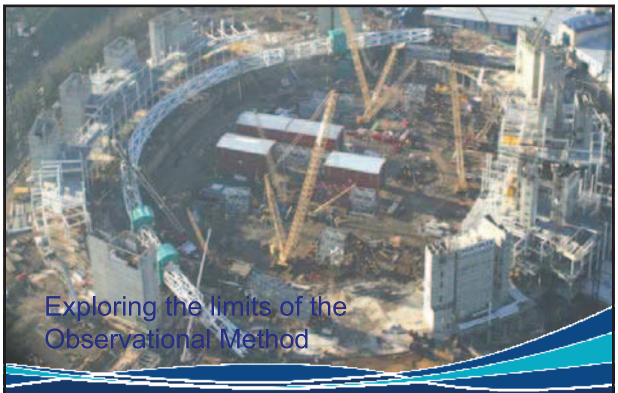

Exploring the limits of the Observational Method

Tony O'Brien

BGA/CFMS Seminar, Paris - December 2011

Mott MacDonald

Exploring the limits of the Observational Method

1. Background
   - key requirements for OM
2. New Wembley Stadium
   - raising the arch (pile group behaviour)
3. Limehouse Basin
   - a step too far? (retaining wall behaviour)
4. Earthworks asset management
   - the weakest link? (degradation of clay fill embankments)

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Key requirements for OM

Peck (1969) outlined 8 requirements →

- Exploration (or Ground Investigation)
- Assessment of variations in conditions - most probable and most unfavourable [now - use of "progressive modification"]
- Design basis
- Key observations and predictions (most probable)
- Key observations and predictions (most unfavourable)
- Design modifications for every foreseeable scenario
- Make observations and evaluate actual conditions
- Modify design based on observations

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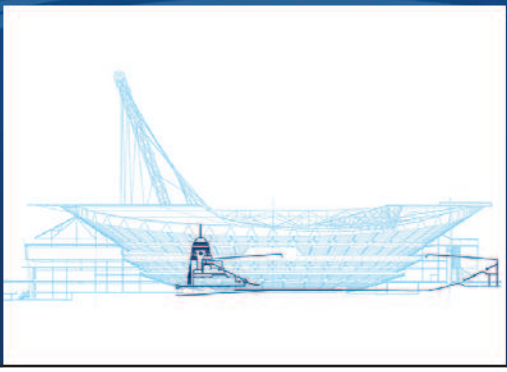
Key factors for Observational Method implementation

Adverse factor	Comment
Brittle failure	Adequate warning when approaching a ULS?
Progressive collapse	Failure of one component, leads to rapid failure of overall system
Lack of stakeholder support	All parties in project need to be actively involved and supportive
Unable to obtain critical observations reliably	Control of works dependant on obtaining pertinent data and acting on it
Implementation of contingency measures is too slow	The contingency plans need to be fully developed and able to be implemented within the available timescale
Contract conditions	Appropriate?

New Wembley Stadium
- raising the iconic arch



Demolition and site preparation

Retaining walls, shear cores and arch fabrication

Raising the arch

- arch: 133m high, 315m span
- longest single span roof structure in the world
- key concern: arch buckling ⇒ pile group deformation critical
- risk management ⇒ use of OM (OM rare for pile groups)

Raising the arch

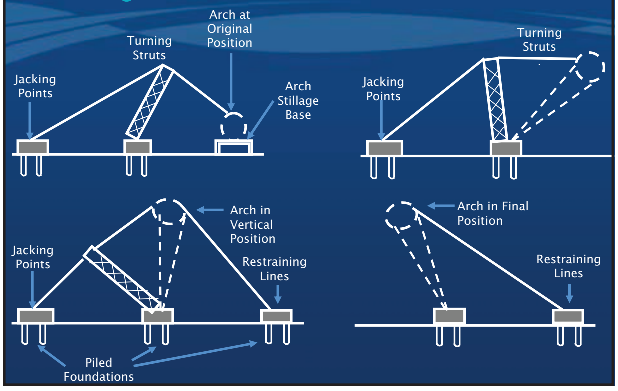
Concerns

- if any pile group was to move excessively, due to its slenderness, the arch may buckle
- no case histories exist for pile groups of this size subjected to complex load combinations vertical, horizontal moment and torsion

