Dynamic Response and Tunnel Damage from Explosion Loading

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Explosives Storage Safety

• Design must consider accidental explosion (airblast, ground shock, debris, fire)

• Internal Safety
  – Chamber separation
  – Prevention of sympathetic detonation

• External Safety
  – Inhabited buildings
  – Public transport route
  – Workshops
Large-scale Tests for Underground Storage

Collaboration with Swedish Defence Research Agency and Armed Forces HQ

Validation of underground facility design
- Airblast propagation
- Door pressure and response
- Ground shock,
- Debris hazards
- Response of tunnels (at criterion distances)
Layout of Test Facility
Test Facility Layout – 3D View
Chamber Sections

Adjacent tunnel

D = 0.6Q^{1/3}

13 m

Exploding chamber

8.8 m

100 m

Surface

Barricade

Tunnel Adit

Old Klotz Group Tunnel

Existing

Detonation Chamber

Slot Tunnel

2 m

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Considerations in Tunnel Design

- 10-ton explosives charge weight
- Fragment loading (155 mm rounds)
- Repeated blasts (3-4 year programme)
- Safety considerations (need to go into tunnel after test)
Requirements for Tunnel Design

• Rock mass properties (can’t take everything for granite!)
• Ground shock prediction
• Tunnel damage criteria (if you know what it means)
# Rock Mass Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type</td>
<td>Red porphyry syenite with grey granitic intrusion</td>
</tr>
<tr>
<td>Density</td>
<td>2620 kg/m³</td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>200-250 MPa</td>
</tr>
<tr>
<td>Uniaxial tensile strength (based on point load tests)</td>
<td>12.5 – 17.5 MPa</td>
</tr>
<tr>
<td>Rock mass quality</td>
<td>Avg Q value: 15-20</td>
</tr>
</tbody>
</table>
Ground Shock Prediction
### Sources of Ground Shock

<table>
<thead>
<tr>
<th>Sources</th>
<th>Illustration</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Tunnelling / mining – blasting               | ![Existing tunnel](image1) ![Blast zone](image2) | Fully coupled charge  
Low charge weight  
Multiple delays  
Repetitive blasting |
| Conventional weapons – penetration bomb      | ![Wireframe structure](image3)!n  ![Penetration effect](image4) | Limited charge weight  
Fully coupled or contact explosion  
Penetration & Cratering effects |
| Nuclear weapons                              | ![Nuclear explosion](image5) ![Nuclear crater](image6) | Largest charge weight (kt or Mt)  
Large displacement  
Generally indirect-induced shock |
| Ammo storage – accidental accidental explosion | ![Ammo storage chamber](image7) ![Explosion effect](image8) | Low probability  
Large charge weight  
Low loading density |
Empirical PPV Equation

\[ V = H \left( \frac{R}{Q^B} \right)^{-n} \]

\( H = \text{constant}; \ B = \text{scaling law}; \)

\( n = \text{attenuation coefficient} \)
### Parameters for Coupled Explosions

\[ H = \frac{(500/C^{2.17})}{(\rho C)}, \text{ mm/s} \]

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Rock Mass Density, ( \rho ), kg/m³</th>
<th>Seismic Velocity, ( C ), m/s</th>
<th>Initial Value, ( H ) (mm / sec)</th>
<th>Attenuation Coefficient, ( n ) D &lt; 6</th>
<th>Attenuation Coefficient, ( n ) D &gt; 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>&gt; 2600</td>
<td>5100-6000</td>
<td>5000</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Fair</td>
<td>2300-2600</td>
<td>4100-5100</td>
<td>4000</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Poor</td>
<td>&lt; 2300</td>
<td>3500-4100</td>
<td>3000</td>
<td>2.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\[ D = R/Q^{1/3}, \text{ scaled range, m/kg}^{1/3} \]

Conservative estimate for spherical charges
Correction Factors for PPV

- Charge geometry (distributed vs concentrated charge)
- Decoupled explosions (explosives not in full contact with rock)
PPV Correction Factor for Decoupled Explosions

Decoupling Factor

- --- Hultgren (1987)
- --- McMahon (1992)
- --- Joachim (1994)
- --- Mandai Granite

LST:
Loading density = 10 kg/m³
### PPV Prediction - Slot Wall

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Charge weight</strong></td>
<td>10000 kg</td>
</tr>
</tbody>
</table>
| **Fully coupled PPV**    | $5000 \left( \frac{R}{Q^{1/3}} \right)^{-1.5}$  
  $= 5000 \left( \frac{14}{10000^{1/3}} \right)^{-1.5}$  
  $= 10,760 \text{ mm/s}$ |
| **PPV correction for charge geometry** | 0.6 – 0.8                   |
| **Decoupling factor**    | 0.116 – 0.23                 |
| **Predicted PPV for slot wall (incipient)** | $10,760 \times 0.6 \times (0.116-0.23)$  
  $= 748\text{-}1,485 \text{ mm/s}$ |
Ground Shock Curves

