OVERVIEW OF TUNNEL AND SHAFT BLASTING TECHNOLOGY

TAC – Rock Tunnelling Workshop
Vancouver, BC
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By: Gordon Revey

SCOPE

• Blasting versus Mechanical Methods
• Managing Risk
• Identifying and Controlling Blast Effects
• Case Histories Demonstrating Controlled Blasting Techniques

EXCAVATION METHODS

TO BLAST OR NOT TO BLAST?

Use of mechanical or blasting methods depends on:
• Volume of material
• Hardness and structure
• Schedule
• Cost
RISKS OF “NO BLASTING”

114 Mpa (16,500 psi)
RQD = 96

RISK MANAGEMENT

SAFE & EFFICIENT BLASTING

1. Risk increases when any of these supporting measures and continuity of purpose are weak

BLASTING PROCESS

INFLUENCING FACTORS

- Rock Characteristics
- Explosive Properties
- Design Variables

RESULTS

- Fragmentation
- Broken Rock Profile
- Damage

The Blasting Process

PHYSICAL PROPERTIES

Stress = F/A (MPa or psi)
Direct Strain = \(\varepsilon/D\)
Tangential Strain = \(\varepsilon/W\)
Poisson’s ratio = \(\nu/D\)
Young’s Modulus = \(F/(\varepsilon/D)\) (GPa or psi)
ROCK PROPERTIES

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Density (g/cm³)</th>
<th>Young's Modulus (GPa)</th>
<th>Static Compressive Strength (MPa)</th>
<th>Static Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>2.4-2.9</td>
<td>35-60</td>
<td>50-300</td>
<td>6-30</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.2-2.7</td>
<td>10-40</td>
<td>40-150</td>
<td>2-15</td>
</tr>
<tr>
<td>Siltstone</td>
<td>2.0-2.8</td>
<td>10-15</td>
<td>40-130</td>
<td>2-12</td>
</tr>
<tr>
<td>Coal</td>
<td>1.2-1.5</td>
<td>2-8</td>
<td>4-40</td>
<td></td>
</tr>
</tbody>
</table>

MODERN EXPLOSIVE TECHNOLOGY

Modern explosives are much safer than the old "Dynamite and fuses" seen in Hollywood Movies.

The effects of controlled construction blasts look nothing like the gasoline explosions used to create spectacular movie scenes.

Commercial blasts are very controlled and carefully regulated.

EXPLOSIVES

Molecular and Composites

EMULSIONS

Oxidizer Salts in Aqueous Phase, surrounded by Oil Phase Matrix

Stiff & Putty Like for Packaged Products
SENSITIVITY

PROJECTILE IMPACT TEST

DYNAMITE VERSUS EMULSION EXPLOSIVE GAP SENSITIVITY

Bullet Velocity Needed To Initiate (ft/sec)

DYNAMITE
H.E. Emulsion
ANFO
H.E. Watergel

EXPLOSIVES HANDLING AND SECURITY

The Canada Explosives Act (R.S.C., 1985, c. E-17)
Canada Department of Natural Resources
Blasting Explosives and Initiation Systems - Storage, Possession, Transportation, Destruction and Sale Rules, March 2008
Guidelines for Bulk Explosive Facilities – Minimum Requirements, July 2010
Transport Canada

BLAST EFFECTS

Shock & Heave Energy
Cracking and Rupture
Vibration and Overpressure

RADIAL CRACKING

Limited Blasthole Crushing—in hard rock

Shock/Wave Front
Radial Compressive Stress
Tangential Tensile Stress
ROCK STRUCTURE
Bedding Planes
Partings & Joints
Caves and Mud Seams
Faults

JOINT EFFECTS
Minor Joints or fissures
Open Joint
Crack fronts are stopped by Open Joints
Cemented Joints

ENERGY LOSS
Gas Venting Though Open Joints
Blast gases venting through open joints (Lost heave energy)