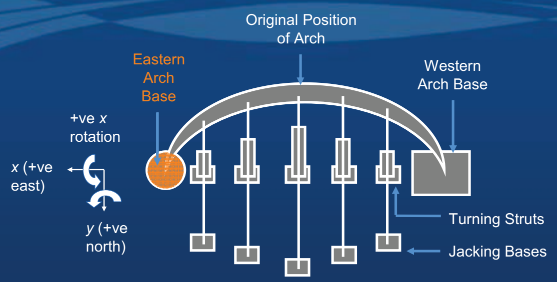
Risk management - use of OM

- complex for piled foundations
  - allowable movement dependent on load combination !
- use of non-linear boundary element analysis
  - pile group displacement
  - structural forces
- instrumentation and observation of pile groups
- consideration of failure/deformation mechanisms
- contingencies
  - kentledge
  - tie backs to shear cores

Lifting mechanism – side elevation



Lifting mechanism – plan view

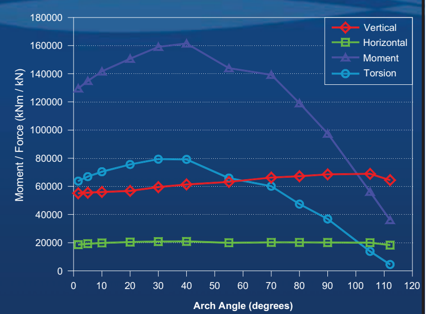


Pile group configurations

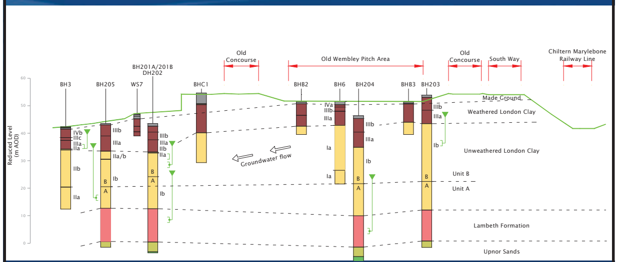
- temporary base pile groups vary from 6 to 12, 1.5m dia piles
- pile length varied from 10 to 42m

Challenges
example of complex loads, eastern arch base

- many load cases
  - 13 different angles
  - 9 per angle
- lack of case history data
  - lateral/moment loading



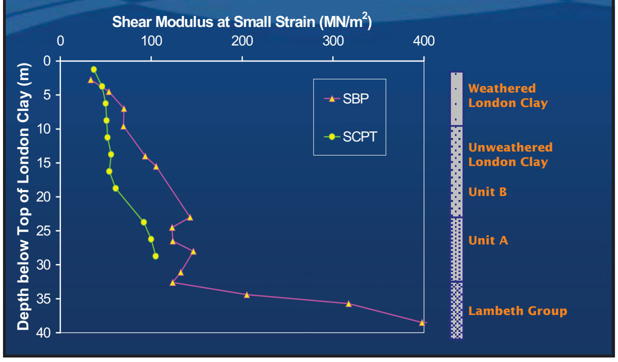
Site geology and topography



- site history
  - influence of old stadium
- topography
  - on top of hill, adjacent rail cutting
- deep weathering of London Clay
  - 8 to 10m
- hence, may be differences in London Clay behaviour across site and c.f. central London

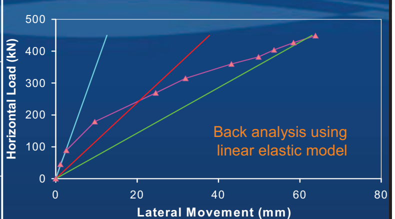
Shear modulus vs. Depth

Seismic cone and self-boring pressuremeter



Analysis Type	Vertical Stiffness (MN/m^2)	Horiz. Stiffness (MN/m^2)
Initial Linear Stiffness	232	171
Stiffness at FOS = 1.7	118	23
Stiffness at Failure	60	9