Scaled horizontal distance, m/kg

Peak particle velocity, mm/s

- Rock free field data
- Tunnel Wall-Adjusted
- Quarry wall adjusted
- Best fit - Decoupled
- Klotz Group Test

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Tunnel Damage – What does it mean?
Damage of Unlined Tunnels – a Sample of Definitions

- Slight damage
- Medium damage
- Severe damage
- Intermittent failure
- Local failure
- General failure
- Tight closure
- Blow out

- Incipient swelling
- Incipient damage
- Dislodge of rock section
- Large displacement
- Minor damage
- Damage!
Damage by Earthquakes

Slot wall: PPV = 0.75-1.5 m/s

Calculated PPV and associated damage to underground excavations by earthquakes, Brady, 1991
## Damage of Swedish Hard Rock (Persson, 1997)

<table>
<thead>
<tr>
<th>Peak Particle Velocity (mm/s)</th>
<th>Tensile Stress (Mpa)</th>
<th>Strain Energy (J/kg)</th>
<th>Typical effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>8.7</td>
<td>0.25</td>
<td>Incipient swelling</td>
</tr>
<tr>
<td>1000</td>
<td>12.5</td>
<td>0.5</td>
<td>Incipient damage</td>
</tr>
<tr>
<td>2500</td>
<td>31.2</td>
<td>3.1</td>
<td>Fragmentation</td>
</tr>
<tr>
<td>5000</td>
<td>62.4</td>
<td>12.5</td>
<td>Good fragmentation</td>
</tr>
<tr>
<td>15,000</td>
<td>187</td>
<td>112.5</td>
<td>crushing</td>
</tr>
</tbody>
</table>
# Tunnel Damage (Li & Huang, 1994)

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Rock Parameters</th>
<th>Peak Particle Velocity, mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit Weight (g/cm³)</td>
<td>Comp. strength (Ppa)</td>
</tr>
<tr>
<td>Hard</td>
<td>2.6-2.7</td>
<td>75-110</td>
</tr>
<tr>
<td>Rock</td>
<td>2.7-2.9</td>
<td>110-180</td>
</tr>
<tr>
<td></td>
<td>2.7-2.9</td>
<td>180-200</td>
</tr>
<tr>
<td>Soft</td>
<td>2.0-2.5</td>
<td>40-100</td>
</tr>
<tr>
<td>Rock</td>
<td>2.0-2.5</td>
<td>100-160</td>
</tr>
</tbody>
</table>
1-D Elastic Calculations (Zukas, 1982)

• A saw-tooth wave pulse travelling along a rock bar

\[ V_{SP} = \frac{2\sigma_m - \sigma_{DT}}{\rho C} = 2 ppv - \frac{\sigma_{DT}}{\rho C} \]

\[ \sigma_m = ppv(\rho C) \]

\( V_{SP} \) = velocity of the first spall; \( s_m \) = magnitude of incipient stress; \( \sigma_{DT} \) = dynamic tensile strength of rock; \( \rho \) = rock mass density, kg/m\(^3\); \( C \) = seismic wave velocity in rock, m/s.
**1-D Spall Calculations**

Assumptions:
- Density = 2650 kg/m³
- Seismic velocity = 5500 m/s
- Dynamic tensile strength = 21.5 Mpa
- Dominant frequency = 100-500 Hz

Threshold PPV = \(0.5 \sigma_T/(\rho C) = 0.5(21.5 \times 10^6)/(2650 \times 5500) = 0.74\) m/s

Slot wall: PPV = .75-1.5 m/s
### UET Tests, Sandstone (after Hendron, 1977)

<table>
<thead>
<tr>
<th>Damage Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage</td>
<td>tight</td>
<td>General</td>
<td>Local</td>
<td>Intermitten failure</td>
</tr>
<tr>
<td>Free-field radial strain</td>
<td>NA</td>
<td>40</td>
<td>13</td>
<td>3-6</td>
</tr>
<tr>
<td>Free-field ppv, m/s</td>
<td>NA</td>
<td>12</td>
<td>4</td>
<td>0.9-1.8</td>
</tr>
<tr>
<td>Calculated thickness of 1st spall, m</td>
<td>0.3-1.4</td>
<td>1-4.2</td>
<td>2-18.5</td>
<td></td>
</tr>
<tr>
<td>Calculated number of spalls</td>
<td>11</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
1-D Spall Calculation for UET