PLASTIC DEFORMATION
- Argillite
- Wollastonite
- Marble
- Conglomerate

Explosive energy is lost to the rock’s internal friction
Limited Radial Cracks
Hole Expands (Plastic Deformation)
Deformation in Soft / Porous Material
TUNNEL BLASTING

1. DRILLING
   - Jumbo Drilling
   - Rock Bolts
   - Laser Beam
   - Face

2. LOADING
   - Shotcrete
   - Rock Bolts
   - Invert
   - Tunnel Face

BLAST AND VENTILATE

3. BLAST
   - Tunnel Face

4. VENTILATE
   - Tunnel Face

SUPPORTING TUNNEL

5. SCALE & MUCK
   - Load Haul Dump Unit
   - Muck
   - Scaling
   - Tunnel Face

GROUND SUPPORT

6. Muck
   - Shotcrete
   - Air & Water
   - Material Hopper
   - Tunnel Face

FINAL SUPPORT

7. ROCK BOLTING
   - Bolter
   - Shotcrete

8. CONCRETE LINING
   - Concrete Pump
   - Alignment Laser
   - Tunnel Face
   - Laser Spot
TUNNEL ROUND ELEMENTS

- Spacing
- Smoothwall or Back Holes
- Rib Holes
- Burden Holes
- Knee Holes
- Lifter Holes

DRILLING GEOMETRY

- Perimeter Hole
- Spacing (S)
- Buffer Hole
- Rib Hole
- Smoothwall Arch Holes
- Knee Hole
- Lifter Hole

TUNNEL BLASTING

- Designed overexcavation to create room for drilling
- Perimeter Hole Lookout Angle (Just enough for drill room)
- Over drill the burn cut
- Round Advance
- Expected Break

CUT METHODS

- Fan Cut Round
- Typical "V" Cut Round

SHIELDED BLASTHOLE BURN CUT

FOR 1 3/4 to 2 INCH JUMBO ROUNDS
EXAMPLE TUNNEL ROUNDS

SMOOTHWALL BLASTING

SMOOTHWALL BLASTING

SMOOTHWALL BLASTING

CONTROLLING OVERBREAK

TYPICAL CHARGES
Ground Shift Cut-off and Charge Separation in Jointed Rock Mass Caused by:

- Overloading
- Poor Tamping or Plugging
HIGH SHOCK EFFECTS

Shock Wave
Rock is Displaced Into Hole
High Pressure Gas Penetrates Into Hole
PRE-COMPRESSION CAUSES IN DELAYED HOLES

