Course in Tunnelling and Tunnel Boring Machine
Kurs w zakresie drążenia tuneli oraz maszyny drążącej

TBM IN SOFT GROUND

Lecture: Eng. Tommaso Grosso – Astaldi S.p.A.
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TUNNEL BORING MACHINE
What is a Tunnel Boring Machine?

A Tunnel Boring Machine (TBM), is a machine used to excavate tunnels with a circular cross section through different kind of soil and rock. Tunnel diameters can range from a metre (micro TBM) to almost 16 metres.

The excavation takes place at full face.

The machine itself provides support to the excavation and protection to tunnel personnel.

After the excavation the same machine erects the tunnel liner.
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The main functions of a TBM

A tunnel boring machine is not really a machine with a single function, but is a series of plant with many functions.

• Excavation

• Lining

• Functions to make possible Excavation and lining
EXCAVATION

• Remove muck to the portal
• Provide excavation fluids
• Provide/change cutting tools
• Provide lubricants and grease
• Provide industrial water
LINING

• Provide pre-cast segments
• Provide rock support (bolts, ribs, shotcrete..)
• Provide backfill grout
• Provide concrete for cast in place lining
FUNCTIONS TO MAKE POSSIBLE EXCAVATION AND LINING

• Provide energy

• Extend rails

• Remove water

• Provide fresh air and suppress dust

• Allow work in hyperbaric atmosphere

• Provide compressed air: breathable for hyperbaric and industrial

• Lighting

• Transport working crew
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TBM IN SOFT GROUND
BASIC PRINCIPLES OF MECHANIZED SHIELD TUNNELLING IN SOFT GROUND.

- Definition of tunnel boring machines
- TBM type:
  - Shielded tunnelling machines
    - EPB-Shield
    - Slurry-Shield
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GEOLOGY + HYDROGEOLOGY

- design of shield structure
- thrust force calculation
- wear prognosis
- support pressure calculation
- torque calculation

GEOTECHNICS
EARTH PRESSURE BALANCE SHIELD

1. Tunnel face
2. Cutting wheel
3. Excavation chamber
4. Pressure bulkhead
5. Thrust cylinders
6. Screw conveyor
7. Segment erector
8. Segmental Lining
The face support is provided by the excavated ground that is kept under pressure inside the excavation chamber by balancing the volume of the extracted and excavated material and by the thrust jacks on the shield. Excavation debris is removed from the excavation chamber by a screw conveyor that allows the pressure control by variation of its rotation speed.
EPB-SHIELD.

FOUR MODI: OPEN TO CLOSED.

- **Slurry mode**
- **Closed mode**
- **Closed (compressed air) mode**
- **Open mode**

- Decreasing face stability
- Decreasing water pressure
EPB-SHIELD.
MODE: SLURRY / CLOSED.
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EPB-SHIELD.
MODE: CLOSED (compressed air) / OPEN.
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EPB-SHIELD: THE SCREW CONVEYOR
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EPB-SHIELD: SCREW CONVEYOR
Course in Tunnelling and Tunnel Boring Machine
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EPB-SHIELD.
SCREW CONVEYOR. PRESSURE DISTRIBUTION.

- Pressure screw conveyor inlet
- Decreasing pressure per helix
- Pressure screw conveyor outlet
The lower part of the bulkhead in the front shield of an EPBS must be equipped with a safety gate, which can be closed when the screw conveyor is retracted for maintenance. This allows the complete insulation of the plenum, avoiding water/material inflow during maintenance.
EPB-SHIELD:
APPLICATION RANGE AND CONDITIONING.

- Clay
- Silt
- Sand
- Gravel

- Open shield possible
- Coarse soil foam + polymers
- Silty sand foam
- Very coarse soil foam, polymers and fuller

Conditioning necessary:
- Foam and additives (clogging – adhesion of soil)

Korngröße [mm]

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GEOTECHNICS: SOIL RECOMMENDATION

Clay vs Silt

- **EPB closed mode**
- **Additive against clogging**
- **Additive to plastify**

Sand vs Gravel

- **very strong permeable**
- **very permeable**
- **high viscosity bentonite**
- **Mixshield**
- **EPB + Additive**
- **Permeability k [m/s]**

Consistency $I_C$

- pulpy
- soft
- stiff
- hard
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FOAM: CLOGGING-ADHESION
ON STEEL SURFACE

Plasticity Index $I_p$ [%]

