Groundborne Noise & Vibration Impact From Rock Tunnel Boring Machines

Wilson Ho, Banting Wong
Wilson Acoustics Limited, Hong Kong

Andy Raine, Ken Kwok
Dragages Hong Kong Limited, Hong Kong
Introduction of Wilson HO

- Chairman of Vibration Sub-committee of HKIOA
- Founding Wilson Acoustics Limited in 2005
- Specialised in
  - Railway vibration and groundborne noise control
  - Floating slab track vibration design
  - TBM noise and vibration assessment

<table>
<thead>
<tr>
<th>TBM Projects</th>
<th>Railway Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSD West Drainage Tunnel 2009~</td>
<td>Taiwan TTY Int'l Airport Railway EMU Noise Control &amp; Trackform Vibration Isolation Design 2008~</td>
</tr>
<tr>
<td>CLP Castle Peak Tunnel 2006-08</td>
<td>MTR SCL &amp; WIL EIA – Operational and Construction Groundborne Noise Assessment 2008~</td>
</tr>
<tr>
<td>KCRC Kowloon Southern Link Tunnel 2006-08</td>
<td>MTR Test the Vibration Insertion Loss of 4 types of Resilient Baseplates 2008-09</td>
</tr>
<tr>
<td>KCRC Lok Ma Chau Tunnel 2003-05</td>
<td>KCR NOL &amp; XRL Prelim Environmental Railway Noise Assessment 2006-07</td>
</tr>
<tr>
<td>CLP Chi Ma Wan Tunnel 2002-05</td>
<td>MTR Olympic Station &amp; Tseung Kwan O South noise enclosure acoustic design &amp; commissioning 2006~</td>
</tr>
<tr>
<td>KCRC DB320 Kwai Chung Tunnel 1998-03</td>
<td></td>
</tr>
<tr>
<td>MTRC Quarry Bay Congestion Relief Works 1998-00</td>
<td></td>
</tr>
</tbody>
</table>
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim
2. Typical TBM GN&V Levels
3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force
4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage
5. Summary
Introduction

- Unrestricted 24-hour TBM tunnelling is always preferred for shortening construction programme

- Avoid TBM stopping at faults
  - Difficult to restart TBM
  - Water leakage
  - Ground collapse

- However, 24-hour tunnelling may not be allowed due to groundborne noise impact to the nearby buildings
TBM Nighttime Operation & Construction Noise Permit (CNP)

- Under Noise Control Ordinance (NCO), CNP is required for any TBM operation after 1900 hours.

- Based on the predicted TBM noise level, EPD may issue a CNP for TBM operation after 1900 hours.
Study Aim

When TBM passing through a sensitive area

- Minimization of groundborne noise is often demanded
- In General, reducing TBM advancing speed can reduce TBM Groundborne Noise and Vibration (GN&V) Levels
- However, a prolonged tunnelling program may eventually increase the overall exposure of noise and vibration dose.

- Any operation mode to minimize overall GN&V Impact?
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim
2. Typical TBM GN&V Levels
3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force
4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage
5. Summary
### Typical TBM Vibration Levels

<table>
<thead>
<tr>
<th>Distance, m</th>
<th>Typical RMS Vibration, mm/s</th>
<th>Typical PPV, mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m</td>
<td>0.1 to 1</td>
<td>-</td>
</tr>
<tr>
<td>10m</td>
<td>0.05 to 0.6</td>
<td>0.3 to 3</td>
</tr>
<tr>
<td>20m</td>
<td>0.025 to 0.4</td>
<td>0.1 to 1.5</td>
</tr>
<tr>
<td>30m</td>
<td>0.015 to 0.3</td>
<td>0.06 to 1</td>
</tr>
<tr>
<td>50m</td>
<td>0.012 to 0.25</td>
<td>0.04 to 0.8</td>
</tr>
</tbody>
</table>
TBM Vibration Criteria

- For annoyance concern, **No statutory limit in HK**

- For building structure concern, TBM induced ground vibration are generally lower than building vibration criteria.

- May cause damage to historical buildings and affect vibration sensitive equipment

- Critical frequency generally below 100Hz

- **TBM induced ground vibration is not a concern for most cases.**
**TBM Groundborne Noise Level**

<table>
<thead>
<tr>
<th>Distance, m</th>
<th>Typical TBM Groundborne Noise Level, dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m</td>
<td>~65 to 75</td>
</tr>
<tr>
<td>10m</td>
<td>~55 to 70</td>
</tr>
<tr>
<td>20m</td>
<td>~40 to 60</td>
</tr>
<tr>
<td>30m</td>
<td>~30 to 50</td>
</tr>
<tr>
<td>50m</td>
<td>~25 to 45</td>
</tr>
</tbody>
</table>

