Introduction to Soft Ground Tunnelling in Urban Environment

Dr. Noppadol Phienwej

Geotechnical and Geo-environmental Engineering
School of Engineering and Technology
Asian Institute of Technology
ITA- Why Tunnel?

- A country’s infrastructure is one of its main assets
- Developed countries require a modern infrastructure
  - Roads
  - Railways
  - Power
  - Communications
  - Water
  - Wastewater
  - Gas
- Congestion above and at surface level in urban metropolis, where space is at a premium, means going under the ground is the only viable option
Infrastructures in Modern Urban Area
Characteristics and Constraints of Urban Tunnelling

- Tunnelling at shallow depth – Mostly soft ground tunnelling
- High risk due to soft ground and groundwater
- Construction in congestion area – Traffic disturbance
- Tunnelling at close proximity to existing buildings and utilities- space constraints
- Need to minimize damages to existing structures and third parties
- Need to control minimize movements
- Many parties involving- Work coordination
TUNNEL GROUNDS

- ROCK TUNNEL
- SOFT GROUND TUNNEL
Rock Tunnelling
Rock Tunnelling
Rock Tunnelling – Investigation, Design & Construction

Egnatia Motorway, Anilio Tunnel (Greece)
Rock Tunnel Excavation

Drill & Blast
Rock Tunnel Boring Machine
Rock Tunnel Boring Machine
Soft Ground Tunnelling
Soft Ground Tunnelling

What is soft ground?

Soft ground consists of various mixtures of sand, silt and clay.

It can be described as firm, raveling, squeezing, running flowing or swelling.

In all types of tunnelling, face stability is the primary goal, this is followed by ground movement control.
<table>
<thead>
<tr>
<th>No.</th>
<th>Classification</th>
<th>Tunnel Working Conditions</th>
<th>Representative Soil Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hard</td>
<td>Tunnel heading may be advanced without roof support.</td>
<td>Very hard calcareous clay; cemented sand &amp; gravel.</td>
</tr>
<tr>
<td>2</td>
<td>Firm</td>
<td>Tunnel heading can be advanced without roof support, and the permanent support can be constructed before the ground will start to move.</td>
<td>Loess above the water table; various calcareous clays with low plasticity such as the marls of South Carolina.</td>
</tr>
<tr>
<td>3</td>
<td>Slow Raveling</td>
<td>Chunks or flakes of material begin to drop out of the roof or the sides sometime after the ground has been exposed.</td>
<td>Fast Raveling occurs in residual soils or in sand with clay binder below the water table. Above the water table the same soils may be Slow Raveling or even Firm.</td>
</tr>
<tr>
<td>4</td>
<td>Fast Raveling</td>
<td>In Fast Raveling ground the process starts within a few minutes; otherwise it is referred to as Slow Raveling.</td>
<td>Soft or medium-soft clay.</td>
</tr>
<tr>
<td>5</td>
<td>Squeezing</td>
<td>Ground slowly advances into tunnel without fracturing and without perceptible increase of water content in ground surrounding the tunnel. (May not be noticed in tunnel but cause surface subsidence.)</td>
<td>Heavily precompressed clays with a plasticity index in excess of about 30; sedimentary formations containing layers of anhydrite.</td>
</tr>
<tr>
<td>6</td>
<td>Swelling</td>
<td>Like Squeezing Ground, moves slowly into tunnel, but the movement is associated with a very considerable volume increase in the ground surrounding the tunnel.</td>
<td>Cohesive Running occurs in clean, fine, moist sand.</td>
</tr>
<tr>
<td>7</td>
<td>Cohesive Running</td>
<td>The removal of the lateral support on any surface rising at an angle of more than 34° to the horizontal is followed by a &quot;run&quot;, whereby the material flows like granulated sugar until the slope angle becomes equal to about 34°. If the &quot;run&quot; is preceded by a brief period of raveling, the ground is called Cohesive Running.</td>
<td>Running occurs in clean, coarse or medium sand above the water table.</td>
</tr>
<tr>
<td>8</td>
<td>Running</td>
<td>Ground advances rapidly into the tunnel is a plastic flow.</td>
<td>Clay and silts with high plasticity-index.</td>
</tr>
<tr>
<td>9</td>
<td>Very Soft Squeezing</td>
<td>Flowing ground moves like a viscous liquid. It can invade the tunnel not only through the roof and the sides but also through the bottom. If the flow is not stopped, it continues until the tunnel is completely filled.</td>
<td>Any ground below the water table that has an effective grain size in excess of about 0.005 mm.</td>
</tr>
<tr>
<td>10</td>
<td>Flowing</td>
<td>Problems incurred in advancing shield or in borehoist blasting or hand-mining ahead of machine possibly necessary.</td>
<td>Boulder glacial till; riprap fill; some landslide deposits; some residual soils. The matrix between boulders may be gravel, sand, silt, clay or combinations thereof.</td>
</tr>
</tbody>
</table>
Soft Ground Tunnelling

