Earth Pressure Balance TBM – Zoltan Budincevic

Lovsuns Tunneling Canada Ltd.
History of LOVSUNS

1972 → CATERPILLAR® → 2014

454 TBMs Built to Date
Agenda

• What is an EPB TBM?
• EPB Principle of operation
• Ground Conditioning
• Main Components of an EPB TBM
• EPB machine future trends
What is an EPB TBM?

• Mechanized Excavation Technique that can be used when Ground is not Self Supporting
• Excavation takes place at full face with full Chamber
• The machine itself provides support during the excavation and protection to the personnel.

The EPB TBM gets its name because it uses the excavated material to balance the pressure at the tunnel face. Pressure is maintained in the cutterhead by controlling the rate of extraction of spoil through the screw conveyor and the advance rate.
What is an EPB TBM?

To avoid settlements, the ground material which has been excavated by the cutting head supports the tunnel face to maintain pressure on the tunnel face. This is known as earth pressure balance (EPB).
When is an EPB TBM is used

EPB method is particularly used when the ground has a high content of clay, loam or silt which have a low permeability of water.

In order to be used as a support medium the excavated material should be characterized as follows:

• High plasticity,
• Liquid to soft consistency,
• Low inner friction,
• Low water permeability.

These properties of the excavated muck can be achieved by ground conditioning.
EPB TBM PRINCIPLE OF OPERATION

- Excavation Chamber
- Propulsion Cylinders
- Screw Conveyor
- Tail seal brushes
- Cuttinghead (Tunnel Face)
- Segment Erector
EPB TBM PRINCIPLE OF OPERATION

TBM operates in two phases:
1. Mining phase
2. Tunnel Lining Phase.
Mining phase

- Electric or hydraulic motors drives the cutting head.
- Cutting head rotates.
- Propulsion cylinders push the TBM forward.
- Cutting tools loose and break material from the tunnel face.
- Excavated material (muck) passes through the cutting head into the open cavity inside the cutting head called cutting head chamber.
Mining phase

Screw conveyor then removes the material from the cutting head chamber.
Mining phase

TBM advances forward grout is injected into the annulus between concrete segment and the excavated tunnel wall.

TBM bore one tunnel lining segment width. After such an advance, mining ceases. Tunnel-lining segments are set in place.
Tunnel Lining

- Segment Erection
- Segment Fixing
Tunnel Lining-Segment Erection

Segment erection is done inside the ring build area.
Tunnel Lining-Segment Erection

Typically three (3) row of tail seal wire brushes and an invert grout flap are installed on the interior of the trailing shield at the end. These brushes are filled with sealant grease to create a continuous hydraulic seal, between the gaps of the TBM’s trailing shield and the erected tunnel lining.
Tunnel Lining-Segment Fixing

Void between the segment ring and ground is filled with grout to prevent settlement.

Grouting: This is done automatically through the trailing shield or manually through segments as the machine advances; dowels are then used to join one ring to the next.
EPB Principle

Excavated material:

- is used to support the face of the excavation.
- is mixed and accumulated under pressure in the muck chamber;
- Extracted in a controlled manner by means of a screw conveyor.

The support or "confinement" of the excavated face is achieved by the contact between the grains of the excavated material and the grains of the working face. Once the appropriate pressure of confinement is reached in the chamber, the excavation progresses by constant volume.

\[ V_{extracted\ from\ chamber} = V_{material\ excavated\ at\ the\ face} \]
In order to mine using EPB, a set point is needed for the pressure inside the cutting head chamber. The earth pressure cannot be measured by the TBM (only material pressure within the cutting head chamber can be measured). Several earth pressure sensors are placed on the bulkhead in the chamber.
The confinement (EPB) pressure exerted at the face is controlled by balancing the thrust exerted by the advancing TBM and the rate of extraction or discharge of the excavated material from the screw conveyor.
EPB Principle – Over Pressure

\[ (P_W + P_E < P_{TBM}) \]
EPB Principle – Insufficient Pressure

Water Pressure ($P_W$)  Ground Pressure ($P_E$)  TBM Pressure ($P_{TBM}$)

$$(P_W + P_E > P_{TBM})$$
The Importance of Control Volume Excavation

If too little muck is excavated from the chamber (i.e. screw is slow and propulsion is fast) = increase in EPB pressure and possible outcomes of either heave or a blow out (when EPB pressure is lost to the surface)

If too much muck is excavated from the chamber (i.e. screw is fast and propulsion is slow) = decrease in EPB pressure and a possible outcome of settlement or even a sink hole
Settlement / EPB Control

Control EPB Pressure in the Cuttinghead Chamber during excavation.