COMPRESSIVE SHOCK WAVE HOLE TO HOLE

POWDER FACTOR

SHIELDED BURN CUTS

CONVENTIONAL VERSUS ELECTRONIC DETONATORS

CONVENTIONAL, LP DETONATOR TIMING

Face Area (m²) Powder Factor Range
<table>
<thead>
<tr>
<th>Face Area (m²)</th>
<th>Low</th>
<th>High</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>40</td>
<td>2.3</td>
<td>6.5</td>
<td>10.5</td>
</tr>
<tr>
<td>4.6</td>
<td>90</td>
<td>2.9</td>
<td>6.3</td>
<td>10.6</td>
</tr>
<tr>
<td>5.6</td>
<td>90</td>
<td>2.7</td>
<td>6.7</td>
<td>9.6</td>
</tr>
<tr>
<td>6.6</td>
<td>70</td>
<td>2.4</td>
<td>6.2</td>
<td>8.7</td>
</tr>
<tr>
<td>7.4</td>
<td>80</td>
<td>2.0</td>
<td>4.4</td>
<td>7.4</td>
</tr>
<tr>
<td>8.4</td>
<td>90</td>
<td>1.8</td>
<td>3.8</td>
<td>6.6</td>
</tr>
<tr>
<td>9.3</td>
<td>100</td>
<td>1.5</td>
<td>3.1</td>
<td>5.3</td>
</tr>
<tr>
<td>10.6</td>
<td>200</td>
<td>1.2</td>
<td>2.6</td>
<td>4.4</td>
</tr>
<tr>
<td>12.3</td>
<td>250</td>
<td>1.0</td>
<td>2.1</td>
<td>3.6</td>
</tr>
<tr>
<td>18.6</td>
<td>500</td>
<td>0.6</td>
<td>1.5</td>
<td>2.7</td>
</tr>
<tr>
<td>25</td>
<td>500</td>
<td>0.8</td>
<td>1.5</td>
<td>2.7</td>
</tr>
<tr>
<td>50</td>
<td>75</td>
<td>1.0</td>
<td>2.1</td>
<td>3.6</td>
</tr>
<tr>
<td>75</td>
<td>100</td>
<td>1.5</td>
<td>3.1</td>
<td>5.3</td>
</tr>
<tr>
<td>100</td>
<td>125</td>
<td>1.2</td>
<td>2.6</td>
<td>4.4</td>
</tr>
<tr>
<td>125</td>
<td>250</td>
<td>1.0</td>
<td>2.1</td>
<td>3.6</td>
</tr>
<tr>
<td>250</td>
<td>300</td>
<td>0.8</td>
<td>1.5</td>
<td>2.7</td>
</tr>
<tr>
<td>300</td>
<td>500</td>
<td>0.6</td>
<td>1.5</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Adapted from Rock Blasting and Explosives Engineering, Persson et al. 1993
### CASE HISTORIES

**CONNECTION TO EXISTING CONCRETE-LINED PENSTOCK**

- **Dowels**
- **Resin**

**Existing Passage**
- **Bulkhead**
- **Wet**
- **Dry**

**Excavation Line**
- Elev. 558

**Platform Barrier**

**Concrete Demolition**

- **Probe Hole**

**Existing Tunnel Face**

- >=1300
- 4400
- 5050

**X X X X X Buffer Holes**

**Trim Holes**

**For Two-Stage Rounds Blast the Center First and then the Remaining Perimeter**

**Adjust to size of Face**

**DRY LAKE TAP**

<table>
<thead>
<tr>
<th>Shaft</th>
<th>Pump</th>
<th>Injection</th>
<th>Concrete</th>
<th>Electrical</th>
<th>Control Room</th>
</tr>
</thead>
</table>

**NEVER TAM**

**Primer Sticks**

12 to 18 inch Collar

**REGULAR BLASTHOLE LOAD**

8-in. Collar

**Collar Plug**

Tamped 1/2 stick (1 1/4 X 12)

**Tamp only the last stick (1 1/4 X 12)**

**Emulsion or semigelatin dynamite**

**Trim Explosive 1/2 Stick (Primer)**

**SMOOTHWALL PERIMETER**

8-feet folded 200 Grain Detonating Cord Taped to Primer Stick (7/8 x 24)

**TVA BLUE RIDGE DAM LOW LEVEL OUTLET**
CONDIT DAM LAKE TAP

*Careful Probing
*Redundancy

KOYNA WET LAKE TAPS

Pipe Spacers or wood blocking to align template normal to desired drilling alignment (Do not cover holes)

Hoisting anchor bolt with attachment ring secured with resin cartridges

Hoist template into position with four chain hoists

Hoist Eye Bolt 860 +/- 900 mm anchor bolts secured with resin cartridges

INSTALLED TEMPLATE (Section A-A)