Calculated Threshold

Assumptions:
- Density = 2400 kg/m³
- Seismic velocity = 2500 m/s
- Dynamic tensile strength = 8 Mpa
- Dominant frequency = 100-500 hz

Free-field Radial Peak Particle Velocity (ppv), m/s
### Explosive Testing of Tunnel Response (Dowding, 1984)

<table>
<thead>
<tr>
<th>Type</th>
<th>Strain%</th>
<th>PPV, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unlined tunnel:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint movement, fall of loose rock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermittent failure</td>
<td>0.015</td>
<td>2.0</td>
</tr>
<tr>
<td>Local failure</td>
<td>0.04</td>
<td>3.6</td>
</tr>
<tr>
<td>Complete closure</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td><strong>Lined tunnel:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracking of liner</td>
<td>0.02</td>
<td>1.0</td>
</tr>
<tr>
<td>Displacement of cracks</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Local failure</td>
<td>0.15</td>
<td>7.4</td>
</tr>
<tr>
<td>Complete failure</td>
<td>0.8</td>
<td>40.0</td>
</tr>
</tbody>
</table>
Design of Tunnel Support

- Unlined tunnel can sustain ground shock of PPV = 1.0-2.0 mm/s before damage begins
- Static support design specified fibre-reinforced shotcrete and rock bolts for increased performance against dynamic loads
- **Swedish Armed Forces HQ Requirements:** all military facilities in rock must use dynamic rock bolts
Swedish Dynamic Rock Bolts

Anchor Section

Smooth Section

Plain shotcrete

Reinforced shotcrete
Tunnel Support for LST

Tunnels supported with dynamic rock bolts
Tunnel Support for LST

Dynamic rock bolts

SFR Shotcrete

Dynamic rock bolts

Chamber

Slot Tunnel
## LST - Instrumentation

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Gauge Type</th>
<th>2000</th>
<th>2001</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOI</td>
<td>Air Blast – Chamber</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airblast – Tunnel</td>
<td>21</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airblast – External</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ground Shock</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>1</td>
<td>12</td>
<td>New - 11</td>
</tr>
<tr>
<td></td>
<td>Smoke puffs</td>
<td>0</td>
<td>0</td>
<td>Consider for future tests</td>
</tr>
<tr>
<td>NDCS</td>
<td>Air Blast</td>
<td>11</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ground Shock</td>
<td>16</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airblast Induced</td>
<td>0</td>
<td>2</td>
<td>New</td>
</tr>
<tr>
<td></td>
<td>Ground shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geophones</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>DTRA</td>
<td>Chamber – Pressure</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chamber – Bargauge</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressure – External</td>
<td>4</td>
<td>8</td>
<td>Stings (4)</td>
</tr>
<tr>
<td></td>
<td>Accelerometer</td>
<td>8</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radar – Fragment Vel.</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time of Arrival</td>
<td>0</td>
<td>15</td>
<td>New</td>
</tr>
</tbody>
</table>

|          |                             | 133  | 170  |
Shotcrete Panels in Slot Tunnel

<table>
<thead>
<tr>
<th>Panel Number</th>
<th>Gauge Number</th>
<th>Panel Thickness (mm)</th>
<th>Fibre Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S50</td>
<td>DA3</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>S51</td>
<td>DA4</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>S52</td>
<td>DA5</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>S100</td>
<td>DA6</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>S101</td>
<td>DA7</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>S102</td>
<td>DA8</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

**KEY**
- Uniaxial Acc. – DTRA
- Biaxial Acc. – FOA
- Biaxial Acc. – DTRA
**TNT Bare Charge (Test #3)**

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>NEQ (KG)</th>
<th>CHARGE TYPE</th>
<th>OBJECTIVES/DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>Bare charge</td>
<td>Ground shock calibration</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>Bare charge</td>
<td>Loading density 0.5 kg/m³</td>
</tr>
<tr>
<td>3</td>
<td>10000</td>
<td>Bare charge</td>
<td>Loading density 10 kg/m³</td>
</tr>
<tr>
<td>4a</td>
<td>2500</td>
<td>Bare Charge</td>
<td>Loading density 2.5 kg/m³</td>
</tr>
<tr>
<td>4b</td>
<td>10000</td>
<td>Cased Charge</td>
<td>Cased charge Test Loading density 10 kg/m³</td>
</tr>
</tbody>
</table>
Vide of Test #3 - 10000 Kg TNT
Chamber

- 10 craters in floor underneath charge
- No rock fall from roof!
Video Of Slot During Test #3
Slot Tunnel

- No visible damage of tunnel wall
- Slight soil movement on floor

Shotcrete Wall

Soil Movement
Slot Tunnel

- Lights (and all other fixtures) fully functional after detonation
Chamber Pressure