1. May be higher, if TBM is located at rockhead interface, and piling close to rockhead.

2. May be lower, if TBM is located at very soft soil, and piling is not close to.
TBM Groundborne Noise Criteria

Groundborne Noise Criteria under NCO and EIAO

- 10dB(A) below airborne noise limits
  - Daytime Noise Criteria: 55 to 65dB(A), (EIAO)
  - Evening Noise Criteria: 50 to 55dB(A), (NCO)
  - Nighttime Noise Criteria: 35 to 40dB(A), (NCO)

- Evaluated based on $L_{eq,5min}$

- Critical frequency range ~ 50 - 500Hz
## TBM Groundborne Noise Level

<table>
<thead>
<tr>
<th>Distance, m</th>
<th>Typical TBM Groundborne Noise Level, dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m</td>
<td>~65 to 75</td>
</tr>
<tr>
<td>10m</td>
<td>~55 to 70</td>
</tr>
<tr>
<td>20m</td>
<td>~40 to 60</td>
</tr>
<tr>
<td>30m</td>
<td>~30 to 50</td>
</tr>
<tr>
<td>50m</td>
<td>~25 to 45</td>
</tr>
</tbody>
</table>

- **Daytime Noise Criteria:** 55 to 65dB(A)
- **Evening Noise Criteria:** 50 to 55dB(A)
- **Nighttime Noise Criteria:** 35 to 40dB(A)
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim
2. Typical TBM GN&V Levels
3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force
4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage
5. Summary
# TBM Noise Prediction Model

The diagram illustrates the noise prediction model for TBM (Tunnel Boring Machine) operations. The model considers the propagation of noise through different layers and environmental factors. The source term includes the Excitation Force Level (EFL), and the propagation factors are Compression and Shear Waves, Surface Rayleigh Waves, and Soil Layer. The building response is influenced by factors such as building coupling loss, floor to floor vibration attenuation, and room acoustic response.

<table>
<thead>
<tr>
<th>Source Term</th>
<th>Propagation</th>
<th>Building Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>(EFL)</td>
<td>(PSR)</td>
<td>Building coupling loss</td>
</tr>
<tr>
<td>Excitation Force Level</td>
<td>Geological dispersion &amp; Soil damping</td>
<td>Floor to floor vibration attenuation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Floor resonance amplification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Room Acoustic response</td>
</tr>
</tbody>
</table>
Excitation Force Level (EFL) Measurement

Determination of EFL

EFL = L - PSR

Vibration Sensors

TBM Drilling

Impact Hammer

Force Sensor

Vibration Levels

Frequency

PSR

Frequency

Wilson Acoustics Limited
Influencing Factors on EFL

**TBM Specification**
- Excavation Mode
- TBM diameter
- Cutter discs arrangement

**TBM Operation**
- Thrusting Force → Penetration
- Rotational Torque → RPM

**Rock Type**
- Rock stiffness

---

Wilson Acoustics Limited
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim
2. Typical TBM GN&V Levels
3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force
4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage
5. Summary
Vibration on Ground Surface

West Drainage Tunnel
~1km from Western Portal at Cyberport
Impact Test Inside Tunnel

Impact test at the excavation face

Sensor at the excavation face

Sensor on the segment ring
# TBM Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation Mode</td>
<td>Open Mode full face hard rock</td>
</tr>
<tr>
<td>Cutter Head Diameter</td>
<td>8.28m</td>
</tr>
<tr>
<td>No. of cutter Disc</td>
<td>55 effective cutters, 60 total cutters</td>
</tr>
<tr>
<td>Cutter Disc Size</td>
<td>17”</td>
</tr>
<tr>
<td>Rotation Power</td>
<td>9 x 375kW (3375kW)</td>
</tr>
<tr>
<td>Motor Supply Voltage</td>
<td>690 Volts</td>
</tr>
<tr>
<td>Motor Maximum Global Current</td>
<td>1800 amps</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>28 MN for TBM hydraulic system</td>
</tr>
<tr>
<td></td>
<td>15 MN set as allowable limit for discs</td>
</tr>
<tr>
<td>Rotation Speed</td>
<td>0-8.4 RPM</td>
</tr>
</tbody>
</table>

Wilson Acoustics Limited
## TBM Operation Modes

### Typical Rock (Slightly Decomposed Fine Granite, ~ Specific Rock Mass Borability Index, SRMBI = 107)

<table>
<thead>
<tr>
<th>Penetration Rate</th>
<th>1 mm/rev</th>
<th>3 mm/rev</th>
<th>5 mm/rev</th>
<th>6 mm/rev</th>
<th>9 mm/rev</th>
<th>12.5 mm/rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 RPM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>3 RPM</td>
<td>O</td>
<td>O</td>
<td></td>
<td></td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>4.5 RPM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>6 RPM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>8 RPM</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td></td>
</tr>
</tbody>
</table>

