TUNNELING BASICS

Why Shafts and Tunnels?

1. Transportation of People
2. Conveyance of Materials
3. Utility Corridors
4. Disposal of Waste
5. Military Defense
Advanced Construction Techniques

Tunneling

Tunneling Basics

Geology

Construction Impacts

Estimated Settlement

Urban Environments

SR 99 Single Bored Tunnel Under Seattle

January 2009

Tunnel Anatomy

Tunneling Basics

Rules of Thumb

1. Minimum ground cover over crown of tunnel ~ 1 diameter
2. Minimum Separation of bored twin tunnels ~ 1/4 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
Tunneling

Ancient Tunneling Techniques
First Tunnel Excavation Cutters

Ancient Tunneling Techniques
Roman Aqueduct - BC 200

Ancient Tunneling Techniques
Tunneling with Fire

Early Tunnel Boring Machines
First Tunnel Boring Machine

Early Tunnel Boring Machines
Tunnel Boring Machine ~1900

New York Subway
CUT and COVER
circa 1902
# 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**

![Simple Open Face Diagram]

### Soft Ground Tunnel Boring Machines

**Earth Pressure Balance (EPB)**
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**Soft Ground Tunnel Boring Machines**

- **EPB Cutter Head**
- **EPB TBM Complete**
- **Cairo Metro 1995**

- **Slurry Pressure**
- **Slurry Pressure TBM**

- **Slurry Process Plant**
Tunneling

**Soft Ground Tunnel Boring Machines**

**Slurry Pressure**

- **Portland, Oregon** – 2003
- **42’ Diameter Road Tunnel – China** – 2005

**Increasing Size of Bored Tunnels**

- **Year**
  - 1975
  - 1980
  - 1985
  - 1990
  - 1995
  - 2000
  - 2005
  - **2010**

**Bored Tunnel Examples**

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

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Tunneling

### Lefortovo
- **Name**: Lefortovo
- **Location**: Moscow
- **Year Completed**: 2003
- **Diameter**: 46.6'
- **Length**: 7,300
- **Number of Lanes**: 3 @ 11.5'
- **Clearance**: 16.4'
- Passed under environmentally sensitive park to connect two C&C tunnels.

### Groene Hart – Holland
- **Name**: Groene Hart
- **Location**: Holland
- **Year Completed**: 2003
- **Diameter**: 48.9'
- **Length**: 23,100
- **Number of Lanes**: 2 tracks
- **Clearance**: NA
- High speed rail connection under wildlife refuge / wetlands to mitigate C&C impacts.

### Calle 30 - Madrid
- **Name**: Calle 30
- **Location**: Madrid
- **Year Completed**: 2007
- **Diameter**: 49.2'
- **Length**: 12,200
- **Number of Lanes**: 3
- **Clearance**: 14.7'
- Passed under existing interchange to provide express connection and complete ring road.

### Shanghai Metro Line M8
- **Name**: Line M8
- **Location**: Shanghai
- **Year Completed**: 2005
- **Diameter**: 21'
- **Length**: 6,600'
- **Number of Tracks**: 2
- **Advance Rate**: 50'/day
- Passed under existing roadway at depth that varied between 10 and 20 feet.
Tunneling

Shanghai Metro 2004

Soft Ground Tunnel Boring Machines
Double Tunnel Lining
Shanghai Metro 2004

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

Precast Liner Segments
One-Pass System

Precast Liner Segments
Two-Pass System

Segmental Liner Fabrication

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Segmental Liner Fabrication

Precast Liner Segments
Liner Erection

Assembled Lining

Precast Liner Segments

Tokyo Metro

Single Gripper
Double Gripper
Shielded
Double Shield

HARD ROCK TBMs

Hard Rock Tunnel Boring Machines
Tunneling

Hard Rock Tunnel Boring Machines

Govales, Texas

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
Cut & Cover Tunnels
Bottom Up Construction

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.
Tunneling

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 ventilation shafts
Shift viaduct traffic into new tunnel

Stage 12
Demolish Alaskan Way Viaduct

Stage 13
Construct central waterfront ramps

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Alaskan Way Viaduct Replacement

Sunken Tube Tunnels
Construction in Dry Dock

BART, San Francisco, CA

Sunken Tube Tunnels
Floating Tubes

Casting Inside Walls

Central Artery - Boston, MA

Sunken Tube Tunnels
Floating into Place

Placing and Connecting Sunken Tube Segments

Central Artery - Boston, MA

BART, San Francisco, CA
Sunken Tube Tunnels
Finished Tunnel

Ted Williams Tunnel, Boston, MA

Sunken Tube Alternate Video

Micro-Tunneling
Cutter Head

Atlanta, GA 1988

Micro-Tunneling
Launching from Shaft

Stacked Drift Tunnel

Mt Baker Rapid Tunnel - Seattle (I-90)

Micro-Tunneling
Pipe Jacking

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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

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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

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 ½” to 1 ½”
5. Application length varies 6 ft to 30 ft
6. Radially in tunnel crown or as spiling
7. Solid bars or multi-strand tendons
8. Typical bar strength fy = 36 to 160 ksi
9. Tendon strength fy = 270 ksi
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
Tunneling

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

Shafts
Secant Pile Wall

Shafts
Access for TBM

Access for TBM
Tunneling

Shafts
Launch TBM

100 years of Tunnel Construction in Seattle

Tunnels in Seattle
Union Pacific - Great Northern RR Circa 1904

Battery Street Tunnel Circa 1950

Tunnels in Seattle
Mt. Baker Ridge Tunnel 1984

Seattle Bus Tunnel Circa 1990
Tunneling

**Tunnels in Seattle**
- **Pioneer Square Station**
  - 1990
- **Beacon Hill Transit Station**
  - Construction 2006
- **Sound Transit Mined Station**
  - Beacon Hill - Exploratory Shaft Construction 2003

**MORE INFORMATION**
- [www.tunnelbuilder.com](http://www.tunnelbuilder.com)
- [www.herrenknecht.com](http://www.herrenknecht.com)
- [www.robbinstbm.com](http://www.robbinstbm.com)
- [www.lovat.com](http://www.lovat.com)
- [www.atlascopco.com](http://www.atlascopco.com)
- [http://home.no.net/lotsberg](http://home.no.net/lotsberg)
- [www.pbs.org/wgbh/buildingbig](http://www.pbs.org/wgbh/buildingbig)
- [www.pbs.org/wgbh/buildingbig/wonder](http://www.pbs.org/wgbh/buildingbig/wonder)