Ground Movement

Face Stability
Tunnel Collapse
M4 metroline crossing Huangpu River in Shanghai
Methods of Tunnel Construction in Soft Ground

- **Cut & Cover Construction**
- **Tunnelling**
  - Shield Tunnelling
  - Non-Shield Tunnelling – Shotcrete & steel arch
- **Pipe Jacking (Micro Tunnelling)**
Soft Ground Tunnel Construction Methods

Tunnelling Method

- Shield Tunnelling Method
  - Open Face Shield
  - Partial Open Face Shield
  - Closed Face Shield

- NATM
  - Shotcrete & Ribs
  - Fore Poling Canopy
  - Soil Improvement

- Pipe Jacking
  - Micro - Tunnelling

Cut and Cover Method
Methods of Tunnel Construction in Soft Ground
Cut and Cover for MRT

Singapore

Hong Kong
Stuttgart, Germany
BANGKOK MRT

PILE SUPPORTED STRUCTURE
SHIELD TUNNELING
Shield Tunnelling
Reinforced Concrete Segmental Lining
Pipe Jacking (Micro Tunnelling)
TBM and first pipe placed on jacking frame and ready to commence excavation through the soft eye.
PIPEJACKING

TBM commences excavation and both pipe and machine together are pushed through the soft eye into the ground by the jacking cylinders.
Excavation is stopped, jacking cylinders are moved backward so that the next pipe can be placed behind the string.
Then the jacking cylinders are again pressed tightly against the pipe end, ready to push the whole line forward.
Jacking Operation - EPB 1500, 2600 and AVN 1200
Shields for Pipe Jacking

AUGER MATERIAL REMOVAL (AVT)

Auger material removal will be applied in soil without ground water. The advantages of the auger system: Simpler machine design than the AVN system and direct discharge of the excavated material, especially with cohesive ground.

1. Cutter head
2. Hard-faced picks
3. Crusher area
4. Crusher
5. Water nozzle
6. Main drive
7. Drive unit
8. Steer cylinder
9. Auger
10. Feed line
11. Laser beam
12. Valve block

SLURRY MATERIAL REMOVAL (AVN)

With the slurry material removal method, bentonite will serve as support and transport medium. The excavated material is transported to the surface via centrifugal pumps. The recycled bentonite is then returned into the circuit. Advantages: Tunneling beneath the water table possible, universal and efficient system.

1. Cutter head
2. Hard-faced picks
3. Crusher area
4. Feed injection nozzles
5. Main bearing
6. Main drive
7. Articulation seal
8. Steer cylinder
9. Discharge line
10. Feed line
11. Target
12. Laser beam
13. Bypass
14. Valve block
World Record Breaking Pipe Jacking Works in Bangkok

Iseki in Bangkok - first in the world to install the largest remotely controlled tunnelled pipeline.
Shield Tunnelling
### Shield Types

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Description</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>Open type</td>
<td>Good for hard, non-collapsing soils or semi-hard soils. Equipped with half-moon and jacks to hold the face. Special equipment, such as movable hood, movable deck, etc., is available if the soil condition requires it.</td>
<td></td>
</tr>
<tr>
<td>Conventional shields</td>
<td>Blind type</td>
<td>Good for soft, silty soils containing less sand. Muck discharge rate controlled by adjusting the aperture ratio in accordance with the excavating speed.</td>
<td></td>
</tr>
<tr>
<td>Semi-mechanical</td>
<td></td>
<td>A mechanized version of the manual open type, equipped with a back-hoe boom cutter if the soil condition requires it.</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
<td>A fully mechanized version of manual open or blind type. Full-face disc cutter is standard.</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
1. A pneumatic method is used to prevent water-seeping in soil which is excavated by an open type conventional shield. (Outside diameter of shield varies from 1.1-12m)
2. A pneumatic method is unnecessary in water-saturated soil and in complex strata thanks to the special shield adaptor. (Outside diameter of shield varies from 1.1-12m)
Jumbo loader and shield after break-through on Contract 3.