Consistency Index $C$

- High clogging risk
- Medium clogging risk
- Low clogging risk

- soft
- pulpy
- hard-stiff
- stiff
- hard
Soil recommendation for EPB-mode:

- cohesive and plastic
- soft stiff consistency
- small inner angle of friction
- low permeability
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CONDITIONING AND FOAM GENERATION

- Tenside
- Water
- Screw conveyor
- Cutting wheel
- Air
- Liquid
- Additive
- Tenside
- Polymer
### FOAM: PROPERTIES

#### Properties of foaming:
- plastic
- short term cohesion
- lower angle of friction
- lower permeability

#### Advantages of foaming in soft soil:
- reduction of friction angle of soil
- short term cohesion of soil
- plasticity and lower permeability of soil
- lower wear
- lower torque
- short term stabilistation of face
- lower clogging
- soil structuring

#### Different foams have different:
- foaming capacity
- stability
- Anti-clay capacity
- rheological impact (liquefaction / stiffening)
- drying-up capacity
FOAM: CONDITIONING IN SOFT SOIL

- Low cohesive sand
- Short-term cohesion via foam
Foam Injection Rate (FIR):

- FIR regulates amount of foam
- FIR correlates with pore volume
- FIR = volume foam / volume soil
- FIR correlates with advance rate
Foam Expansion Rate (FER):

- FER regulates quality
- low FER = wet foam
- high FER = dry foam
- FER = volume foam/volume liquid
Use of Anti-clay-Additives in clay as well as in silt & sand:

- Problem
  - adhesion on steel surface
  - cohesion of greater clay lumps
- Conclusion
  - clogging of cutting wheel
  - clogging of screw conveyor or excavation chamber
FOAM CONTROL AND FOAM GENERATOR.

- Automatic Mode
- Semi-Automatic Mode (FER)
- Manual Mode (FIR/FER)

- short distance to tunnel face
SLURRY/HYDROSHIELD TBM

- 1. Cutting wheel
- 2. Pressure bulkhead
- 3. Compressed air
- 4. Submerged wall
- 5. Slurry line
- 6. Stone crusher
- 7. Feed line
- 8. Segment erector
HYDROSHIELD OPERATION PRINCIPLE.

- 1. Submerged wall
- 2. Working chamber
- 3. Compressed air
- 4. Pressure bulkhead
HYDROSHIELD / MIXSHIELD: OPERATION PRINCIPLE.

The slurry shield is a machine that is able to support the excavation front by the pressurized, bentonite slurry pumped into the excavation chamber. The slurry is substantially composed of a bentonite suspension in water, if necessary with some additives. The excavation chamber, called “plenum”, is a space between the excavation front and a steel bulkhead, where the excavated material is collected and mixed with the slurry. A pumping system performs the functions of feeding the fresh slurry to, and removing the muck from the plenum, through a pipeline.
The balance between inflow and outflow involved in this cycle allows to maintain the slurry under pressure in the plenum. By the variation of the inflow and/or outflow of the slurry, it is possible to control the face-support pressure value.
In the case of the Hydroshield a supplementary bulkhead, installed further behind the primary bulkhead, creates a room or an auxiliary chamber, which is divided into two functional compartments.
Slurry feeding pipe and slurry discharging pipe.
The mechanism by which the pressure is applied is the following: The plenum is physically separated from the tunnel by a bulkhead, and it is divided into two compartments, by the front bulkhead. The front compartment, where the cutter head is located, is kept full of slurry. The rear compartment and the front compartment are connected in the lower part of the chamber but they are separated by the front bulkhead in the upper part. The rear compartment is filled with slurry only in the lower part, while compressed air is fed into the upper part (forming the so-called “air cushion”).
The compressed air present in the air cushion can push the slurry to the front part of the plenum, maintaining it under pressure. The air cushion pressure can be managed through an automatic regulation system. Consequently, it is possible to control the slurry pressure. The air bubble also acts as a ‘shock absorber’ and is able to give a fast compensation to the unavoidable pressure fluctuations in the plenum.

„closed“
- Normal advance

„semi - closed“
- Drawdown 1/2

„open“
- Drawdown 1/1
The correct application of pressure is closely related to the correct reaction of the “slurry-ground” system. The pressure pushes the slurry into the ground pores, shedding its portion of solids and thus forming a film (called “cake”, which allows the correct distribution of the applied pressure to the entire face.

3 types of mud cake:

- Membrane cake (in fine sandy soils),
- Impregnation cake (in gravel soils with high permeability),
- Mixed cake, partly impregnated with a membrane cake.

