Consideration is generally given to:

- the ground conditions and its variability;
- the geometry, diameter and length of the tunnel;
- the tolerance of nearby structures to ground movement;
- the consequences of ground losses;
- the tunnelling cost;
- the safety of tunnel workers.

Selection of a tunnelling system (i.e., tunnelling method with/without additional measures, e.g., ground conditioning) involves choosing a method that is suitable for and compatible with the given ground and project constraints.
Cut & Cover

For shallow tunnels, cut & cover provides one of the most cost effective means of tunnelling (in terms of direct construction costs and operating economics, although incidental costs can change the balance completely).

Construction typically involves excavating a trench and placing pre-cast concrete tunnel segments in the trench. The trench is then backfilled and the road restored.

Cut & Cover

Distance from Excavation
Maximum Depth of Excavation

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sand and Soft to Hard Clay</td>
</tr>
<tr>
<td>2</td>
<td>Average Workmanship</td>
</tr>
<tr>
<td>3</td>
<td>Very Soft to Soft Clay</td>
</tr>
<tr>
<td>4</td>
<td>Limited depth of clay below bottoms of excavation</td>
</tr>
<tr>
<td>5</td>
<td>Significant depth of clay below bottom of excavation but</td>
</tr>
<tr>
<td>6</td>
<td>( T_H &lt; ) about 5</td>
</tr>
<tr>
<td>7</td>
<td>Settlements affected by construction difficulties</td>
</tr>
<tr>
<td>8</td>
<td>Very Soft to Soft Clay to a significant depth below bottom of excavation and with</td>
</tr>
<tr>
<td>9</td>
<td>( T_H &gt; ) about 5</td>
</tr>
</tbody>
</table>

Notations:
- \( T_H \) = Total overburden stress at bottom of excavation (subgrade)
- \( C \) = Undrained shear strength of the clay at subgrade (also designated \( S_C \))

Notes:
- All data shown are for excavations using standard soldier piles or sheet piles braced with cross-bracing or telesca.
Bracing & Shoring

Shoring: involves any method used to prevent the collapse of ground surrounding an excavation; built top-down as excavation proceeds.

Richmond-Airport-Vancouver Rapid Transit

Approximately 75% of the Vancouver segment of the Canada Line was built by "cut and cover".

<table>
<thead>
<tr>
<th>Contribution in Real $2003 (billion)</th>
<th>(1) Federal Government $140</th>
<th>(2) Province of BC $230</th>
<th>(3) VTA $277</th>
<th>(4) TransLink $100</th>
<th>(5) Concessionaire $49</th>
<th>Total $1.220</th>
</tr>
</thead>
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</table>

* Includes $152M deferred Provincial contribution.
Cut and cover is generally quicker than tunnel boring and more predictable in terms of scheduling.

The design involved two vertically stacked tunnels along Cambie St. in order to narrow the footprint of the cut & cover construction site and to help minimize disruption to traffic.

Tunnel Excavation in Soft Ground Conditions
Tunnel Excavation in Soft Ground Conditions

Tunnelling in soft, water saturated ground began with Marc Brunel in the early 19th century, when he invented the principle of shield tunnelling and undertook a contract in 1825 to tunnel under the Thames.

His shield consisted of 12 independent cells on three levels in which workers hand excavated the ground behind a secure wall of ‘poling boards’. One board would be removed to provide access for digging, after which it would be replaced and pushed forward by hydraulic jacks to re-engage the face support.

Brunel’s shield was 22’ high and 38’ wide, and enabled 36 miners to work the face at one time. The brickwork built right behind the ‘shield’ served as an abutment for the whole frame. On average, progress was 8’-14’/week.

Flooding was a constant problem for Brunel, with one such breach causing 6 men to drown. Brunel’s complaint to those offering advice on such difficult conditions, “In every case they make the ground to suit the plan and not the plan to suit the ground”.

