## EXHIBIT LIST

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<td>1</td>
<td><strong>R1246 Tun_sett_Teachin_V2_Final_5Jun15 (R1246)</strong></td>
<td>2 - 62</td>
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Tunnelling-induced ground movements and their effects

Professor Robert Mair CBE FREng FICE FRS
Cambridge University
June 2015
Outline of Presentation

- Background
- Sources of ground movement
- Settlement assessment
- Additional considerations for listed buildings
- Mitigation measures
- Pile-tunnel interactions
- Utilities
- Conclusions
• HS2 Route – Tunnelled Section (London Area)
• Ground & Groundwater Conditions
Background

West Ruislip Portal to Old Oak Common

R1246 (4)
Ground Conditions

**Tunnel Alignment**

- **West Ruislip Portal**
- **London Clay**
- **Lambeth Group**
- **Chalk**
- **Thanet Sand**
- **Old Oak Common**

- **100m**
- **4km**
Lambeth Group Example (HS1, Stratford Box)
Groundwater Level in the Deep Aquifer

West Ruislip Portal

Tunnel Alignment

Old Oak Common

100m ATD

Groundwater level in the deep aquifer
Sources of Ground Movement

- Why Settlement Occurs
- Tunnelling Methods
- Volume Loss & Patterns of Settlement
- Measured Volume Losses
- Portals and Shafts
- Long Term Settlement
Sources of Ground Movement

Why Settlement Occurs

• HS2 requires excavation of ground to form the tunnels, shafts and portals

• The ground around these excavations requires structural support - linings for tunnels and shafts, and walls for portals

• Excavation and installation of support to the ground inevitably produces small, controlled ground movements

• The ground movements cause settlement of the ground surface and buildings and utilities
Tunnelling Methods:
– Earth Pressure Balance Machine (EPBM)

1. Tunnel face
2. Cutting wheel
3. Excavation chamber
4. Pressure bulkhead
5. Thrust cylinders
6. Screw conveyor
7. Segment erector
8. Segmental Lining
Tunnelling Methods: Earth Pressure Balance Machine (EPBM)

1. Tunnel face
2. Cutting wheel
3. Excavation chamber

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Crossrail Bond Street Station - Construction of Sprayed Concrete Lining (SCL) Platform Tunnel

Pilot tunnel (5m diameter)

Monitoring targets

12m outer diameter
SCL – Typical Excavation Sequence with Pilot Tunnel

Step 1: excavate pilot tunnel

Step 2: enlarge in 3 stages
Sources of Ground Movement
Developing Settlement Trough

Extent of settlement trough

Longitudinal

Transverse

Direction of tunnel drive
Sources of Ground Movement

Longitudinal Settlement Trough

Ground Level

Settlement

Tunnel
Sources of Ground Movement - Volume Loss

Transverse settlement trough

Volume loss (VL, %) = \frac{\text{Volume settlement trough (A)}}{\text{Volume tunnel (B)}}

Typical EPBM VL is consistently < 1%

Typical SCL VL is consistently < 1.5%
Effect of Tunnel Depth - Schematic

Distance (m)

Settlement (mm)

Flatter slopes

Settlement

Tunnels

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Effect of Tunnel Diameter - Schematic

Distance (m)

Settlement (mm)

Depth (m)

Tunnels

Settlement
Measured Volume Losses in Various Soil Strata
Volume loss for Up-Line EPBM tunnel
CTRL Contract 220 (Wongsaroj et al, 2005)

Typical EPBM VL consistently < 1%
## Case Histories
### Volume Loss in SCL Projects in London Clay

