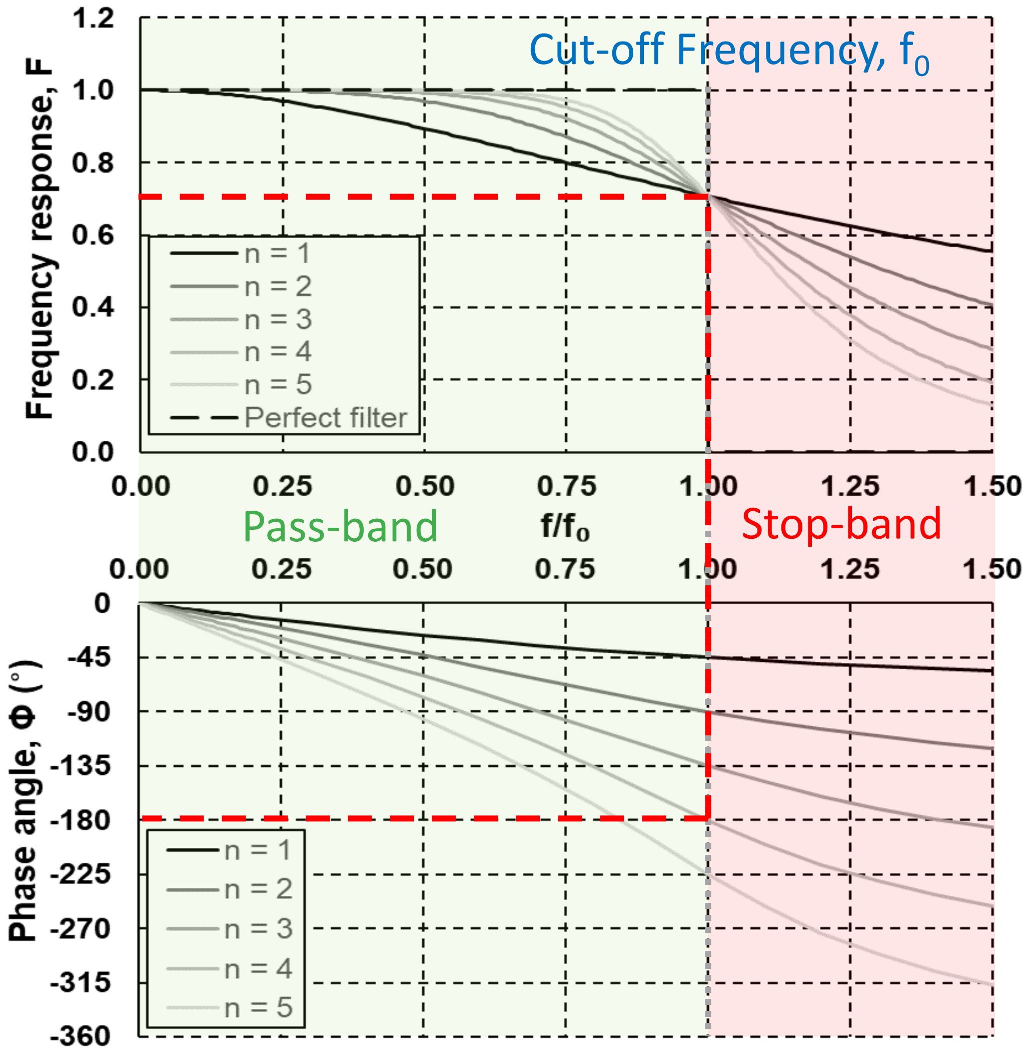
- What are the different stages where monitoring is involved?
- Who is responsible at each stage for the monitoring (planning-design/writing of specs/execution/check-review/analysis) and which background/knowledge is required? How can information be transferred from 1 company to another?
- In which way does the input/requirements differ when the observational method is to be used?
  - Real time verification/interpretation of the data
  - Required accuracy?