The depth of penetration and quality of mud cake depends on:
- Rheological properties of slurry,
- Pressure applied,
- Physical characteristics of the ground excavated,
- Hydrogeological conditions of the ground excavated.
The penetration distance and the cake thickness are functions of the applied pressure, of the grain size of the ground, and of the slurry as well. The higher the ground permeability, the more difficult is the formation of a cake. So there must be an upper limit to the particle size of the ground in the face to be excavated, which is strictly related to the permeability. But also, the finer the particle size, the more problematic the functioning of the separation plant. So it is also necessary to impose a lower limit to the particle size, just from an operational point of view.

- **Fine grained soil**
  - Filter cake \( d_{10} < 0.2 \text{ mm} \).

- **Coarse grained soil**
  - Sandy gravel.
  - Stagnation of slurry.
### SLURRY CHARACTERISTICS. TEST METHODS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>units</th>
<th>Test method</th>
<th>Type of test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density - $\rho$</td>
<td>kg/m$^3$</td>
<td>cylinder + scales</td>
<td>laboratory / site</td>
</tr>
<tr>
<td>Solids content</td>
<td>%</td>
<td>oven drying</td>
<td>laboratory</td>
</tr>
<tr>
<td>PH</td>
<td>-</td>
<td>test paper or meter</td>
<td>site</td>
</tr>
<tr>
<td>Marsh fluidity - $t_M$</td>
<td>s</td>
<td>EN ISO 13500</td>
<td>site</td>
</tr>
<tr>
<td>Plastic Viscosity - $\eta$</td>
<td>Pa.s</td>
<td>EN ISO 13500</td>
<td>laboratory – rarely measured</td>
</tr>
<tr>
<td>Yield value - $\tau$</td>
<td>Pa</td>
<td>EN ISO 13500</td>
<td>site</td>
</tr>
<tr>
<td>Filtrate water</td>
<td>m$^3$</td>
<td>EN ISO 13500</td>
<td>laboratory / site</td>
</tr>
</tbody>
</table>
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HYDROSHIELD / MIXSHIELD. FILTER CAKE.
The position and structure of the excavating tools on the cutter head influences the capacity for removing the on-site material by a given stroke and rotation speed. The ratio between the opening area in the cutter head and the excavated section has a direct influence on the mechanical-support capacity of the front and on the face-support pressure control. Usually, for a HS it should be higher then 35-40%.
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CUTTERHEAD AND EXCAVATION TOOLS

[Image of tunnel boring machine with text logos and names: Astaldi, Gülermak, PBdim, and others]
CUTTERHEAD AND SUPPORT PLATES
CONTROL SYSTEM

The following are the fundamental parameters that are necessary for monitoring the process and controlling the excavation (in the form of graphs and tables.

- Air Pressure in the excavating chamber.
- Slurry Pressure in the excavating chamber.
- Excavated and extracted quantities of material.
- Volume and pressure of injected grout in the annular gap.
- Torque, stroke, rotating speed of the cutter head, and advancement speed of the Shield.
MANAGING THE EXCAVATION PROCESS

The parameters to be monitored:

Face-support pressure: the control will proceed by means of compressed-air pressure
• Quantity of mucked, solid materials: it will be determined as a function of the difference between the outlet and inlet flows, density measures, and slurry level in the chamber.
• Slurry characteristics: density, yield value, viscosity, and quality/cake-thickness of the filtered material (checked at the treatment unit laboratory).
• Segments mortar grouting: it deals with control on volumes and pressures recorded during the backfilling around the segments and automatically checked by sensors connected to injection pumps.
THE CONTROL OF THE FACE SUPPORT PRESSURE

The compressed air chamber performs several functions. It regulates the pressure transmitted by the slurry to the ground at the face, thus controlling the face stability and, at least partially, the surface subsidence. On the other hand, it is the essential tool for the maintenance operations.

