OUTLINE

1. Tunneling Basics
2. Brief History of Tunnel Construction
3. Modern Tunnel Construction
   • Bored (circular)
   • Cut and Cover (rectangular)
4. Shotcrete
5. Slurry Wall Construction
6. Shaft Construction
7. Tunneling in Seattle
TUNNELING BASICS

Why Shafts and Tunnels?

1. Transportation of People
2. Conveyance of Materials
3. Utility Corridors
4. Disposal of Waste
5. Military Defense
Tunneling Basics

Topography

Tunneling Basics

Tunnel Benefits
Tunneling Basics

Geology

Estimated Settlement

Construction Impacts
Urban Environments

SR 99 Single Bored Tunnel Under Seattle

January 2009

Washington State Department of Transportation
King County
City of Seattle

Russian Tunnel Traffic Video
Tunneling Basics

Rules of Thumb

1. Minimum ground cover over crown of tunnel ~ 1 diameter
2. Minimum Separation of bored twin tunnels ~ ½ diameter
3. Minimum radius of horizontal curvature ~ 15 diameters
4. Maximum vertical grade ~ 10%
5. Maximum external water pressure on a TBM ~ 7 bar (100psi)
6. Average advance rate in soft ground ~ 30 feet / day
7. Average advance rate in hard rock ~ 50 feet / day
8. Average advance rate in soft rock ~ 100-200 feet / day
9. Cost of 20 ft diameter EPB Tunnel Boring Machine ~$8M
10. Cost of twin 20 ft diameter lined tunnels ~ $15-$20K / ft
Brief History of Tunneling

Ancient Tunneling Techniques
First Tunnel Excavation Cutters
Roman Aqueduct - BC 200

Tunneling with Fire
Early Tunnel Boring Machines
First Tunnel Boring Machine

Wilson's Tunneling Machine 1851

Early Tunnel Boring Machines
Tunnel Boring Machine ~1900
New York Subway
CUT and COVER

circa 1902

Modern Tunnel Construction
Modern Tunnel Construction

1. Bored (circular)
   - Soft Ground Tunnel Boring Machines
     - Digger Shield
     - Earth Pressure Balance
     - Slurry
   - Hard Rock

2. Cut and Cover (rectangular)

3. Immersed Tubes (binocular)

4. Micro

5. Stacked Drift

6. Mined

Soft Ground Tunnel Boring Machines - TBM

- Open Face Digger Machine
  - Stable ground or with compressed air
  - Pressures up to around 20 psi
- Hard Rock TBM
- Earth Pressure Balance TBM
  - Uses excavated material to maintain pressure
  - Diameters up to 40 feet
- Slurry Pressure TBM
  - Uses slurry to maintain pressure on face
  - Diameters up to 50 feet (so far)
Tunnel Boring Machine

Simple Open Face

Soft Ground Tunnel Boring Machines

Earth Pressure Balance (EPB)
Soft Ground Tunnel Boring Machines

Earth Pressure Balance (EPB)

Soft Ground Tunnel Boring Machines

EPB Cutter Head
Soft Ground Tunnel Boring Machines

EPB TBM Complete

Cairo Metro 1995

Soft Ground Tunnel Boring Machines

Slurry Pressure
Soft Ground Tunnel Boring Machines

Slurry Pressure

Slurry Pressure TBM

Slurry Shield (2)
Soft Ground Tunnel Boring Machines

Slurry Process Plant

Slurry Pressure

Portland, Oregon 2003
Soft Ground Tunnel Boring Machines

Slurry Pressure

42' Diameter Road Tunnel – China 2005

Soft Ground Tunnel Boring Machines

Slurry Pressure

42' Diameter Road Tunnel – China 2005
Bored Tunnel Examples

- Lefortovo – Moscow
- Groene Hart – Netherlands
- Calle 30 – Madrid
- Subway Tunnel, Line M 8 - Shanghai
Lefortovo – Moscow

<table>
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<tr>
<th>Name</th>
<th>Lefortovo</th>
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<tr>
<td>Location</td>
<td>Moscow</td>
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<tr>
<td>Year Completed</td>
<td>2003</td>
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<tr>
<td>Diameter</td>
<td>46.6'</td>
</tr>
<tr>
<td>Length</td>
<td>7,300</td>
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<tr>
<td>Number of Lanes</td>
<td>3 @ 11.5'</td>
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<tr>
<td>Clearance</td>
<td>16.4'</td>
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Passes under environmentally sensitive park to connects two C&C tunnels.
Groene Hart – Holland

