Case Studies of Tunnel Inspection and Assessment

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CH2M (subcontracted to RISA for ROBO-SPECT Project)
Outline

• London Underground Tube Tunnels
  – A glimpse at tube tunnel history
  – Tube tunnel assessments 2003-2008

• Could tube tunnels in service fail?
  – 3 case studies where failure was averted

• Conclusions
A Key point in Tunnelling Development

• City and South London Railway......
• First cast iron tube railway completed in 1889
• From King William Street to Stockwell
• 4 miles of twin 10ft 6in tunnel in 4 years
• Compressed air working
• Greathead shield, JH Greathead was the engineer
• Original concept cable-hauled but changed to electric power
• Not a single life lost
Another key point? - The London Underground PPP Contract

- Under the London Underground PPP Contract (Tony Blair’s Labour government - late 1990s)
  - London Underground was the operator
  - Tube Lines Ltd were responsible for the maintenance and upgrading of the Jubilee, Northern and Piccadilly Lines
  - Metronet Ltd were responsible for the maintenance and upgrade of the rest of the network – they went into administration in 2007
  - Tube Lines was bought back into TfL in 2010
• Uniquely, under the PPP Tube Lines were required to carry out a tunnels “knowledge and inspection programme” – approx £10m allocated for this work

  – Work commenced in 2003

  – 210km of running tunnels, station tunnels, shafts, back of house tunnels, openings, headwall and all ancillary structures – 1000 assets, tens of thousands of sub assets

  – Completed and submitted to London Underground in 2008
Traditional Tunnel Analysis & Design

Elastic Continuum Method

- Morgan, Muir Wood, Curtis, Peck, Arends etc
- We used TOTALINE spreadsheet program (Curtis full bond).
Geotechnical FE

LH tunnel constructed first

- Ground loss at excavation = 1.93% first tunnel, 1.69% second tunnel

Long term deformed mesh
A closer look at a tunnel length..

- Distorted rings
- Cross passage opening, cross passage
- Cracked segments
- Ventilation opening
- Pump sump
- Disused station
- Shield chamber
- Cross tunnel

Varying separation, but normally less than 1 diameter
Risk Studies – How can LU tunnels fail?

Inspection/Assessment Options

Factors Affecting Failure Behaviour

What Tools are (or could be) Available?

What are the Engineering Factors that Influence Failure?

How Good? Mature?

Significance?

Linkage?

How will the Failure Happen?

Confidence?

So What?

Development

Consequence

How Good? Mature?

Consequence
Case Study 1 - Openings
“Unsupported” openings

1. Bolt Shear
2. Compression

Lintelled openings

1. Bolt Shear + Beam shear
2. Web buckling
3. Lintel Bending
4. Compression
5. Compression
Year 100!!

What happens next?
Case Study 2 – Expanded Concrete Tunnels
Visible signs of distress

- Spalling on edges of segments
- Horizontal Cracking of segments
“Real-time” Monitoring

Vibrating Wire Gauges - from Spring 2007
Why is failure occurring 35 years after construction?

- Overburden Load?
- Segment Strength?
# Strength vs Loading

## Segment Capacity (kN) vs Geometry

<table>
<thead>
<tr>
<th></th>
<th>Good</th>
<th>Poor</th>
</tr>
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<tbody>
<tr>
<td>Lower Bound Test result</td>
<td>1100</td>
<td>950</td>
</tr>
<tr>
<td>Reduced for low concrete strength</td>
<td>880</td>
<td>770</td>
</tr>
<tr>
<td>With Material safety factor of 1.5</td>
<td>590</td>
<td>510</td>
</tr>
</tbody>
</table>

## Applied Load (kN)

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<table>
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<tbody>
<tr>
<td>100% Hoop Load with safety factors</td>
<td>1360</td>
</tr>
<tr>
<td>Realistic range of Hoop Load</td>
<td>600 to 800</td>
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</tbody>
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Construction Issues

Quotes from Lyons, 1979
Pt 44. “the main problems were associated with bad ground. Expanded concrete linings built in the Woolwich and Reading Beds (Lambeth Group), some formations of which had very low cohesion, met trouble with falls of ground above shoulder level. The problem was overcome by the use of steel headboards attached to the rear of the shield body cylinder... (these) were given a slight overcut to prevent them being trapped as the ground swelled.”