<table>
<thead>
<tr>
<th>Project and SCL works in London Clay</th>
<th>Volume loss measured at end of construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redcross Way Trial</td>
<td>1.0%</td>
</tr>
<tr>
<td>Jubilee Line Extension Project, Waterloo Station</td>
<td>1.0% to 1.5%</td>
</tr>
<tr>
<td>Heathrow Express Trial Tunnel</td>
<td>1.05% to 1.37%</td>
</tr>
<tr>
<td>Heathrow Express Main Works - T4 Station Platform Tunnels</td>
<td>0.6% to 0.9%</td>
</tr>
<tr>
<td>Heathrow Express Baggage Transfer Tunnel</td>
<td>0.5%</td>
</tr>
<tr>
<td>Kings Cross Station Redevelopment Phase II</td>
<td>0.65% to 1.25%</td>
</tr>
<tr>
<td>Crossrail</td>
<td></td>
</tr>
<tr>
<td>1) Whitechapel Station Platform</td>
<td>1.22% - 1.29%</td>
</tr>
<tr>
<td>2) Liverpool St Station Platform</td>
<td>0.92% - 1.41%</td>
</tr>
<tr>
<td>3) Stepney Green Caverns</td>
<td>1.25%</td>
</tr>
</tbody>
</table>

**Typical SCL volume loss consistently less than 1.5%**
Portals and Shafts

• Excavation of portals and shafts cause ground movements

• Extent of settlement depends on shape and depth of excavation (H)

In the range of H to 2.5H

Magnitude of settlement is related to dimensions of excavation and stiffness of the props and walls
Long Term Settlement

• The settlements described previously are immediate - occurring during construction

• In the long term, further settlements could develop - these occur as a result of slow drainage of pore water from the soil into the new tunnel

• Long term movements occur very slowly and result in much wider and flatter settlement troughs

• Long term settlements are not usually damaging to structures and utilities
Settlement Assessment

- Settlement Assessment Process
- Definition of Risk Categories
- Basis of HS2 Assessments
- Examples from Crossrail & Jubilee Line Extension
- Conclusions for HS2
Assessment of Effects of Settlement

- Assessment of the risk of damage to assets is carried out using a screening process.
- The HS2 process is based on that used successfully on Crossrail, Jubilee Line Extension, Channel Tunnel Rail Link and many other projects worldwide.
- The approach is intentionally conservative.
- *Protective measures* will be provided where predicted effects are above acceptable limits.
Settlement Assessment – 3 Phases

Phase 1: simple criteria based on settlement and slope to eliminate buildings subjected to minimal effects.

Phase 2: conservative assessment of potential damage to buildings through distortions based on ‘greenfield’ settlements.

Phase 3: detailed assessment to determine risk of potential damage and design of protective measures if necessary.

Experience has confirmed that results of Phase 2 are conservative.
## Definition of Risk Categories (Building Research Establishment)

<table>
<thead>
<tr>
<th>Damage Risk Category</th>
<th>Degree of Damage</th>
<th>Description of typical damage</th>
<th>Limiting tensile strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Negligible</td>
<td>Hairline cracks less than about 0.1mm</td>
<td>0-0.05</td>
</tr>
<tr>
<td>1</td>
<td>Very Slight</td>
<td>Fine cracks treatable during decoration generally restricted to internal wall finishes. Typical crack widths up to 1 mm</td>
<td>0.05-0.075</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
<td>Cracks easily filled. Re-decoration probably required. Cracks visible externally and repainting required. Doors and windows may stick slightly. Typical crack width up to 5 mm</td>
<td>0.075-0.15</td>
</tr>
</tbody>
</table>
## Definition of Risk Categories
*(Building Research Establishment)*

<table>
<thead>
<tr>
<th>Damage Risk Category</th>
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<th>Limiting tensile strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Cracks may require patching. Repointing and replacement of parts of external brickwork. Doors / windows sticking. Utility service interruption. Crack widths 5 to 15mm</td>
<td>0.15-0.30</td>
</tr>
<tr>
<td>4/5</td>
<td>Severe / Very Severe</td>
<td>Major structural damage requiring extensive repair. Floors slope and wall bulge noticeably. Loss of bearing in beams. Utility disruption. Crack widths 15 to 25mm</td>
<td>&gt;0.30</td>
</tr>
</tbody>
</table>

Potential impact on function or structural damage
Tunnels: Summary of Typical Volume Loss Experience and Basis of HS2 assessments

EBP Machines
- Channel Tunnel Rail Link: 0.5 – 1.0%
- Jubilee Line Extension: 0.5 – 1.0%
- DLR Woolwich Extension: 0.5 – 1.0%
- Crossrail: 0.2 – 1.0%