<table>
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<tr>
<th>Name</th>
<th>Groene Hart</th>
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<tr>
<td>Location</td>
<td>Holland</td>
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<tr>
<td>Year Completed</td>
<td>2003</td>
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<tr>
<td>Diameter</td>
<td>48.9'</td>
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<tr>
<td>Length</td>
<td>23,100</td>
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<tr>
<td>Number of Lanes</td>
<td>2 tracks</td>
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<tr>
<td>Clearance</td>
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<td></td>
<td>High speed rail connection under wildlife refuge / wetlands to mitigate C&amp;C impacts</td>
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Calle 30 - Madrid

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<tr>
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<th>Calle 30</th>
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<tr>
<td>Location</td>
<td>Madrid</td>
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<tr>
<td>Year Completed</td>
<td>2007</td>
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<td>Diameter</td>
<td>49.2'</td>
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<td>3</td>
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<tr>
<td>Clearance</td>
<td>14.7'</td>
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Passed under existing interchange to provide express connection and complete ring road
Shanghai Metro Line M8

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<th>Line M8</th>
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<tr>
<td>Location</td>
<td>Shanghai</td>
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<tr>
<td>Year Completed</td>
<td>2005</td>
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<tr>
<td>Diameter</td>
<td>21'</td>
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<tr>
<td>Length</td>
<td>6,600'</td>
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<tr>
<td>Number of Tracks</td>
<td>2</td>
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<tr>
<td>Advance Rate</td>
<td>50'/day</td>
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Passed under existing roadway at depth that varied between 10 and 20 feet.
Soft Ground Tunnel Boring Machines

Double Tunnel Lining

Shanghai Metro 2004

Segmental Tunnel Lining Systems
- One-Pass Liner
- Two Pass Liner
- Bolted and Gasketed Segmental
Precast Liner Segments

**One-Pass System**

- Plastic grout threaded lifting socket with non-return valve
- Key segment
- Gasket waterproof
- Compression joint packer
- Lock-up bolt pocket
- Circumferential lock-up bolt

*Tunnel Lining - One Pass*

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**Two-Pass System**

- Initial liner
- HDPE membrane
- Invert
- Final liner
- Walkway

*Tunnel Lining - Two Pass*
Segmental Liner Fabrication
Segmental Liner Fabrication

Precast Liner Segments
Liner Erection
Precast Liner Segments

Assembled Lining

Tokyo Metro

Precast Segments Video
Advanced Construction Techniques

Tunneling

HARD ROCK TBM's

Single Gripper
Double Gripper
Shielded
Double Shield

Hard Rock Tunnel Boring Machines
Hard Rock Tunnel Boring Machines

Govales, Texas
Advanced Construction Techniques
Tunneling

Hard Rock TBM Video

Sequentially Excavated Tunnels
Cast in Place Lining

Washington Park Station, Portland Metro
Cut & Cover Tunnels

Baggage Handling Facility Denver Airport 1993

Cut & Cover Tunnels

Open Cut Construction

63rd Street, New York City
Cut & Cover Tunnels

Bottom Up Construction

Westlake Station, Seattle, WA

Metro, Los Angeles, CA
Cut & Cover Tunnels

Top Down Construction

Bregenz, Germany

Cut & Cover Tunnels

Bottom Up Construction

Shanghai, China  1992
Cut & Cover Tunnels
Bottom Up Construction

Shanghai, China 1992

Stage 1
Existing Alaskan Way Viaduct, Seawall and Surface Street
Stage 2
Reduce parking, shift NB surface traffic under viaduct
Remove trolley, shift SB surface traffic to west of viaduct
Construct west tunnel wall/seawall

Stage 3
Excavate west side utilities and relocate or support in place
Set deck beams for temporary road surface over excavation
Stage 4
Construct temporary road surface over excavation

Stage 5
Shift SB surface traffic to temporary road on west side
Construct east tunnel wall and relocate/support utilities
Set support beams and construct temporary road surface
Stage 6
- Install dewatering systems
- Excavate below temporary road surface
- Place tiebacks and struts to support walls during excavation

Stage 7
- Cast lower slab, place waterproofing and construct lower box
- Progressively remove excavation supports as required
- Ventilate confined spaces with forced air from surface
Stage 8
Construct upper box, place waterproofing and cast top slab
Progressively remove excavation supports as required
Remove dewatering systems

Stage 9
Remove parking under viaduct and re-stripe for two way traffic
Shift SB surface traffic to under viaduct
Restore relocated utilities and place new utilities as required
Stage 10
Remove deck beams and construct permanent roadway
Shift SB surface traffic back to west side

Stage 11
Shift NB surface traffic back to west side of construction
Construct emergency exit stairwells and ventilations shafts
Shift viaduct traffic into new tunnel
Stage 12
Demolish Alaskan Way Viaduct

Stage 13
Construct central waterfront ramps
CM 510 ——— Advanced Construction Techniques

