Case study – Wembley Stadium

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Experience from new Wembley Stadium

- With 90,000 seats, the new Wembley stadium will be the largest football stadium in the world with every seat under cover. There will be NO obstructed views.

- The main architectural feature is a 133m high triumphal arch, 7.4m in diameter, with a weight of 1,750 tonnes. With a span of 315m, it is one of the largest and most slender structures in the world.

- Construction of 4000 piles, pile diameter 0.45-1.5m, pile lengths up to 40m. Extensive pile testing programme.
Experience from new Wembley Stadium

- Design by Mott MacDonald who performed extensive Repute analyses (both linear and non-linear) of pile groups during raising of triumphal arch.

- Large pile groups subject to complex loading (V, H, M, T)
  - soil non-linearity essential for realistic prediction

- During raising of the arch, monitoring was installed to determine the movements of the pile groups. These were compared to Class A predictions from Repute (see Hardy & O’Brien, 2006, for more information).
Ground conditions

- Made ground (varying thickness)
- 30-35m London Clay
  - unit weight $\gamma = 20$ kN/m$^3$
  - undrained strength
    - $C_u = 40 + 7.5z$ kPa ($z$ in m) for $z < 10m$
    - $C_u = 115 + 4.5z$ kPa ($z$ in m) for $z \geq 10m$
  - Young’s modulus → stiffness anisotropy:
    - Vertical $E_v = 60-232$ MPa (depending on strain level)
    - Horizontal $E_h = 9-171$ MPa (ditto)
- Chalk
- Water table at 2.5m depth
Shear modulus from seismic cone & self-boring pressuremeter

Shear Modulus at Small Strain (MN/m$^2$)

Depth below Top of London Clay (m)

- Weathered London Clay
- Unweathered London Clay
- Unit B
- Unit A
- Lambeth Group

SBP
SCPT
Using linear model to match lateral pile tests

- \( E_v \) drops: 232 MPa (initial) > 118 (FoS = 1.7) > 60 (failure)
- \( E_h \) drops: 171 MPa (initial) > 23 (FoS = 1.7) > 9 (failure)
- Non-linear analysis essential if large lateral loads exist
Using non-linear model to match lateral pile tests

Test Data

Non-linear

Single pile testing
Arch lifting mechanism

- The most critical engineering activity during the stadium construction was raising the arch to its final position ($112^\circ$).
Design of permanent Eastern Arch Base

• Pile group
  – No. 19 Piles (L =33m, D =1.5m)
  – Spacing: $S_x = S_Y = 5m$
• No. 121 load cases covering each angle of the arch at 5° intervals
• “Observational method” applied:
  – System of precision levelling (+/- 0.1mm) to determine movements of pile groups (settlements, deflections, rotations) during the arch lift
  – On the basis of the non-linear Repute analyses, amber and red limits were set
Comparison Repute vs measured behaviour: pile-group deflection in y direction

-4 -2 0 2 4 6 8 10 12 14

0 20 40 60 80 100 120

Measured
Repute
Amber limit
Red limit
Conclusions (from Hardy & O’Brien, 2006)

• “The predicted movements correlated very well with the observed movements and illustrate the importance of non-linear soil behaviour in modelling pile groups.
• If linear analyses had been undertaken, the movements and structural forces could have been under or over estimated by a considerable amount.
• Consequently the amber and red limits would have been set incorrectly and the safety of the arch lift could have been compromised”.