Sprayed Concrete Lining (SCL)
- JLEP, HEX, KX & Crossrail: 0.6 – 1.5%

**HS2 assessments based on:**
1% for EPBM running tunnels
1.5% for SCL tunnels

\[
\text{Volume loss (\%)} = \frac{\text{Volume settlement trough}}{\text{Volume tunnel}}
\]
Assessment – Deformation Types

- **Sagging** (Compression)
- **Hogging** (Extension)
Deformation of Building above a Tunnel

Calculate the maximum tensile strain to determine damage risk category
Example from Crossrail - Phase 2
Assessment Results – Liverpool St Station

EPBM running tunnels usually do not cause significant damage
Case History (JLE)
Elizabeth House
Elizabeth House (JLE)

Comparison of Observations to Predictions

The Phase 2 assessment is intentionally conservative.

No damage observed in Elizabeth House due to tunnelling.
Conclusions for HS2 London Area

- A conservative and internationally accepted process is used to assess the risk of excavation-induced damage to buildings by the HS2 Project.

- For buildings affected by the EPBM tunnelling, the potential damage category is *Negligible* to *Slight* (i.e. Category 0 to 2).

- For some buildings close to shallow SCL tunnels, shafts and portals the potential damage category can be *Slight*, occasionally *Moderate* (i.e. Category 2 to 3).
Additional Considerations for Listed Buildings

- All listed buildings within the 10mm contour are automatically subject to a Phase 3 assessment.
- Additional considerations are taken into account for listed buildings, allowing for:
  i. Structural condition;
  ii. Structural sensitivity, and
  iii. Sensitivity of heritage features
## Additional Considerations for Listed Buildings

<table>
<thead>
<tr>
<th>Score</th>
<th>Criteria</th>
<th>Increasing vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Sensitivity of the structure to ground movements and interaction with adjacent buildings</td>
<td>Masonry building with lime mortar not surrounded by other buildings. Uniform facades with no particular large openings. No particular sensitive features</td>
</tr>
<tr>
<td>1</td>
<td>Buildings of delicate structural form or buildings sandwiched between modern framed buildings which are much stiffer, perhaps with one or more significant openings. Brittle finishes, e.g. faience or tight-jointed stonework, which are susceptible to small movements and difficult to repair.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Buildings which, by their structural form, will tend to concentrate all their movements in one location. Finishes which if damaged will have a significant effect on the heritage of the building, e.g. cracks through frescos.</td>
<td></td>
</tr>
</tbody>
</table>
Mitigation Measures

- General
- Compensation Grouting
- Big Ben Case History
Mitigation Measures

- Industry best practice during construction, including comprehensive monitoring
- Good control of the EPBM and good SCL construction - minimising volume losses
- If ground movements are still excessive, other measures include strengthening, underpinning, jacking or compensation grouting
Principle of Compensation Grouting

Grout injection

Excavated shaft

Tube a manchette (TAM)

Compensation grouting zone

Tunnel

Slight settlement with compensation grouting

Severe settlement without compensation grouting

Extent of trough
Principle of Compensation Grouting

Grout injection

Slight settlement with compensation grouting

First application of compensation grouting in UK Waterloo International Terminal
Principle of Compensation Grouting

Compensation grouting may possibly be required for HS2 at a few locations.
Big Ben Clock Tower
JLE Westminster Station Under Construction
Big Ben & Westminster Station (JLEP)

Tilt = $\frac{\Delta}{H}$

H = 55m

$\Delta = 31m$

JLE Escalator Box

JLE Platform Tunnels

Portcullis House

New Parliamentary Building

Palace of Westminster

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Big Ben & Westminster Station (JLEP)
Big Ben & Westminster Station (JLEP)
Plan Layouts of Grout Tube Arrays
Control of tilt of Big Ben Clock Tower by compensation grouting

Tilt of Clock Tower (mm/55m)

Tunnel Progress: Pilots

Enlargements

Grouting Episodes

Box Excavation Progress [m]:

Construction Control Range

Start of Grouting

Optical Plumb

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Tunnel may give Big Ben that Pisa tilt

The Tower of Big Ben may be moved 2cm out of place by tube tunneling work close to the Palace of Westminster, according to engineers.