A reference pressure is fixed by assigning a threshold pressure to the automatic system regulating the compressed air. When the pressure increases, the system opens the discharge valves and lets out the air, until the required pressure is re-established. When the pressure gets lower, the valves open and the pressure is returned to the established level.
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HYDROSHIELD / MIXSHIELD.
MUD TREATMENT.
STAGE OF SEPARATION:

Screening
Hydro cycloning
Filtering
  - Centrifuge
  - Belt press
  - Filtro press
Output
  - Screening
  - Centrifuge
  - Belt press
  - Filtro press
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HYDROSHIELD / MIXSHIELD.
MUD TREATMENT. SEPARATION PLANT.
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HYDROSHIELD / MIXSHIELD.
STONE CRUSHER.
The position and structure of the excavating tools on the cutter head influences the capacity for removing the on-site material by a given stroke and rotation speed.
SHIELD TBM: CUTTER HEAD

OPEN RATIO = OPEN AREA / TOTAL AREA [%]

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SHIELD TBM: CUTTER HEAD.
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CUTTERHEAD: TOOLS

- Ripper Teeth
- Center Nose Cone
- Scraper Teeth
- Spade Teeth
- Flood Doors
- Chromium Carbide Plating
- Injection Ports
- Scraper buckets

Ripper tooth
Peripheral disc

Disc cutters
Center nose cone
Role of shield skin:

- Support of ground
- Stability of TBM
- Safety area for the workers

- Shield skin is conical (gets smaller from front shield to tail skin)
- Segment erection within shield skin
- Tail skin is thinnest part of shield >> greatest deformation
- Soil improvement through shield
Shield structure is a steel structure consists of:

- Front shield with cutting edge
- Centre shield
- Tail skin

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Every “city machine” has to be provided with one or more “hyperbaric chambers” (or “man locks”) that allow maintenance works.
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MAIN DRIVE

FUNCTION
• TURN CUTTINGHEAD
• PROVIDE ADEQUATE SPEED, TORQUE, POWER TO EXCAVATE THE REQUIRE
GROUND CONDITIONS

FACTORS AFFECTING DESIGN
• GEOLOGY
• TBM DIAMETER
• REQUIRED TORQUE AND SPEED
THRUST CYLINDERS

Jacks providing the thrust force necessary for advancement
The propulsion of the TBM is provided by a set of thrust cylinder, which thrust the front section forward using the leading face of the erected tunnel lining as its reaction platform. The thrust rams can operated individually or in groups to provide the basic steering capability for the front shield.
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SHIELD MACHINES.
ERECTOR.

- with suction plate (vacuum).
- with segment grab (mechanical).

mechanical erector:

vacuum erector:
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SHIELD MACHINES.
ERECTOR.
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SEGMENT FEEDER AND CRANES HANDLING SYSTEMS
ACTIVE AND PASSIVE ARTICULATION

To better control the alignment during the excavation the TBMs are equipped with a device to articulate the head respect the shield, that is the active articulation.

Center and rear shield are connected by set of passive articulation cylinders, that permit the machine to better follow the alignment in case of minimum radius.
Every kind of parameters has be displayed in real time on the control panel in the TBM operator cabin.

The TBM has to be equipped with PLC system able to record all the data (excavation and mechanical parameter) from the machine.
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SHIELD MACHINES. CONTROL. MUCK CONTROL.

- Laser scanner
- Belt scale
- Flow measurement
GUIDANCE SYSTEM
Back filling =

Filling of the gap between lining (i.e. segment) and excavated profile

Purpose of back filling:

**Short term:**
- Ensuring efficient contact to the ground.
- Minimisation of deformation and surface settlements

**Long term:**
- Ensuring uniform bedding of the segments to the ground.
- Function as an additional sealing ring (in individual cases).
SHIELD MACHINES.
BACK FILLING THROUGH TAIL SKIN.
SHIELD MACHINES.
BACK FILLING THROUGH SEGMENT.

10 mm overcut for TBM control
TBM shield
seal brush
segment
circular injection

min 80 mm
thrust cylinder
cylinder shoe
opening for mortar injection
THE BACK-UP OR SYSTEM OF GANTRIES

- The equipment needed to enable the TBM to perform the excavation are located on mobile platforms which follow the machine and as a whole are called back-up.

The equipment and plants installed on the platforms are:

- Hydraulic power packs
- Electrical cabinets, transformers and the MV cable reeler (motorized)
- Mucking out system (conveyors)
- Muck cars movers or muck conveyor extension system
- Ventilation system and dust scrubber system
- Compressed air plant
- Water supply system (1.5 l/s motors + 1 l/s cutterhead)
- Segmental lining handling and erection system or supports erection system
THE BACK UP-SYSTEM

Auxiliary equipment (cont.):

- Probing and ground treatment ahead system (including the equipment needed for consolidation grouting ahead and for water ingress control)
- Equipment for rails and service lines extension
- Sanitary facilities for personnel
- Lighting system
- Communication system
- Closed circuit video system (spot cameras at critical locations)
- Automatic fire suppression system
- Toxic and explosives gases monitoring system
EPB TBM vs. SLURRY TBM
TBM DESIGN CONSIDERATION