Lateral pile test results



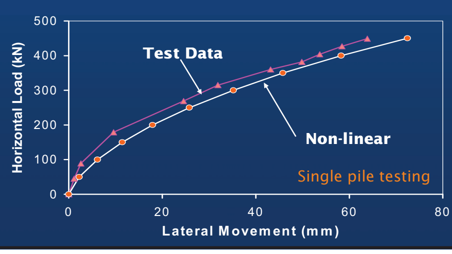
E_h drops by 19x during loading !

$\Delta E_h >> \Delta E_v$

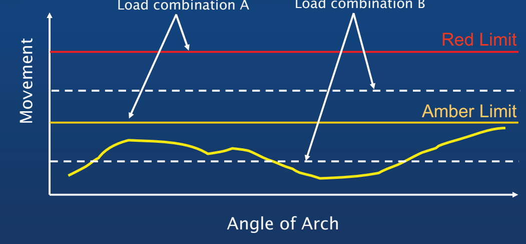
Non-linear analysis essential for large lateral loads

Lateral test pile results

- initial tangent stiffness, assumed anisotropic
  - vertical - seismic cone
  - horizontal - SBP



The use of the observational method -
application to piled foundations



Allowable movement dependent on load combination !

Identifying threshold limits

1. 121 Load combinations for each pile group
   - → Displacements
   - → Structural forces (BM/SF/Axial) in piles [CRITICAL]
2. Red Limit
   - a) Full load combination
     (Horizontal force/overturning moment/etc) x Factor
     → Failure of a pile in group
   - b) (Dominant load only) x Factor
     → Failure of a pile in group

Worst of a) and b) ⇒ Red Limit (two-thirds of ultimate structural capacity)

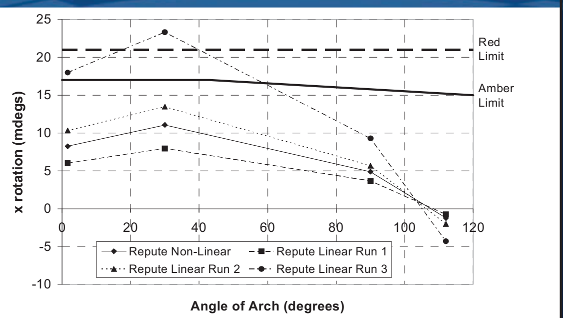
Identifying threshold limits

3. Amber Limit

   4 Criteria →

   - a) Predicted pile group deformation - most likely load combinations + plausible ground stiffness variations (± 25%)
   - b) Sufficient "distance" between Amber + Red to facilitate timely implementation of contingencies
   - c) Sufficiently beyond "expected" deformation to avoid regular breaches of Amber limit
   - d) Deformation monitoring accuracy

Predicted x Rotation for eastern arch base



Non-linear analysis - essential

Monitoring strategy

- primary system
  - precise levelling (± 0.1mm) and surveying (± 1.5mm)
  - had to measure small movements accurately
  - Survey 3 months before arch raising
  - Initial 6 weeks survey accuracy improved, ± 5mm → ± 1.5mm
- secondary system
  - electrolevel beams, selected pile groups

Raising the arch

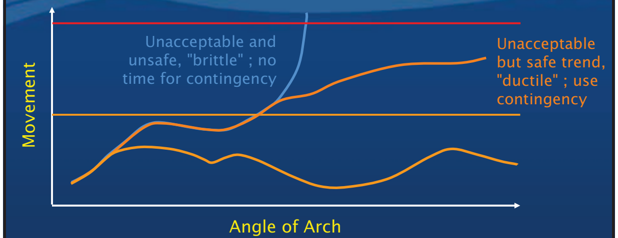
Jacking initially applied 14MN at each JP