Completed in 1843, Brunel’s tunnel is still in full use as part of London’s Underground railway system, exactly as built!
Tunnel Excavation in Soft Ground Conditions

James Greathead’s tunnel under the Thames (the 1869 Towers Subway) was built using a 7' diameter circular shield propelled by screw jacks, that employed the first use of cast iron segments for the lining. Greathead’s circular shield became the model for later open-face shields.

Shield Tunnelling

Advantages of shield tunnelling in soft ground:

1. Tunnel construction can be performed as one step at its full dimensions.
2. Constant support is provided to the advancing tunnel even though it takes the form of a moving system.
3. Omission of temporary support is compensated for by virtue of the immediate installation of the permanent lining.

Whittaker & Frith (1990)
Shield Tunnelling

Open- & Closed-Face Shields - When the tunnel face is free standing and does not require continuous support, the shield is operated in 'Open Mode'. The face is mechanically supported by the cuttinghead while the flood control doors regulate muck flow. With a closed-face, an airlock and bulkhead are used to allow the "excavation chamber" to be pressurized with compressed air or a slurry to aid face support.

Shield Tunnelling – Compressed Air

James Greathead solved the problem of containing groundwater during the construction of subaqueous tunnels in loose soil, by combining shield tunnelling with the use of compressed air during his 1886 construction of the London Underground.

This led to a considerable increase in the number of shield driven tunnels worldwide. At the beginning of the 20th century, the majority of the tunnels were built with Greathead shields.
**Shield Tunnelling – Compressed Air**

Factors to account for when tunnelling with compressed air:

- **Air pressure must be kept in balance with the hydrostatic pressure**;
- **Maximum pressure cannot exceed 4 bar (or 400 kPa), i.e. 3 bar excess pressure**;
- **Earth pressure cannot be resisted directly, it has to be withstood by natural or mechanical support**;
- **Ability to maintain pressure may be compromised by the air permeability of the ground (i.e. leakage)**;
- **Cover above the tunnel must be 1 - 2 tunnel diameters (depending on ground type) to avoid blow-outs**;
- **Shorter working hours result from loss of time during compression and decompression**;
- **Reduced performance of miners (danger of caisson’s disease)**;
- **Increased danger of fire (due to increased oxygen content)**.

**Slurry Shields**

Due to problems regarding health and safety as well as operations (in highly permeable ground, maintaining air pressure at the tunnel face is difficult), compressed air shields are being used less and less. Instead, slurry shields and earth-pressure balance shields are more favored.

Slurry shield operating principle:

- **Tunnel face is supported by bentonite slurry (i.e. tunnel is free from compressed air)**;
- **The slurry is mixed and pumped into a closed excavation chamber**;
- **The slurry enters the ground, sealing it (filter cake) and enabling pressure to be built up and balanced with the earth and water pressure**.
**Slurry Shields**

As the ground is excavated, it is mixed with the slurry in the excavation chamber. The suspension mixture is then pumped to the surface. In a separation plant, the slurry is separated from the ground. New bentonite is added as required, and the fluid is pumped back to the tunnel face.

Overall, slurry shields provide a safe tunnelling method causing low settlements. Application is possible in all kinds of loose ground with/without groundwater. Disadvantages include the separation plant (cost, space, energy requirements) and environmental hazards related to tailings (non-separable bentonite slurry containing fines).

Maidl et al. (1996)

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**Ground Loss**

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Earth Pressure Balance Shields

With a growing percentage of fines, slurry shield tunnelling requires an increasing degree of sophistication and cost for separation (and increasing frequency of slurry renewal). Apart from the high costs and environmental hazards involved, the confined space in most major cities makes the installation of a separation plant on surface difficult. Such were the conditions encountered in the early 70's in Japan, which led to the development of Earth-Pressure Balance shields (EPB).