CRITERIA FOR SELECTION OF EPB OR SPB

Geological conditions
- Grain size distribution
- Water level and pressure
- Presence of boulders or obstructions along the alignment

Availability of use of conditioning agents and/or bentonite
Feasibility and space for treatment plant
Final use and discharge of excavated muck
Experience of contractor
Capital cost
The basic design of an EP TBM and a SPB TBM are quite similar. The overall appearance and many systems from one type are used directly on the other. These similarities include:

- Main structures
- Propulsion
- Trailing gantry Structure
- Segment Erector and handling
### EPB vs. SLURRY

#### EPB TBM
- Overall simpler system to learn, operate and maintain
- Applicable to a wider range of grounds
- Requires limited addition of conditioning materials (lower consumption of additives – no slurry circuit)
- Incase of face collapse amount of ground loss is limited

#### SLURRY TBM
- Overall a more complicated system (to learn, operate and maintain)
- Applicable to a restricted range of grounds
- Requires extensive addition of materials
- In case of face collapse amount of ground loss is considerable
## EPB vs. SLURRY

<table>
<thead>
<tr>
<th>EPB TBM</th>
<th>SLURRY TBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Muck is immediately ready for disposal</td>
<td>• Requires a sophisticated slurry separation plant</td>
</tr>
<tr>
<td>• Able to take advantages of selfsupporting grounds (i.e. open mode)</td>
<td>• Cannot take advantage of selfsupporting grounds (i.e. no open mode)</td>
</tr>
<tr>
<td>• Higher overall production rates</td>
<td>• Advance rate of TBM directly affects all aspects of slurry performance</td>
</tr>
<tr>
<td>• Requires a limited space for assembly and launching</td>
<td>• Requires a large size job site</td>
</tr>
<tr>
<td>EPB TBM</td>
<td>SLURRY TBM</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>• Lower capital cost</td>
<td>• High environmental impact</td>
</tr>
<tr>
<td>• Required confinement pressure must be calculated in advance of tunnelling</td>
<td>• Higher capital costs</td>
</tr>
<tr>
<td>• Requires higher torque</td>
<td>• Required confinement pressure is detected and controlled by the system</td>
</tr>
<tr>
<td>• Requires greater Cuttinghead power</td>
<td>• Requires lower torque</td>
</tr>
<tr>
<td></td>
<td>• Requires less Cuttinghead Power</td>
</tr>
</tbody>
</table>
## Course in Tunnelling and Tunnel Boring Machine
### EPB vs. SLURRY

<table>
<thead>
<tr>
<th>EPB TBM</th>
<th>SLURRY TBM</th>
</tr>
</thead>
</table>
| • Muck is exposed into tunnel, contaminated grounds can present problems  
• Able to process a larger diameter boulder | • Contaminated muck is not exposed until it reaches the surface  
• Requires a sophisticated extraction system  
• Insulation of pipes from weather  
• Higher accuracy in pressure confinement  
• Higher power requirement |
### EPB vs. SLURRY

<table>
<thead>
<tr>
<th>EPB TBM</th>
<th>SLURRY TBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High usage of energy on site, the slurry pumps must continuously function</td>
<td>• Requires a overburden of at least one TBM diameter as a minimum</td>
</tr>
<tr>
<td>• Constant monitoring and adjustment of slurry parameters are required to achieve production and muck removal requirements</td>
<td>• Difficult to maintain slurry pressure at constant level when the extracting pipe clogs - up</td>
</tr>
<tr>
<td>• Able to integrate rock crusher</td>
<td></td>
</tr>
</tbody>
</table>
# TYPE OF FACE SUPPORT

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>EPB</th>
<th>SLURRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuttinghead Power/Torque</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Overall site Power Requirements</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Use of Additives</td>
<td>Required</td>
<td>Required</td>
</tr>
<tr>
<td>Capitol Cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Required Site Size</td>
<td>Moderate</td>
<td>Large</td>
</tr>
<tr>
<td>Disposal excavated Material</td>
<td>Easy</td>
<td>Complex</td>
</tr>
<tr>
<td>Speed of Excavation</td>
<td>Fast</td>
<td>Moderate</td>
</tr>
<tr>
<td>Cleanliness of Tunnel</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Calculation of Required Pressure</td>
<td>Predetermined</td>
<td>Automatic</td>
</tr>
</tbody>
</table>
THANK YOU FOR YOUR ATTENTION!!

Eng. Tommaso Grosso – Astaldi S.p.A.