They fear the possible stresses on the ground supporting the foundations of the Parliament building and the 186-year-old tower could result in damage. Their fears are revealed in leaked documents from the major engineering consultant firms of Ove Arup & Partners and Alan Baxter Associates who are helping to build the Jubilee Line Extension.

Two tunnels — each 23 feet wide — have been bored near the buildings. The tunnels are so close to the tower's foundations than an immense cage of steel tubes, filled with concrete, is being installed to shore up the ground.

The problem is no one can say for certain how much stress the ancient buildings and clock tower can take.

Displacement (10-20mm?) leaving the Palace of Westminster behind. Perhaps we could discuss this at our next meeting.

Although there have been fears before about the Big Ben tower leaning these have always been firmly denied by LU. Also, the amount of lean has always been put in the region of 3mm-5mm which engineers say is an annual occurrence, possibly as a result of the effects of the tidal Thames and change in seasons.

Moving experience: Big Ben may be put 2cm out of place.

Leaning tower of Big Ben is saved from an untimely fall

By James Chapman
Science Correspondent

Why Big Ben is leaning... and how it was fixed

1. Excavations for new Jubilee Line station caused the clock tower to lean by 25mm
2. With only 10% of foundations below 30ft tower, extra shoring was needed to stabilize big ben
3. From 40ft long tunnel, 29 steel tubes are fed below tower
4. Liquid cement pumped through tubes and forced out of bores at measured intervals. This allows precise reinforcement at specific points
5. Laser beam and plum line in tower will monitor any further movement

"It could have been grave"

with 'serious damage' by subsidence caused by the excavation, efficiently for us to bring in protective measures. It started to move as soon as the westbound tunnel was bored.

One man said that 500s had
Pile-Tunnel Interactions

- Examples for buildings
- Examples for piled bridges
Crossrail – Kempton Court

- Residential Flats
  - Constructed in 1996, Load bearing masonry
  - No basement – 4 storeys
  - Piled
Crossrail – Kempton Court

- **Bored Piles**
  - Pile cutting necessary for tunnel enlargement
  - Most piles within 4 m of tunnel crown
  - 350 mm Diameter Piles ~ 16 m length
  - 10.7m Diameter Platform Tunnels with 6.3m diameter Pilot Tunnels

[Diagram showing EB Tunnel and WB Tunnel with overlay of Superficial Deposits, River Terrace Gravels, London Clay, Toe Levels, and mATD values: ~110 - 111 mATD, ~+112.0 mATD, +92.0 mATD, +98.0 mATD, +87.5 mATD.]
Crossrail – Kempton Court

- Building settlements very similar to `Greenfield’ surface settlements
- Building settlements were tolerable
Crossrail Whitechapel Station - Swanlea School
Case Histories – HS1, London (bridges)

- Renwick Road (end-bearing piles in gravel), Jacobsz et al (2005)
  - Driven piles
  - 1% Volume Loss
  - Piles settled similarly to ‘greenfield’ settlements at pile toe
Case Histories – HS1, London (bridges)

- A406 Viaduct (friction piles), Jacobsz et al (2005)
  
  - Low Volume Loss ~ 0.3%
  - Pile settled similarly to ‘greenfield’ surface settlements
Pile-Tunnel Interactions - Conclusions

- On HS1 and Crossrail new tunnels were successfully constructed beneath and through existing piles.
- The settlement of the buildings and bridges were acceptable.
Utilities

• Similar to buildings, a risk-based, damage assessment process will be adopted for key utilities potentially affected by HS2.

• These utility assessments will be undertaken in full consultation with the utility providers.

• Mitigation and monitoring measures (if necessary) will be developed with the utility providers.
Conclusions

- There is considerable experience in UK from Crossrail, Jubilee Line Extension, HS1 and many utility tunnels – very little building damage occurred

- A conservative, internationally recognised methodology for the assessment of the risk of damage to buildings is being used

- Proven and effective protective measures are available - these will ensure that the planned works can be undertaken without significant settlement impacts
References

DoT (2013) IMPACTS OF TUNNELS IN THE UK Non-technical summary, August 2013

HS2 (2013) - Impacts of tunnels in the UK, May 2013

C3: Ground Settlement