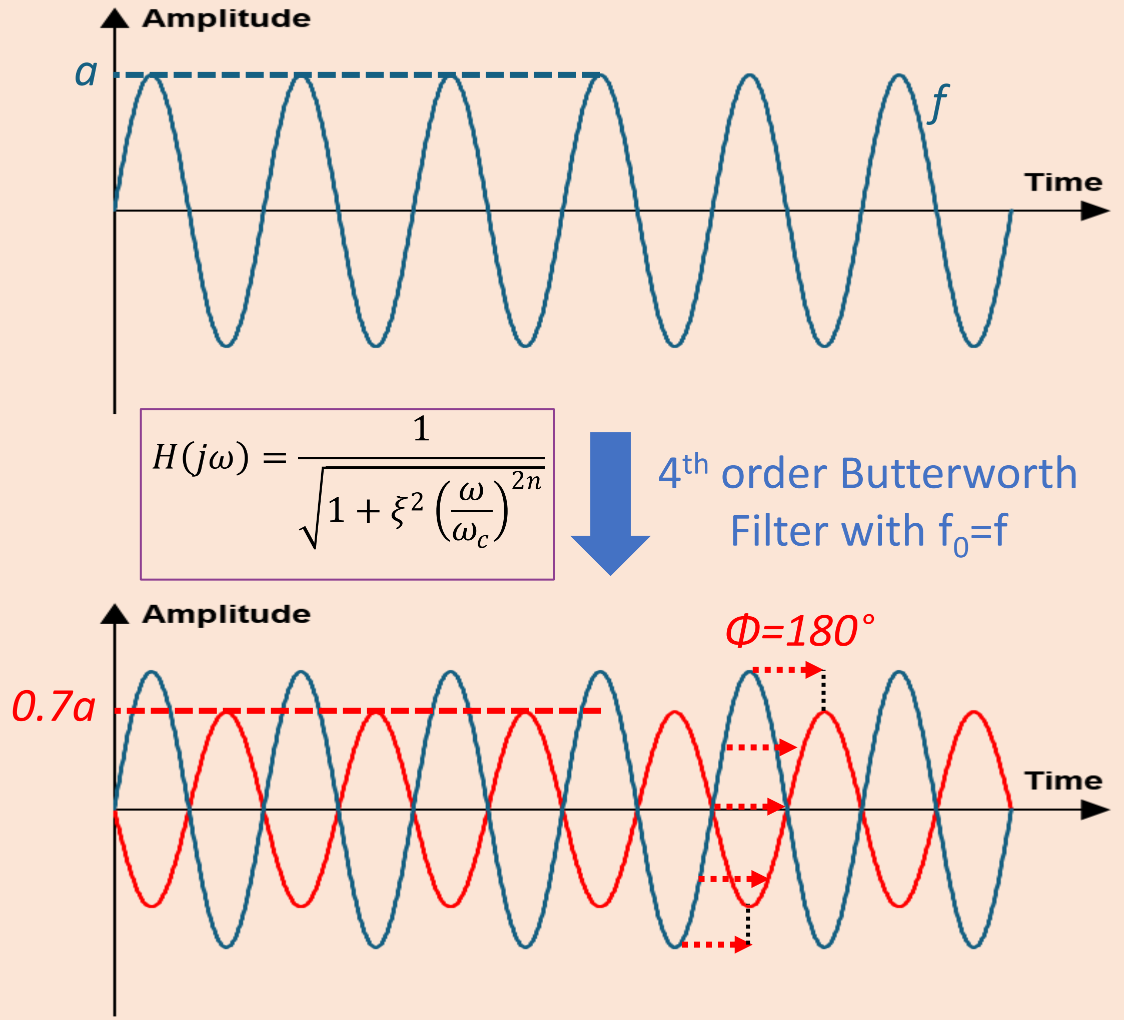
Discussion - 3

- Standardised approach? Data cleaning and processing.
- Testing in real time?
- More in-depth investigation into:
  - into seasonal variation?
  - prop stiffness?
  - variation with depth?