- Vary load at each jack to maintain arch alignment

→ torsion to pile group

A critical risk "brittle" failure of corner pile

(combined tension and shear) due to torsional loading

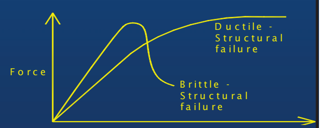


- brittle mechanism
  - occur at small displacement
  - no warning
  - unacceptable

Risk mitigation

OM contingency measures (pre-designed)

- apply large "kentledge", put corner pile into compression → ductile mechanism
- other contingencies
  - install and pre-stress tie backs
  - modify jacking forces
- if adverse trend
  - pile specific capacity checks for current (rather than critical) load combination

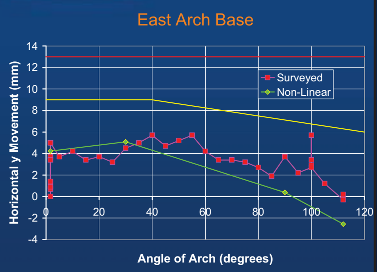


Construction of the arch

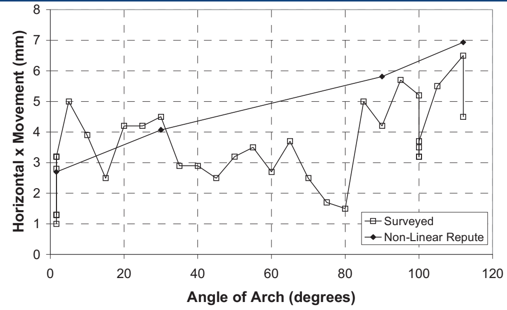
Pin at eastern arch base

Monitoring results

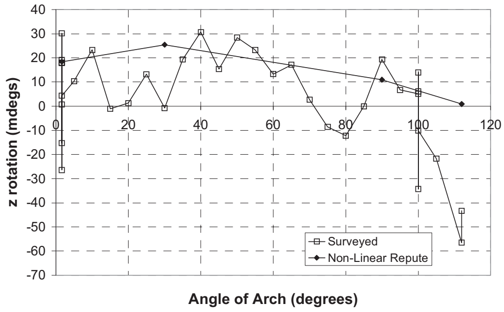
- predictions: non-linear (hyperbolic) analyses
  - initial elastic stiffness: SBP and Seismic Cone
  - calibration vs single pile tests
  - scale up to 1.5m dia and model Pile Group
- monotonic loading
  - good prediction
- load reversal
  - underpredict (but anticipated!)
- monitoring data overload?
  - 72 graphs per arch lift increment



Predicted and observed horizontal movement in the x direction of eastern arch base



Predicted and observed z rotation of eastern arch base



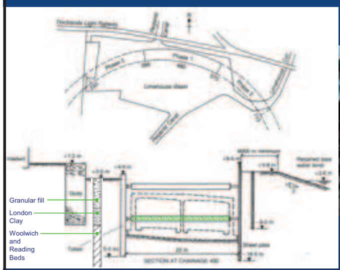
Arch roll up phase 3 - OM successfully implemented

Limehouse Basin

- old project (early 1990's, but important lessons on "limits" of OM

Limehouse Basin

- OM introduced - eliminate the need for mid-height props?

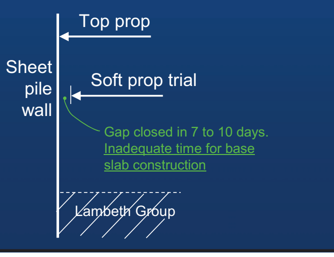


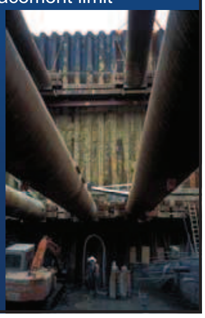
Limehouse Basin

- load on cofferdam
  - mainly groundwater pressure (control of water levels in fill?)
- failure mode
  - excessive bending of sheet pile wall
- critical measurements
  - complex due to stiffness contrast between N. wall ("stiff" steel tubes) and S. wall ("soft" sheet piles)
  - (absolute wall movement not wall convergence)