92mm Hole 636.4

2mm Pipe Wall +/- 150

800

212.13

212.13

800

106.06

FOLSOM DAM TUNNEL

混凝土坝

CAVATATION IN OUTLETS
AERATION TUNNEL

BLAST EFFECTS MEASUREMENTS

Criteria Defined by Scaled Tests

FOLSOM DAM TUNNEL BLASTS

AERATION TUNNEL IN FOLSOM DAM
VIBRATION AND AIR-OVERPRESSURE PREDICTION AND CONTROL

AIR-OVERPRESSURE LIMITS

<table>
<thead>
<tr>
<th>USBM RECOMMENDATION from RI 8485¹</th>
<th>Lower Frequency Limit of Measuring System</th>
<th>Maximum Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 Hertz high pass system</td>
<td>Flat Response</td>
<td>134 Peak</td>
</tr>
<tr>
<td>2 Hertz high pass system</td>
<td>Flat Response</td>
<td>133 Peak</td>
</tr>
<tr>
<td>5 or 6 Hertz high pass system</td>
<td>Flat Response</td>
<td>129 Peak</td>
</tr>
<tr>
<td>C-weighted system for events with duration less than 2.0 sec.</td>
<td>Slow Response</td>
<td>105 Peak</td>
</tr>
</tbody>
</table>

LOGARITHMIC SCALE!

\[
\text{Decibels (dB)} = 20 \log \left( \frac{\text{psi}}{2.9 \times 10^{-4}} \right)
\]

Example: Absolute pressure (psi) = 0.01 psi
\[
\text{Decibels (dB)} = 20 \log \left( \frac{0.01}{2.9 \times 10^{-4}} \right) = 130 \text{ dB}
\]

If Absolute pressure = 0.1 psi, then:
\[
\text{Decibels (dB)} = 20 \log \left( \frac{0.1}{2.9 \times 10^{-4}} \right) = 151 \text{ dB}
\]

A 16% increase in Decibels equates to a 10-fold increase in real pressure.

Noise Control
AIR-OVERPRESSURE

STEMMING AND DIRT & MAT COVER

NOISE MITIGATION

EFFECT OF “CAP SCATTER”
ELASTIC STRAIN WAVES

Abbreviations:
SH = Shear wave, horizontal
SV = Shear wave, vertical
R = Rayleigh wave
P = Compressional wave

ATTENUATION RATE

VIBRATION AND AIR-OVERPRESSURE MONITORING

PLOTTING MOTION
**Velocity of Particle Motion or Air Overpressure Plotted with respect to time:**

- **PPV or dBL (in)**
- **Peak Amplitude**
- **Event Duration**
- **Background Noise**

**Event Duration**

- **Base Line**

**Concrete Motion at Yuba - Narrows 2 Project**

Displacement and corresponding strain caused by Earthquake is 416 Times greater than that of High-frequency Blast-Induced Motion

**Blast Vibration Criteria**

1. Intended for prevention of cosmetic damage in plaster-lath and gypsum drywall.
2. Too often misapplied to protect new or cured concrete structures.
3. These limits can make some work impossible or needlessly increase cost.

**Importance of Frequency and Duration**

- **LOMA PRIETA QUAKE - 1989**
  - Duration = 36 Seconds
  - Maximum PPV = 13.0 in/s
  - Frequency = 0.8 Hz
  - Displacement = 2.5 inches

**Concreta Motion at Yuba - Narrows 2 Project**

- Duration = 0.8 Seconds
- PPV = 3.2 in/s
- Frequency = 84 Hz
- Displacement = 0.006 inches

**Vibration Impact to Rock**

Approximate adjustment of rock mass quality after vibration. After Page 1987

- Effect of peak particle velocity on rock quality.