Appendix I: Low pass Butterworth Filter

Normalised Bode Plot





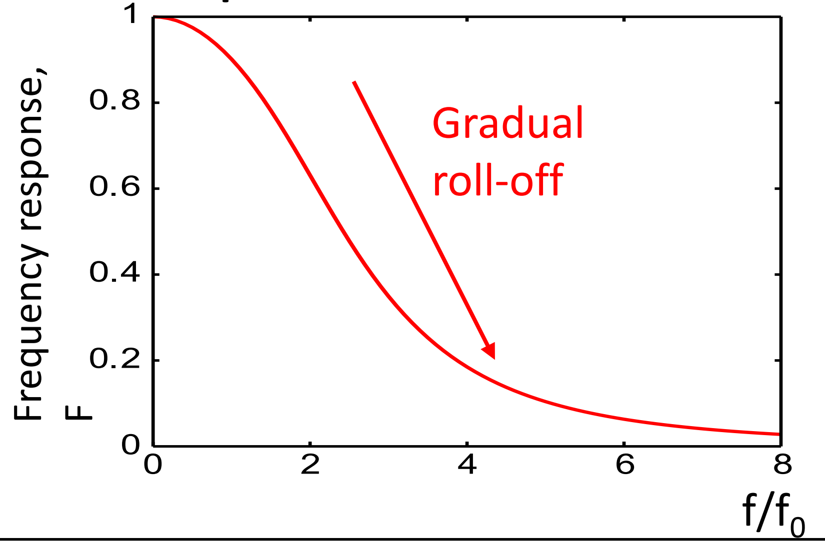
$$H(j\omega) = \frac{1}{\sqrt{1 + \xi^2 \left(\frac{\omega}{\omega_c}\right)^{2n}}}$$

Appendix II: Digital Filters

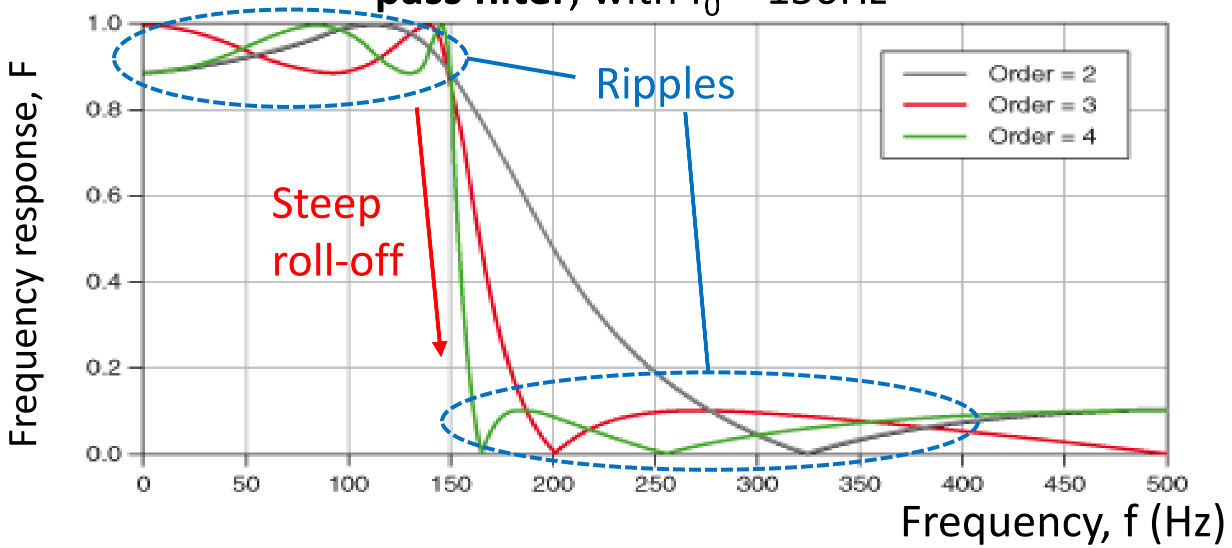
Comparing Filters on the two criteria of roll-off and phase response

Digital Filter	Roll-off	Phase Response
Bessel (Thomson, 1949)	Gradual	Flat
Butterworth (Butterworth, 1930)	Gradual but steeper than Bessel	Reasonably linear in passband
Chebyshev Type I and Type II (Cauer, 1931)	Steep	Non-linear due to ripples
Elliptic (Cauer, 1931)	Steep	Non-linear due to ripples