Scale:
Horizontal 1:1250
Vertical 1:250

Showing the extent of Contract 3.
EPB Shield

- Cutter disc
- Overcutter
- Cutter bit
- Additive injection hole
- Mixing blade
- Collapse detectors
- Simultaneously back-filling injection pipe
- Segment circularity maintaining device
- Belt conveyor
- Screw conveyor
- Segment erector
- Shield jack
- Tail seal
- Cutter drive hydraulic motor
- Segment erector
- Shield jack
General arrangement – EPB Shield Machine
Non-Shield Tunnelling
Conventional Method
Non-Shield Tunnelling
Shotcrete + Steel lattice
Soil Improvement
NATM
TUNNEL WITH SHOTCRETE AND STEEL ARCH
Invert Shotcreting
SEQUENTIAL EXCAVATION

Sequence of Construction by CRD Method

Standard Cross Section

Sequence of Construction

Backhoe Excavation
Muck removal
Belt loader
Invert concrete
L = 3.0m
Center diaphragm removal
Reinforcing steel
Concrete Lining
L = 6.0m
SEQUENTIAL EXCAVATION
UNSTABLE GROUND
ROOF SPILING
FOREPOLING
When there are stability problem of ground

Umbrella Roof Method
PIPE JACKED ROOF
Auxiliary gallery for groundwater infiltration, bulkhead freezing, temperature measurement of the frost blanket

Infiltration pipe

Temperature measurement

Shotcrete lining

Freezing pipe

Frost blanket

Inner lining

Sand

Gravel

Final state → Construction state

Each 47m launch for the sheet large tunnel
Figure 4.3 Displacement Measured at a model tunnel Heading Close to Collapse (C/D=1.2 P/D=0.1) (Casarin and Hair, 1981).
Squeezing when

\[
\frac{\gamma D - Pa}{C} > 5
\]

\(\gamma\) = Unit weight of Clay
\(c\) = Shear Strength
\(D\) = Depth of Tunnel
\(Pa\) = Compressed Air Pressure
Figure 5-4 Resaturation of the Ground to Reduce Air Leakage
Freezing method was used to remove the old structure and build new structure.

Freezing pipes needed to freeze the ground under the pre-existing tunnel. It could not be installed from the road.

Therefore, the curve boring method was adopted.
Fig. 39  Tunnel built beneath a building's

Fig. 40  Soil consolidation by chemical grouting
WORK CARRIED OUT

Tunnel excavation
(3.40 x 1.80 m) .................................. 333.4 m
Injection of limestone rock 1380 m²
Reinforced concrete
internal lining .................................. 975 m²

SCHEMAS 1, 2, 3, 4
Method of execution of the tunnel No. 1

SCHEMA 5
After the rock is tunnelled from
the first tunnel, the second
and third tunnels can be deepened.
INTERVENTION SHAFT EXCAVATION

Soft Clay

Stiff Clay

Sand
TUNNEL PORTALS AND SHAFTS
TUNNEL PORTAL – Slope Stability
Permanent Shaft Sinking
Completed Shaft from tunnel level
TUNNEL SUPPORT
Cross section showing primary and secondary lining, after Hughes (1987)

- A = Rearguard waterstop
- B = Invert concrete
- Primary lining:
  - P1 = Weldmesh
  - P2 = Lattice girders
  - P3 = Shotcrete
- Secondary lining:
  - S1 = Drainage fleece
  - S2 = Waterproof membrane
  - S3 = Final concrete lining
DESIGN PRINCIPLES

PRIMARY LINING OF SHOTCRETE INSTALLED CLOSE BEHIND FACE AS EXCAVATION PROCEEDS TO MINIMISE GROUND RELAXATION

• thin shell design approach (limited moment capacity)
• applied loads less than full overburden due to negative pore pressure leading to arching support
• time dependent build up of loads
• allow for stress concentrations from nearby tunnels
• limited duration of use before secondary lining cast
• includes load factor of 1.4
• structural analysis using bedded beam model
- Secure space in tunnel by supporting external force.
- **Primary lining:** Segment
- **Secondary lining:** Cast-in-place concrete
Installed Segmented Rings Behind Shield Tail Skin
Figure 2.1 Wedge block expanded concrete lining
Segmental Lining
Primary Grouting After Segment Erection

Cement / Bentonite

Sodium Silicate

Grouting Material gels within 8 Sec.
**Figure 26 Roof Load in Crushed Rock and Sand**

- **a) Ground Arch**
  - Surface
  - $w_1$
  - $B_1$
  - $H$
  - $D$ (Zone of Arching)

- **b) Assumed Support Loading**
  - Surface
  - Carried by Arching
  - Approx. $B + H_f$
  - Carried by Wedge 1, Carried by roof, Carried by Wedge 2
  - Direction of movement during excavation process
  - $H_p$
  - $H_f$