<table>
<thead>
<tr>
<th>Peak Particle Velocity (mm/s)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>254</td>
</tr>
<tr>
<td>25</td>
<td>254 to 625</td>
</tr>
<tr>
<td>50</td>
<td>254 to 625</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>&gt;2540</td>
</tr>
</tbody>
</table>

After Bauer and Collier (1977)
**Oriard Mass Concrete PPV Limits**

<table>
<thead>
<tr>
<th>Concrete Age From Batching</th>
<th>Allowable PPV - mm/s (in/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 4 hours</td>
<td>102 (4) x DF</td>
</tr>
<tr>
<td>4 hours to 1 day</td>
<td>152 (6) x DF</td>
</tr>
<tr>
<td>1 to 3 days</td>
<td>229 (9) x DF</td>
</tr>
<tr>
<td>3 to 7 days</td>
<td>305 (12) x DF</td>
</tr>
<tr>
<td>7 to 10 days</td>
<td>375 (15) x DF</td>
</tr>
<tr>
<td>10 days or more</td>
<td>508 (20) x DF</td>
</tr>
</tbody>
</table>

**Distance Factors (DF):**
- Distance = 0 – 15 m (0 – 50 ft) DF = 1.0
- Distance = 15 – 46 m (50 – 150 ft) DF = 0.8
- Distance = 46 – 76 m (150 – 250 ft) DF = 0.7
- Distance > 76 m (250 ft) DF = 0.6

Oriard and Coulson – 1980

Distance Factors are intended to reduce PPV levels at greater distances to account for higher displacements caused by lower frequencies.

**Relative Effects**

**Relative Vibration Impacts**

- More than 20 times higher than motion predicted at properties closest to CSO Blasts

- Buried Raw Eggs and Lightbulbs Survive 5.0 in/s PPV

**Displacement and Strain**

\[ \text{Displacement} = \frac{\text{PPV}}{(2 \pi f)} \]

1) Displacement at low frequency motion greater than at peak!

2) Time history reveals more than summary of motion at PPV
VIBRATION AND NOISE CONTROL

- Structural and Cosmetic Damage
- Human Response
- Animal Response

HUMAN RESPONSE

<table>
<thead>
<tr>
<th>Particle velocity (in/sec)</th>
<th>Exposure time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>10.0</td>
<td>100</td>
</tr>
<tr>
<td>100.0</td>
<td>1000</td>
</tr>
</tbody>
</table>

Strongly perceptible
ISO reduced comfort
Severe
Distinctly perceptible
Barely perceptible

ANIMAL RESPONSE

- "Pete" the Black Rhino
- Elephants
- Red Pandas
- Naked Mole Rats

DRILLING SMALL HOLES FOR SHAFT BLAST
REDUCE CHARGE PER DELAY

Separate Trunklines for each quadrant

+0  +126
+42  +84

PREDICTING PPV

PPV = K \left( \frac{D}{\sqrt{W}} \right)^m

Where:

K and m are constants defining initial vibration and rate of attenuation
D = Distance between blast and prediction location (m or ft)
W = Maximum charge weight per 8-millisecond delay (kg or lb)

DIMENSIONAL SIMILITUDE

Point 2
W = 100 kg
D = 100 m

Point 1
W = 1 kg
D = 10 m

PPV = K (Ds)^m

Linear in Log-Log Scale

PPV = K \left( \frac{D}{\sqrt{W}} \right)^m

Ds = \left( \frac{D}{\sqrt{W}} \right)

Log PPV = m Log (Ds) + Log K

y = a x + b

D = Ds
ORIARD PPV RANGE

\[ PPV = K \left( \frac{D}{\sqrt{W}} \right)^{1.6} \]

Where:
- \( D \) = Distance (ft)
- \( W \) = Charge per Delay (lb)

\[ PPV = 160 \left( \frac{D}{\sqrt{W}} \right)^{1.6} \]

Where:
- \( D \) = Distance (in)
- \( W \) = Charge per Delay (oz)

\[ PPV = 114 \left( \frac{D}{\sqrt{W}} \right)^{1.8} \]

Where:
- \( D \) = Distance (m)
- \( W \) = Charge per Delay (kg)

CASE STUDY

LEGEND
- Plaintiff's Home
- Monitoring Location

SCALE

0
500'
1000'

CURVE SLOPE

Harrod PPV Curve

Based on 519 Data Points. Correlation coefficient = 0.752

\[ PPV = 86.0 \left( \frac{D}{\sqrt{W}} \right)^{1.0} \]