Normalised frequency response of 3rd order **Bessel low-pass filter**

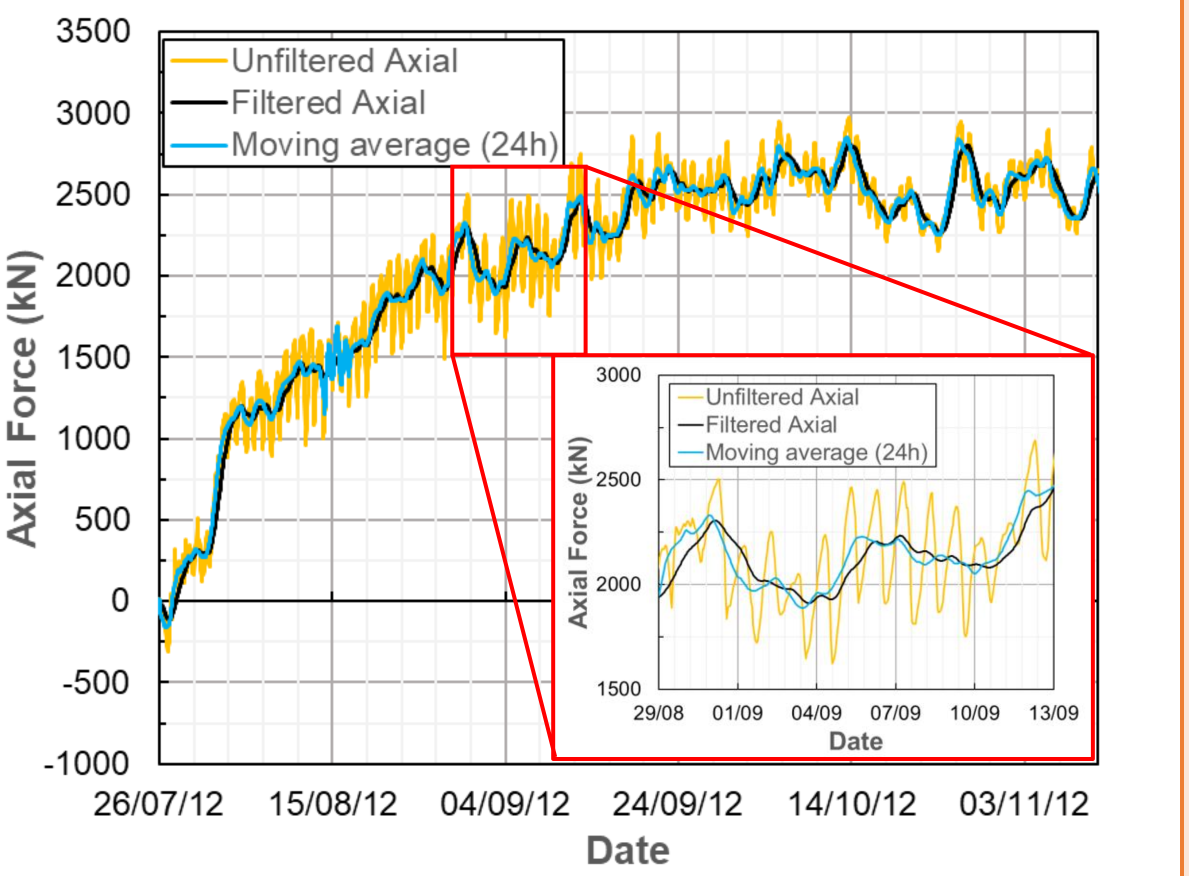


Frequency response of 2nd, 3rd and 4th order **Elliptic low-pass filter**, with f_0 = 150Hz



Appendix III: Moving Average vs Butterworth Filter

P3S2 Axial Force



- Moving average is a FIR filter, while Butterworth is an IIR filter. FIR filters are generally more computationally expensive vs IIR filters.
- Moving average is only capable of filtering exactly one pre-determined frequency (i.e. it is dependent on the selected box size). Position of the box w.r.t. datapoint will result in a phase shift.
- Butterworth filters can be applied to filter out a range of frequencies (e.g. noise; seasonal variations over several years). Application of multiple Butterworth filters at key cut-off frequencies allows for separation of original signal into multiple components of distinct frequencies.

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