Assessment of ageing London Underground tunnels:
- Applying new technologies to old problems

Tim Morrison and Peter Wright
Tube Lines
Contents

- Background and purpose
- Scope and programme
- Methodology
- Generic studies
- Case study
  - Analysis
  - Site measurements
- Summary & conclusions
Background and purpose

- PPP contract requirements
  - Status of assets before contract
- Asset knowledge and condition
- Maintenance requirements
  - Running an efficient service
- Long term investment needs
  - Second review period
Scope

• Deep Tube Tunnel assets on the Jubilee, Northern and Piccadilly lines
• Approximately 187km of asset
  - Running/platform tunnels, station passageways and shafts
• Approximately 1700 assets in total

Programme

• Commenced in January 2003
• Contractual deadline is end of December 2008
• 18 months prior to end of first review period
• Last 18 months to agree management process for Deep Tube Tunnels in second review period
Methodology (1 of 2)

- Detailed review of contract requirements
- What existing data did we have?
- Identify knowledge gaps
- What information is required?
- Infrastructure to hold data
  - Asset database
  - Geographical Information System (GIS)
- Staged approach (next slide)
- Identify problem areas early in programme
Methodology (2 of 2)
STAGED APPROACH

Year 1 – Detailed desk study and initial assessments

LESSONS LEARNT

Year 2 – Detailed assessment (10%) and 12 generic studies

LESSONS LEARNT

Year 3 – Detailed assessment (20%) and 4 generic studies

LESSONS LEARNT

Year 4 – Detailed assessment (70%)

LESSONS LEARNT

Year 5 – Special access arrangements and completion of assessment programme
Generic studies

• Investigate on a global basis, rather than asset specific, wherever possible
• Apply results of these studies
• Examples:
  - Lining circularity
  - Cast iron lining thickness & strength
  - Geotechnical parameters
Tunnel case study

- Twin cast iron running tunnels 11ft 8.25in dia, built 1907
- 50m deep, 1.5m apart in London clay
- Location: Golders Green - Hampstead
- Assumed London clay characteristics
  - $S_u = 50 + 8z$ kPa where $z =$ depth
  - $E_{\text{undrained}} = 400.S_u$ (for geotech FE)
  - $E_{\text{eff long term}} = 200.S_u$ (for el. cont and struct FE)
Tunnel case study

• Analysis by
  - Elastic continuum
  - Geotechnical FE
  - 3D structural FE

• Site Measurements
  - Methods used
  - Interpretation

• Synthesis

• Discussion and tentative conclusions
Elastic continuum analysis

- Actually it’s a single tunnel
- $K_0 = \frac{\sigma_h'}{\sigma_v'} = 0.7$ (to give a conservative result)
- Perfect build, no surcharge (not assessment)
- Using Curtis/Muir Wood full-bond (conservative)
  - Stiff Ring
  - Flexibility adjustment according to Muir Wood
    - $I_{eff} = I_j + I. \left(\frac{4}{n}\right)^2$ for $n>4$ ($I_j = 0$)
Elastic continuum results

- **Stiff (monolithic)**
  - Def 6.2mm; 12.4mm squat
  - CI Stress -101 to +12 MPa
  - N = 95%OB, M = 12kNm

- **6 segment flexible**
  - Def 6.5mm; 13mm squat
  - CI Stress -75 to -15 MPa
  - N = 95%OB, M = 5.5kNm
Geotechnical FE

- Using Crisp
- CI Linings modelled as stiff ring $E = 100$ Gpa
- 50% OB earth support / lining preload.
- Lining assumed permeable long term
- London clay soil model
  - Mohr-Coulomb, non-associated dilation of 12.5%
  - $c' = 15$ kPa, $\Phi' = 25$ deg,
  - $k = 1E-10$ m/s
  - $K_0 = 1.0$ initially
K₀ Values

- Jakis eqn
- K₀ (unload)
- K₀ (reload)
- K₀ (50% underdrain)
- K₀ (Chudleigh)
- K₀ (underdrained)
Geotechnical FE

- LH tunnel constructed first
- Ground loss at excavation = 1.93% first tunnel, 1.69% second tunnel
- Initial, long term squat = -1mm, 6mm

Long term deformed mesh
Geotech FE

Hoop load
Max H = 1638 kN/m,
Equivalent overburden
= 84% for 1st tunnel
= 50% for 2nd tunnel

Moment
Max M = 13.5 kNm/m
Or approx 7 kNm/ring
Geotechnical FE

- Substantial long term settlement due to drainage of pore water into tunnel.

Long term settlement – 36%
3D structural FE

- Model of tunnel ring, non-linear cast iron
- “No tension” interfaces at radial joints
- “No tension” springs to simulate soil support
  - Stiffness = $E/R$
  - $= 40000$ kN/m
- OB load = 80%,
- $K_0 = 0.7$
Stresses along tunnel axis range from 54 MPa in tension to 41 MPa in compression.
Stresses around tunnel ring range from 89 MPa in tension to 97 MPa in compression.
3D structural FE

Looking at invert
Looking at invert, with LH segment removed

3D structural FE
3D structural FE results

- Lining behaviour is complex
- Despite joints opening there is no tension at bolt positions
- Similar run on monolithic lining yields similar results
- “Effective” stresses difficult to assess, but larger than expected from 2D analysis.
- Lining squat = 25mm
- Soil stiffness is main determining factor
Site measurements

- Lining thickness and loss of section
- Strength of cast iron
- London Clay strength and stiffness
- Pore water pressures
- Tunnel circularity
- Tunnel stresses
Coring and ultrasonics in grey cast iron
Typical coring and ultrasonic readings