P = 115 Mpa

Equivalent PPV = \([\frac{115 \text{ Mpa}}{(2620 \times 5000)}] = 8.8 \text{ m/s}\)
VERTICAL BOREHOLE

LST Test #3 - NEQ = 10000kg
Location: Vertical Borehole @ 16m from Chamber Roof (Vertical)
Guage No.: G4

Acceleration, g

Time, ms

Velocity, m/s

Displacement, E-03 m

Time, ms
HORIZONTAL BOREHOLE

LST Test #3 - NEQ = 10000kg
Location: Horizontal Borehole @ 18m from Chamber Wall (Horizontal)
Gauge No.: G10

Time, ms
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Velocity, m/s
-0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2
Displacement, E-03 m
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6

3/16/01

Horizontal Borehole
Slot Tunnel
Detonating Chamber
Access Tunnel
Ground Shock on Slot Walls

LST Test#3 - NEQ=10,000 kg
26.4 m from back of slot - Shotcrete 100 mm - Fibre 60 kg/m³
Gauge No.: DA6

Acceleration

LST Test#3 - NEQ=10,000 kg
26.4 m from back of slot - Shotcrete 100 mm - Fibre 60 kg/m³
Gauge No.: DA6

Velocity, cm/s
Displacement, cm

Time, ms

1/18/01

Barricade
Tunnel Adit
Existing
Old Klotz Group Tunnel
Access Tunnel
Detonation Chamber
Slot Tunnel
Debris
PPV’s from Test #3

- Distance from Chamber Wall / Roof, m
- Peak Particle Velocity, mm/s

Graph showing data points for:
- Horizontal Hole
- Vertical Hole
- Slot Wall Peak
- Slot wall - Predicted
Strain on Rock Bolts (T3)

LST - Test#3
Rock Bolt
Strain - TT6

Strain = 0.00011
Fragment Loading (Test #4b)
Video of Test #4b
Damage in Chamber

- Spalling of shotcrete layer
- Still no rock fall from roof!
Slot Tunnel

- Lights (and fixtures) still fully functional during and after the test
- Damaged shotcrete fell off to floor
Comparison of PPV’s

**Bare TNT**
Best Fit for Test#3 - 10-ton TNT Charge
\[ \text{PPV}_{\text{TNT}} = 0.94 \left( \frac{R}{Q^{1/3}} \right)^{-1.3} \]

**Cased charges**
Best Fit for Test#4b - 10-ton Cased Charge
\[ \text{PPV}_{155} = 0.72 \left( \frac{R}{Q^{1/3}} \right)^{-1.3} \]

- Measured 10-ton TNT Charge
- Measured 10-ton Cased Charge
### Effects of Fragment Loading

Mostly fragments from outer row of rounds were loading the tunnel walls.

<table>
<thead>
<tr>
<th>Items</th>
<th>Test #3</th>
<th>Test #4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min PPV, m/s</td>
<td>0.94</td>
<td>0.62</td>
</tr>
<tr>
<td>Ratio of Min PPV</td>
<td>1.00</td>
<td>0.66</td>
</tr>
<tr>
<td>Max PPV, m/s</td>
<td>1.70</td>
<td>1.84</td>
</tr>
<tr>
<td>Ratio of Max PPV</td>
<td>1.00</td>
<td>1.09</td>
</tr>
<tr>
<td>Average PPV, m/s</td>
<td>1.39</td>
<td>0.98</td>
</tr>
<tr>
<td>Ratio of Avg PPV</td>
<td>1.00</td>
<td>0.70</td>
</tr>
<tr>
<td>Equivalent TNT Ratio</td>
<td>1.00</td>
<td>0.54</td>
</tr>
<tr>
<td>Test and Charge</td>
<td>Peak Chamber Pressure, MPa</td>
<td>Average PPV on Tunnel Wall, mm/s</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>-----------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Test 1 – 10 ton bare TNT</td>
<td>100</td>
<td>1390</td>
</tr>
<tr>
<td>Test 2 – 2.5 ton bare TNT</td>
<td>622</td>
<td>622</td>
</tr>
<tr>
<td>Test 3 – 10 ton TNT (1450 155mm shells)</td>
<td>50</td>
<td>977</td>
</tr>
<tr>
<td>Ratio of Seismic Velocity after Test 2</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
Conclusions

• Fresh rock damage appears to begin at PPV’s of 1-2 m/s

• At incipient PPV’s of 2-4 m/s, static support with rock bolts and fibre-reinforced shotcrete sufficient for tunnels in competent rock

• For low loading densities (10 kg/m$^3$), tunnels sited at 0.6Q$^{1/3}$ in hard rock can remain fully functional against ground shock loading
Finally,

If in doubt . . .

. . . build in rock
THANK YOU
THANK YOU