Based on 329 Data Points. Correlation coefficient = 0.782

\[ PPV = 7.10 \left( \frac{D}{\sqrt{W}} \right)^{1.0} \]

\[ PPV = 86.0 \left( \frac{D}{\sqrt{W}} \right)^{1.0} \pm 95\% \text{ Confidence Interval} \]

CRACK DILATION
COMPARABLE EFFECTS

<table>
<thead>
<tr>
<th>Crack Location (Wall Material)</th>
<th>Comparative Changes in Crack Width</th>
<th>Effect</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside (Brick wall)</td>
<td>Inside Basement (Concrete Block)</td>
<td>Inside Bedroom (Dry Wall)</td>
<td>Inside Bedroom (Dry Wall)</td>
</tr>
<tr>
<td>Effect</td>
<td>Micro inches</td>
<td>Micro inches</td>
<td>Micro inches</td>
</tr>
<tr>
<td>Occupant Activity</td>
<td>400</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Wind</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Weather/Environmental</td>
<td>(18,000)</td>
<td>6000</td>
<td>(750)</td>
</tr>
<tr>
<td>Blasting Max</td>
<td>200</td>
<td>200</td>
<td>50</td>
</tr>
</tbody>
</table>

* Environmental effects on existing cracks in structures were 50 times greater than those caused by blasting.

DAMAGE CAUSES

Temperature Changes
Humidity Differences
Soil Expansion or Collapse
Water Damage
Wind and Weather
Aging Processes
Wear and Tear

CADOMIN ALBERTA

BLASTING NEAR NEW CONCRETE
CHARACTER OF MOTION

PPV > 30 in/s
Frequency: >1,000 Hz
Displacement: 0.0048 in
(Hair thickness: 0.008 in)

BLASTING NEAR SOLDIER PILES

Direct rupturing causes damage. High PPV at high frequency motion with light decoupled charges does not!

BLASTING NEAR FREEZE PIPES
**STRAIN CALCULATIONS**

* Free Face
* Orientation
* Timing

\[ V_b = V_s \times SF \]

If swell factor (SF) = 1.3
Swelled Volume (Vs) = Vb x SF

---

**CHARGE RELIEF AND SWELL**

**Swell factor Principle**

\[ V_s = 1.3 V_b \]

Swelled volume (Vs) Bench volume (Vb)

**RISK MANAGEMENT**

SAFE & EFFICIENT BLASTING

- Prequalification
- Design
- Specifications
- Specifications
- Pre-construction Inspections
- Apply Blasting Controls
- Charge Weight Limits
- Noise Control Measures
- Public Communication
- Project Hotline
- Open Meetings
- Government Approvals
- Perform Work Safely
- Continuous Blast Effects Monitoring

---

**BEST MANAGEMENT PRACTICES**

- Evaluate Area Property
  - Pre-construction Inspections
- Apply Blasting Controls
  - Charge Weight Limits
  - Noise Control Measures
- Public Communication
  - Project Hotline
  - Open Meetings
- Government Approvals
- Perform Work Safely
- Continuous Blast Effects Monitoring
SUCCESSFULLY MANAGING HIGH-RISK BLASTING WORK

There are four layers of expertise:

The first layer starts with designers who develop specifications, geotechnical reports, and other documents that:

1) define challenges of the work;
2) limit allowable methods;
3) specify performance requirements and;
4) establish experience requirements for key participants

SUCCESSFULLY MANAGING HIGH-RISK BLASTING WORK

The third layer of risk management is expected from third-party blasting/vibration consultants representing the contractor.

SUCCESSFULLY MANAGING HIGH-RISK BLASTING WORK

The last layer of risk management is delivered by a third-party construction manager, supported by inspectors, project designers, and additional specialists as needed.

QUESTIONS?