### Position of Coring & Ultrasonic Inspection Results

#### NORTHBOUND RUNNING TUNNEL:

Position of cores relative to each other (in all cases):

<table>
<thead>
<tr>
<th></th>
<th>R1930</th>
<th>R1940</th>
<th>R3260</th>
<th>R3241</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1930</td>
<td>23.12</td>
<td>21.91</td>
<td>24.30</td>
<td>23.80</td>
</tr>
<tr>
<td>R1940</td>
<td>23.33</td>
<td>22.94</td>
<td>23.00</td>
<td>23.58</td>
</tr>
<tr>
<td>R3260</td>
<td>27.45</td>
<td>22.57</td>
<td>26.00</td>
<td>27.70</td>
</tr>
<tr>
<td>R3241</td>
<td>27.60</td>
<td>24.05</td>
<td>24.77</td>
<td>27.80</td>
</tr>
</tbody>
</table>

Average measured thickness of core:

<table>
<thead>
<tr>
<th></th>
<th>R1930</th>
<th>R1940</th>
<th>R3260</th>
<th>R3241</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1930</td>
<td>22.88</td>
<td>20.10</td>
<td>24.60</td>
<td>20.38</td>
</tr>
<tr>
<td>R1940</td>
<td>19.10</td>
<td>20.20</td>
<td>25.08</td>
<td></td>
</tr>
<tr>
<td>R3260</td>
<td>20.20</td>
<td>20.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3241</td>
<td>21.77</td>
<td>24.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Grey cast iron strength testing
Grey cast iron strength testing

![Graph showing tensile strength over time for different tests. The graph includes points for Transverse Rupture Test, Wedge Fracture Test, and Direct Tension Test, with trend lines for each.]
Grey cast iron strength testing

![Graph showing tensile strength distributions for Transverse Rupture Strength, Direct Tension, and Wedge Penetration tests.](image-url)
CPT and soil testing
CPT and soil testing

Su by all methods

- CPT
- Pressuremeter
- Lab
- Linear (Pressuremeter)
- Linear (CPT)
- Linear (Lab)

Equations:
- $y = 8.187x + 91.912$
  $R^2 = 0.8244$
- $y = 7.1962x + 63.639$
  $R^2 = 0.5926$
- $y = 11.03x + 0.0564$
  $R^2 = 0.9882$
CPT and soil testing

All tests for Su

- \( y = 9.74x + 49.85 \)  
  \( R^2 = 0.7095 \)
- \( y = 2.6097x + 162.07 \)  
  \( R^2 = 0.229 \)

- Up to 36m deep
- Golders
- Linear (Up to 36m deep)
- Linear (Golders)
CPT and soil testing

G = 4.5 + 1.3z MPa

E = 10.8 + 3.1z MPa

Assumed undrained E of 400.(50+8z)kPa equates to 20+3.2z MPa
CPT and soil testing

Graph: Pileometer Reading vs Distance from Tunnel lining

- **Y-axis**: Pore Water Pressure (kPa)
- **X-axis**: Horizontal Distance from Tunnel (m)

Lines represent different locations:
- Leicester Square
- Swiss cottage
- Goodge Street
- Heathrow T4
- Green Park
- Oval
- Bond Street
- Golders Green 1
- Golders Green 2
- Aldwych
Circularity measurement

Circularity carried out using Leica 3000 track trolley

Typical circularity measurement, showing approx 1% squat
Circularity measurement

Typical longitudinal plot showing tunnel deformations between Golders Green and Hampstead
ACSM - StressProbe
ACSM - StressProbe

Stress across CI pan (N/mm²)

Hoop Load adjacent to Opening
# Tentative Summary

<table>
<thead>
<tr>
<th></th>
<th>El Cont</th>
<th>Geo FE</th>
<th>3D FE</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diametric squat (mm)</td>
<td>12.4, Stiff 13, flexible</td>
<td>6.0 Stiff 25, flexible</td>
<td>≈ 0.67% 26</td>
<td></td>
</tr>
<tr>
<td>Max tens stress (kPa)</td>
<td>12, stiff -14 flexible</td>
<td>0</td>
<td>89</td>
<td>-</td>
</tr>
<tr>
<td>Max comp stress (kPa)</td>
<td>101, stiff 75, flexible</td>
<td>78</td>
<td>95</td>
<td>35-65</td>
</tr>
<tr>
<td>% Hoop load</td>
<td>95, stiff and flexible</td>
<td>84, first 50, second</td>
<td>Assumed 80 50-80</td>
<td></td>
</tr>
<tr>
<td>Max moment/ring (kNm)</td>
<td>12, stiff 5.5, flexible</td>
<td>7</td>
<td>-</td>
<td>4, axis</td>
</tr>
</tbody>
</table>
Summary and conclusions

- Tunnel assessment work now nearly complete
- Tube Lines Tunnels team have used a combination of in house and external expertise to carry out
  - Analysis
  - Investigation
  - Inspection
  - Assessment
  - Reporting
  - Classification
- Further back-analysis work required to be done to understand the tunnels more completely
  - Tim Morrison (Tim.Morrison@tubelines.com)
  - Peter Wright (Peter.Wright@tubelines.com)
Acknowledgements

London Underground  
Metronet  
Mott MacDonald  
Halcrow  
Sir Robert McAlpine  
Ove Arup & Partners  
Lankelma CPT Limited  
Castings Technology International  
Comech  

Norwegian Geotechnical Institute  
Constructive Evaluation Ltd  
TSC Inspection Systems  
Manex UK Ltd  
Geotechnical Consulting group  
Corus