EPB Shields: provide continuous support to the face by balancing earth pressure against machine thrust. As the cutterhead rotates and the shield advances, the excavated earth is mixed with foams in the cutterhead chamber to control its viscosity. The pressure is then adjusted by means of the rate of its extraction (by screw conveyor).

The key advantages of EPB Shields are that no separation plant is required and that the method is economically favourable in ground with a high percentage of silt/clay.

When using EPB tunnelling mode, no bentonite and special treatment plants are necessary and the outgoing soil is nearly natural. If additives like Foam or Polymers are used, highly biodegradable versions exist which can be 95% destroyed after 28 days.
Earth Pressure Balance Shields

Maidl et al. (1996)

Rysdahl et al. (2015)

Earth Pressure Balance Shields

Pressures at Excavation Face

Pressures Around TBM and Tunneling

Pore water pressure
Lateral effective stress
Cutterhead pressure
Slurry face pressure
Slurry tail shield pressure
Great annulus pressure

Cutterhead
Excavation chamber
Submerged wall
Air Bubble
Slurry feed line (blue)
Slurry return line (green)

Working chamber
Bulkhead
EPB Shields - Operation Modes

Babendererde et al. (2005)

Preventing Sinkholes - Discussion

Unit 3 – Lower Till
Unit 3 comprises two distinct soil types:
1. The prominent soil type is a well-graded mixture of silt, sand and gravel, with trace amounts of clay (generally <10%); and
2. Granular layers comprising sand and gravel.

Unit 5 – Sand/Silt Mixtures and Interlayered Sands and Silts
As for the other soils encountered along the Bored Tunnels, sand layers are to be expected in this soil unit. Similarly, gravel, cobbles and boulders are expected to be encountered in this deposit, occurring as drapestones.
Canada Line - EPB Bored Tunnel

An Earth Pressure Balanced system was used for part of the Canada Line. The TBM was launched from 2nd Ave., advanced under False Creek, then along Davie and Granville St. A TBM exit shaft was constructed on Granville south of Dunsmuir to extract the TBM. The TBM was then brought back to 2nd Ave. to be launched again to construct the second bored tunnel.

Stage 1
- Establish worksite
- Excavate entry shaft
- Cast slab base of entry shaft

Stage 2
- Ground conditioning prior to boring
- Set up crane and set up other equipment at worksite
- Set up and test TBM

Stage 3
- Perform tunnel boring
- Install pre-cast tunnel segments
- Remove excavated material through the tunnel and extract at entry shaft worksite

Stage 4
- Construct wet shaft prior to TBM arrival
- Remove TBM from wet shaft
- Repeat stages 1 through 3 for second tunnel
Tunnel Excavation in Soft Ground Conditions

<table>
<thead>
<tr>
<th>Shield Type</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Shield</td>
<td>Free standing ground</td>
</tr>
<tr>
<td>Mechanized Supported Closed Shield</td>
<td>Very weak ground (e.g., soft clay, silt, or running sand)</td>
</tr>
<tr>
<td>Mechanized Supported Open Shield</td>
<td>Slurry shields are favoured for water-saturated sandy soils and gravels (&lt;10% clay and silt content; e.g., running sand)</td>
</tr>
<tr>
<td>Compressed Air Caved Shield</td>
<td>EPB shields are favoured for water-saturated silty soils (&gt;7% clay and silt content; &lt;70% gravel content)</td>
</tr>
<tr>
<td>Compressed Air Open Shield</td>
<td></td>
</tr>
</tbody>
</table>
Special Cases – Immersed/Floating Tunnels

Immersed tunnels can be constructed in otherwise difficult/expensive conditions (e.g. soft alluvial deposits characteristic of large river estuaries). They can also be designed to deal with the forces and movements in earthquake conditions.

Submerged floating tunnels allow for construction in extremely deep water, where alternatives are technically difficult or prohibitively expensive. Likely applications include fjords, deep, narrow sea channels, and deep lakes.
Lecture References