- **Note:** The diagram illustrates the distribution of loads and supports in a tunnel or similar structure, with emphasis on the arching effect and the distribution of forces through the ground and the roof.
Figure 25 Design Loads for Tunnel in Soil

LOADS

1. The weight of the upper half of the tunnel.
2. The weight of the earth within the area marked 2.
3. A uniform upward force balancing 1 and 2.
4. The weight of the loading above the top of the tunnel.
5. A uniform upward reaction balancing 4.
6. The horizontal pressure due to the water above the top of the tunnel.
7. The horizontal pressure due to the water from top to bottom of the tunnel.
8. The horizontal pressure due to the earth above the top of the tunnel equal to the product of the weight of earth (buoyant unit weight if submerged) above the top of the tunnel and the factor K.
9. The horizontal pressure due to the earth between the top and the bottom of the tunnel. At any point, the pressure is the product of the weight of soil between that point and the top of the tunnel and the factor K. Soil weighed as in B.
Ring Deformation + Pressure

Unconfined ring, uniform load.

Partially confined ring, concentrated load.

Unconfined ring, concentrated load.

Fully confined ring, concentrated load.
Collapse Ground Arch
Grout Port
Annular Tail Void
Grout
Excavated Perimeter

Active Pressure
Deformed Ring
Passive Pressure

Fully confined ring, random load.

Grout pressures on segmented linings.
OBSTRUCTION
I-I BRIDGE UNDER PINNING
Difficulties in Tunnelling and Effects on Building Foundation
BUILDING PROTECTION PRINCIPLES

- DESIGN & CONSTRUCTION METHODS TO MINIMISE GROUND MOVEMENTS
- PREDICTION OF MOVEMENTS REQUIRED
- BUILDING CONDITION SURVEY
- 2nd & 3rd STAGE ASSESSMENT IF REQUIRED
- ALERT LEVELS IDENTIFIED BEFOREHAND
- BUILDING PROTECTION IF REQUIRED
- INSTRUMENTATION & MONITORING
BUILDING DAMAGE
6.3 m outer-diameter
Single Track
TUNNEL–PILE RELATIVE POSITION
SUMMARY

- Angel Underground Station, London
- MRT North-East Line C704, Singapore
- MTR Island Line, Hong Kong
- MRTA Subway, Bangkok
- Electric Power Tunnel, Japan
- MRT Circle Line C825, Singapore
- Tokyo Subway Line 7, Japan
- Jubilee Line Extension, London
- Channel Tunnel Rail Link 2, London
- North/South Metroline, Amsterdam

Existing super-structure
Tunnel

Type 1
Type 2
Type 3
Type 4

45°
TUNNELLING NEAR TO PILE FOUNDATION

Columns

Building

Pile cap

Soil movement

Negative skin friction (NSF)

Downdrag

Resisting force

Lateral deflection

Piles

Tunnelling in progress
Transverse Settlement Trough due to Tunnel Boring

Location: Settlement Array, CS-9A (SS-9-1A-T)

Underground South Structures: Petchaburi Station to Rama IX Station

Figure 5.18: Transverse Settlement Trough due to Tunnel Boring (Parallel Running)
Vertical Movement Contour for Twin Tunnels (Case 3)

Loganathan and Poulos (1998)’s method
TYPICAL CROSS SECTION AND CONSTRUCTION ZONE FOR SINGLE TRACK BORED TUNNEL
RESPONSE OF PILE FOUNDATION TO TUNNELLING

- Pile lateral deflection and bending moment
  - Transversely (Perpendicular to tunnel advancing direction)
  - Longitudinally (Parallel to tunnel advancing direction)

- Tensile force in pile
  - Possible near pile head depending on the type of restraint

- Dragload (additional axial force) in pile
  - Above tunnel springline or invert level

- Pile settlement
  - Due to downdrag

- The type of response depends on the tunnel-pile relative position
Bangkok Tunnelling Experiences
RISK IN TUNNEL CONSTRUCTION
Causes of Soft Ground Tunnel Collapses

- Weak/variable grounds
- Uncontrolled groundwater
- Incompatible TBM (shield)
- Improper construction procedures and sequences
- Improper lining and installation
- Unforeseen buried obstruction
- Lack of experiences and workmanship
RISK IN TUNNEL CONSTRUCTION

- Considerably High
- Inherent Uncertainty in Geological Condition (Variability in Ground Type & Groundwater)
- Potential of Large-scale accidents
- Damages to Third Party (Urban tunnelling)
Thank You