Progressive modification

- soft prop trial - gap at "safe" wall displacement limit
- risks associated with OM → too high





- OM did facilitate project benefits
  - Phase 2 - construction sequence changed

Original	After OM
Exc. to mid-height prop	Excavate to base slab level
Install mid-height prop	Install mid-height prop
Exc. to base slab level	

  - Phase 3 - reduction of sheet pile wall embedment, from 4m to 0.5m
    reduced sheet pile damage, hard driving
    reduced risk of declutching of sheet piles

Earthworks asset management
Potential for long term (decades) application of OM?

- most of UK rail network built >100 years ago
- embankments - end tipping of clay fill
- increasing problems of delayed failure and excessive track deformation

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Deep Seated Delayed Failure of Railway Embankment (6m high Grass Covered Slope)

Track Deformation. Seasonal Movement of Railway Embankment (Mature Tree Covered Slope)

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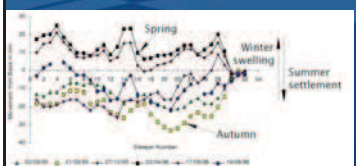
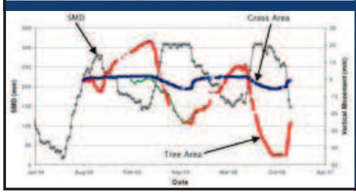
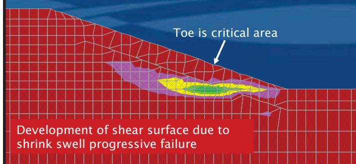
Field observations indicate embankment deformation critically influenced by





- Climate
- Vegetation
  - eg. High water demand trees on slope or grass covered slope

'Fatigue' failure of high PI clay fills
Consequence of seasonal changes in pore water pressure



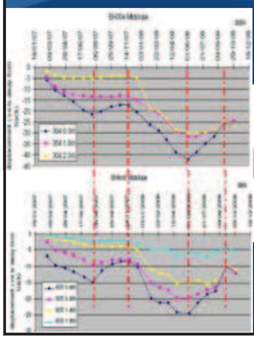
High plasticity clay, post-peak strain softening

NB Mechanism observed in both numerical and centrifuge modelling and in field

Development of Reidel Shear Zones

Can OM lead to more cost-effective stabilisation?

Complexity of ground movements



Normal seasonal movements vs. Movements prior to failure. Can we differentiate?

Numerical modelling shown wide range of movements may be acceptable, depending on local conditions

Long term Observational Method applications - Challenges

- site access often difficult
- local environmental constraints

} Speed of contingency measure implementation vs. speed of failure (days/weeks)

- duration and cost of monitoring (decades)
- organisational/human challenges → communication and control over long term
- potential to save money vs. cost of OM

Exploring the limits of the Observational Method

Conclusions

1. OM for pile groups - raising the Wembley Arch
   - pile groups, intrinsically stiff structures
   - monitoring system, reliable measurement of small movements
   - threshold limits (amber/red), depend on load combination
   - simple contingency, rapidly implemented

- challenging application!
- OM successful for managing risk during a unique task

Exploring the limits of the Observational Method

Conclusions

2. Limehouse Basin - a step too far
   - OM benefits outweighed by risks
   - BUT
   - introduction of OM created opportunities:-
   - improved construction sequence
   - reduced wall embedment

- hence, cost and time savings still achieved!

Exploring the limits of the Observational Method

Conclusions

3. Earthworks asset management - the weakest link?
   Long term application of OM
   - delayed failure of clay embankments
   - potential need for very long term application (decades)
   - prime challenge is human rather than technical

     ie. Ability of any organisation to apply OM over many years

(OM successful for cutting stabilisation, short term during construction)

Overall

Conclusions

Reliability of key measurements ↔	Mode/magnitude of deformation	← Human vs Technical Issues
Speed of response ↔	Type of failure mechanism	←
"Team" communication ↔	Team organisation/interfaces	←