LONDON CLAY
LAMBETH CLAY
CHALK
# Progression Towards Failure?

<table>
<thead>
<tr>
<th>Time</th>
<th>Defects</th>
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<tbody>
<tr>
<td>Normal operating condition</td>
<td>Typically design life</td>
</tr>
<tr>
<td>First signs of distress</td>
<td>Hard to define but could be months or years</td>
</tr>
<tr>
<td>Increasing deterioration rate</td>
<td>Typically days to weeks</td>
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### Typical Behaviour
- Performing within specification, minor spalls and cracking but within reasonable expectation, maintenance costs minimal. This (for non compliant structures) is also a function of the overburden load coming.

### Mitigation
- Maintenance, 4 yearly inspection
- Monitor distress using tell tales and gauges (BOTDR), take regular tunnel surveys, install strapping on rings that monitoring indicates are showing a trend towards failure condition. Increased inspection.
- Amber level to red level status. Install strapping on failing rings, Fill tunnel with foam concrete.

### Asset approaching or in Failure Mode
- Spalling and cracking occurs at rate greater than deemed normal and may impact on strength of individual rings. Tunnel and segment deformation becomes measureable (on sub mm scale). Out of Tunnel circularity measured at around 4 degrees (way below 19 degrees deemed for failure).
- Movement of segments and tunnel becomes measureable (on sub mm scale). Out of tunnel circularity measured at around 4 degrees (way below 19 degrees deemed for failure).

- Rate at which spalling and cracking is identified starts to increase significantly, Glass tell tales start to crack, and re-crack. Movement of segments and tunnel.

- Significant spalling, cracking, deflection of joints (approaching 19 deg) and tunnel.
Short Term Solution?

Strapping can be installed where monitoring shows the condition of a segment is deteriorating towards potentially a failure condition.
Case Study 3 – Fine Sand Ingress

• Sand and water ingress began approx July – August 2010.
• Not seen in previous Principal Inspections.
November 2010

- Manual monitoring results a concern for Tube Lines
- Frequent Special Inspections
- Emergency Preparedness Plan (EPP) in place
- Tunnel Risk considered to be ALARP
- But tunnel status at AMBER in terms of EPP
- Engineering Review Panel meets weekly
- Risk Assessment leverages funds for remediation
Upper Mottled Beds Sand Channel in Newman 2009

Fig. 10. (a) Relict sand channel encountered beneath Gloucester Place during investigation for Stage 2A (Battersea to Barrow Hill).
(b) Plan of suspected extent of relict sand channel encountered beneath Gloucester Place.

Slide courtesy of Jackie Skipper, GCG
Sounding and Probing

• Hammer Sounding has revealed significant drummy areas
• Probe in drummy areas may penetrate to 0.5m.

Possible Scenario
As at January 2011…..

- A concern that ongoing sand loss could adversely impact the integrity of the structure. How long before “failure”?
- Remedial grouting has a limited effect.
- Anticipated cement grouting project would go beyond normal Tube Lines maintenance and requirement to keep risks ALARP.
- LU Investment to remediate this tunnel was required as a matter of urgency; subsequently LU raised a CE with Bond St Station Upgrade project.
Tunnel Grouted during 2011-12 to fill voids
Conclusions

• Tunnel Assessments/Design normally done using
  – Elastic Continuum Approach eg Muir-Wood
  – Numerical Methods

• Tunnel Assessments are more detailed and include ancillary structures
  – Openings, Headwalls etc
  – Adjacent Structures

• Tunnels are Robust Structures, but they can fail in service.

• Carefully targeted investigations and assessments to understand the assets during the working life can help to “catch” failures. But simple inspection may not understand developing failure. ROBO-SPECT, with assessment tool, is better.

• Better understanding and modelling of failure, together with the intelligent use of instrumentation and monitoring on old assets, is recommended as a research opportunity.
Thank You