### Stiff Rock (Very Strong, Fresh to Slightly Decomposed Granite, ~ SRMBI = 195)

<table>
<thead>
<tr>
<th>Penetration Rate</th>
<th>0.5 mm/rev</th>
<th>1 mm/rev</th>
<th>1.5 mm/rev</th>
<th>2 mm/rev</th>
<th>3 mm/rev</th>
<th>3.5 mm/rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 RPM</td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 RPM</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>4.5 RPM</td>
<td></td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 RPM</td>
<td></td>
<td>O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 RPM</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>
Rock Types

Penetration Rate Against Thrust at a fixed rotational speed of 3RPM

- **Typical Rock**
  - ~ slightly decomposed fine granite
  - ~ SRMBI = 107

- **Stiff Rock**
  - ~ very strong, fresh to slightly decomposed granite
  - ~ SRMBI = 195
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim
2. Typical TBM GN&V Levels
3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force
4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage
5. Summary
Wilson Acoustics Limited

Rotational Speed & EFL

\[ y = 15590x + 14525 \quad R^2 = 0.994 \]

\[ y = 32140x + 59888 \quad R^2 = 0.9943 \]

Typical Rock SRMBI = 107
Stiff Rock SRMBI = 195

Overall Excitation Force (N) vs. Rotational Speed (rev/min)

R^2 = 0.994

R^2 = 0.9943
Rotational Speed & EFL

Excitation Force, dB re 1N

1/3 Octave Band Center Freq, Hz

Stiff Rock

Wilson Acoustics Limited
Rotational Speed & EFL

Typical Rock

Excitation Force, dB re 1N

Rotational Speed & EFL

Wilson Acoustics Limited
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim

2. Typical TBM GN&V Levels

3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force

4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage

5. Summary
Penetration Rate & EFL

Wilson Acoustics Limited
Penetration Rate & EFL

Stiff Rock

Typical Rock
Penetration Rate & EFL

Excitation Force, dB re 1N

3.1mm/rev @8rpm 12.7MN
1.6mm/rev @8rpm 11.6MN
0.7mm/rev @8rpm 10.6MN
2.0mm/rev @3rpm 12.7MN
1.2mm/rev @3rpm 11.1MN
0.5mm/rev @3rpm 9.3MN

Penetration Rate & EFL

Stiff Rock
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim

2. Typical TBM GN&V Levels

3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force

4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - **Noise and Vibration Dosage**

5. Summary
Rotational Speed & Noise Exposure

* Noise Exposure Level is projected to receiver at 30m

Wilson Acoustics Limited
Rotational Speed & Vibration Dosage

VD per cubic meter excavation, \([\text{mm/s}^2 \text{s} / \text{m}^3]^{1/2}\)

Typical Rock
Stiff Rock

(solid) - evaluated based on the 2nd power of vibration amplitude
(dashed) - evaluated based on the 4th power of vibration amplitude
Penetration Rate & Noise Exposure

* Noise Exposure Level is projected to receiver at 30m
Penetration Rate & Vibration Dosage

2\textsuperscript{nd} Power Vibration Dose

4\textsuperscript{th} Power Vibration Dose
Penetration Rate & Vibration Dosage

VD per cubic meter of excavation, $\left[ \frac{\text{mm}^2}{\text{s}^2 \text{m}^3} \right]^{1/2}$

- Typical Rock, 8RPM
- Stiff Rock, 8 RPM
- Typical Rock, 3RPM
- Stiff Rock, 3 RPM

2nd Power Vibration Dose
Penetration Rate & Vibration Dosage

VD per cubic meter of excavation, [(mm/s)^4 s / m^3]^{1/4}

Typical Rock, 8 RPM
Stiff Rock, 8 RPM
Typical Rock, 3 RPM
Stiff Rock, 3 RPM

Penetration Rate (mm/rev)

4th Power Vibration Dose
Outline

1. Introduction
   - TBM Nighttime Operation Requirement in HK
   - Study Aim

2. Typical TBM GN&V Levels

3. Prediction Model for TBM GN&V Levels
   - Measurement of TBM Excitation Force

4. Measurement Results
   - Rotation Speed Dependent
   - Penetration Rate Dependent
   - Noise and Vibration Dosage

5. Summary
Summary

- TBM ground vibration is generally **not** a concern
- TBM noise limits its nighttime operation
- Soft & hard rock lead to different noise spectrum
- Doubling rotation speed lead to 4-5dB increase in N&V levels
Summary

- Reducing RPM decreases overall N&V dosage, but prolongs tunnelling programme.

- For typical rock, optimal PR (5 to 10 mm/rev), where N&V levels achieve maximum.

- Further increasing the PR would not further increase the N&V levels, but decrease the overall N&V dosage. Only observed in “typical rock”, may not apply to “stiff rock”

- For minimization of overall N&V impact, slower RPM and higher PR may be considered.
Thanks