Tunneling
10 minute Break

Sunken Tube Tunnels
Construction in Dry Dock

BART, San Francisco, CA
Sunken Tube Tunnels

Floating Tubes

Central Artery - Boston, MA

Sunken Tube Tunnels

Casting Inside Walls
Sunken Tube Tunnels
Floating into Place

Central Artery - Boston, MA

Sunken Tube Tunnels
Placing and Connecting
Sunken Tube Segments

BART, San Francisco, CA
Sunken Tube Tunnels

Finished Tunnel

Ted Williams Tunnel, Boston, MA

Sunken Tube Alternate Video
Micro-Tunneling

Cutter Head

Micro-Tunneling

Launching from Shaft
Advanced Construction Techniques

Tunneling

Micro Tunneling Video

Underwater Micro Tunneling Video
Advanced Construction Techniques

Tunneling

Micro-Tunneling

Pipe Jacking

Atlanta, GA 1988

Stacked Drift Tunnel

Mt Baker Ridge Tunnel - Seattle (I-90)
**Stacked Drift Tunnel**
Under Construction

Mt Baker Ridge Tunnel – Seattle (I-90)

**Mined Tunnel**
Drill & Shoot + Shotcrete

TARP Drainage Tunnel, Chicago
Sequentially Excavated Tunnels

Road Header

Mined Tunnels

Shotcrete Lined

H3 Hawaii
Mined Tunnels

Unlined Tunnels

NORAD Facility – Colorado Springs

Sequentially Excavated Tunnels
Sequentially Excavated Tunnels

Sequential Excavation

Mined Tunnels

Shotcrete Lined

Beacon Hill, Seattle, WA
Shotcrete & Rock Bolts

**Shotcrete**

1. Concrete sprayed from nozzle
2. Applied to bare rock or ground for support
3. Typically not a final finish but can be troweled
4. Application thickness varies ½" to 4" per layer
5. Two types – wet or dry
6. May contain fiber or be sprayed over mesh
7. Typical strength $f'_c$ 3000 to 6000 psi
8. Can be built up in layers over 12" thick
Shotcrete & Rock Bolts

Shotcrete

Beacon Hill, Seattle, WA

Shotcrete & Rock Bolts

Shotcrete
Rock Bolt – Soil Nail

1. Steel reinforcement anchored into rock
2. Mechanical fastener, cement grout, or epoxy
3. Tensioned or passive
4. Application diameter varies \( \frac{1}{2} \)" to 1 ½"
5. Application length varies 6 ft to 30 ft
6. Radially out in tunnel crown or as spiling
7. Solid bars or multi-strand tendons
8. Typical bar strength \( f_y = 36 \) to 160 ksi
9. Tendon strength \( f_y = 270 \) ksi

ROCK BOLT

Mechanical Anchor

Polyethylene Shrink

150mm x 150mm x 4mm

Drill Piece

Hemispherical Washer

Grouting Injection Hole

Figure 9. CT bolt
Shotcrete & Rock Bolts

ROCK BOLT

Slurry Wall Construction
Slurry Wall Construction

Portland CSO Shaft Collar

Slurry Wall Construction
Slurry Wall Construction

Portland Westside CSO
Tunneling

Slurry Wall Construction

Portland Westside CSO

Drilled Shaft Construction
Shafts
Ventilation Shaft

Detroit MI

Shafts
Deep Metro Shaft

Tri-Met Washington Park Station
Portland, Oregon
Shafts

Physics Facility Shaft

SSC Waxahatchie, Texas 1992

Shafts

Physics Facility Shaft

SSC Waxahatchie, Texas 1993
Shafts
Rings and Liner Plates

Portland Westside CSO, 2003

Shaft Sinking Video
Shafts
Secant Pile Wall

Shafts
Access for TBM
Shafts
Access for TBM

Shafts
Launch TBM
100 years of Tunnel Construction in Seattle

Tunnels in Seattle

Union Pacific - Great Northern RR
Circa 1904
**Advanced Construction Techniques**

**Tunneling**

**Tunnels in Seattle**

**Battery Street Tunnel**  
Circa 1950

**Mt. Baker Ridge Tunnel**  
1984
Advanced Construction Techniques
Tunneling

Tunnels in Seattle

Seattle Bus Tunnel
Circa 1990

Pioneer Square Station
1990
Tunnels in Seattle

Sound Transit Mined Station
Beacon Hill - Exploratory Shaft Construction 2003

Tunnels in Seattle

Beacon Hill Transit Station
Construction 2006
Tunneling

Alaskan Way Tunnel Video

MORE INFORMATION

www_tunnelbuilder_com
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www_atlascopco_com
http://home.no.net/lotsberg
www.pbs.org/wgbh/buildingbig
www.pbs.org/wgbh/buildingbig/wonder