Continuous Grouting of Tail Void as TBM advances.

Control of spoil quantity in relation to TBM advance to prevent over excavation.

Use Ground Conditioning system to modify soil for EPB operation

Maintain pressure in the Cuttinghead Chamber during Segment Erection and Stoppages.
  - Continuous advance under extreme sensitive areas
  - Maintain material motion/pressure in the Cuttinghead Chamber
  - Propulsion Cylinder Automatic Extension
  - Ground mix Injection to compensate for volume loss

Maintain Pressure over the length of the shield
  - Injection of ground mix into annulus to fill void
EPB Control and Operation

Information Input:
- EPB (max and min)
- Screw Conveyor Speed and Torque
- Propulsion Cylinder Advance Rate
- Thrust

Control:
- Advance Rate
- Muck Extraction Rate

PLC Control
- Preset Limits for EPB Sensor Readings
Calculating EPB Pressure

REQUIRED INFORMATION

- DEPTH OF TUNNEL
  - GROUND SURFACE TO TOP OF TUNNEL
  - IF BELOW WATER THE DEPTH OF THE RIVER OR LAKE ABOVE THE TUNNEL ALIGNMENT

- GROUND WATER LEVEL
  - HEIGHT ABOVE TUNNEL
  - PRESENCE OF MULTIPLE WATER TABLES
  - PERCHED WATER
  - ARTESIAN WATER

- TYPE OF SOIL
  - CLAY TO BOULDERS
  - SOIL PARAMETERS – COHESION, ANGLE OF FRICTION ETC.

- DIAMETER OF TUNNEL
CALCULATING EPB PRESSURE
Ground Conditioning

Ground Conditioning - WHY?
Ground Conditioning

- When a ground does not have the ideal characteristics of fluidity and plasticity it can be modified to improve its ability to transmit the confinement pressure.
  - Reduction of angle of friction
  - Improvement of plasticity & fluidity
  - Reduction of permeability
  - Reduction/Improvement of cohesion
  - Reduction of cuttinghead torque
  - Reduction of metal wear
  - Reduction of “stickiness”
Ground Conditioning-Ground types

CLAY  
<0.002mm

SILT  
0.002mm-0.06mm

GRAVEL  
2.0mm – 60mm

Silty Clay  
<0.002mm and 0.002mm-0.06mm
Silty Sand  
0.002mm-0.06mm
Sand  
0.06mm – 2.0mm
Ground Conditioning - Ground types

- Clay adhesion & clogging
  - Use foam and anti-clay additives

- Silty sands
  - Use foams

- Coarse, frictioned soil
  - Use foam & polymers

- Very coarse, frictioned soil
  - Use foam & special polymers + fine filler
Ground Conditioning - Ground properties

- Compressibility
- Permeability
- Shear Strength
Ground Conditioning - Ground Treatment

**FOAM AGENT**
- Filling of Chamber
- Advance Rate
- Torque, Wear

**ANTI CLAY AGENT**
- Advance Rate
- Clogging of Chamber
- Adhesion

**POLYMER AGENT**
- Soil Structuring
- Ground Permeability
- Settlements
Ground Conditioning - Equipment

- Foam / Polymer / Water/Additives
  - Cutting head Face
  - Cuttinghead Chamber
  - Screw Conveyor

- Independent Flow per Line

- Includes:
  - Variable speed pumps (- allow different additive concentrations)
  - Air Flow regulators- (to vary the air content)
  - Flow Meters
  - Pressure Control Valves
Ground Conditioning Equipment
GROUND CONDITIONING SYSTEM
Ground Conditioning

Foam Expansion ratio (FER) regulates quality
- low FER = wet foam
- high FER = dry foam

Foam injection ratio (FIR) regulates amount of foam

\[
C_f = 100 \cdot \frac{m(\text{Foaming Concentrate})}{m(\text{Foaming Solution})}
\]

\[
C_p = 100 \cdot \frac{m(\text{Polymer})}{m(\text{Foaming Solution})}
\]

\[
FER = \frac{V(\text{Compressed Air})}{V(\text{Foaming Solution})}
\]

\[
FIR = 100 \cdot \frac{V(\text{Foam})}{V(\text{Soil})}
\]
Ground Conditioning System
Ground Conditioning

GCS BENEFITS

■ Muck Conditioning
  – Muck control is enhanced
  – Muck viscosity is reduced
  – Muck permeability is reduced
  – Risk of sticking/clogging of chamber is reduced
  – EPB Pressure stability increased

■ TBM Mechanical Performance
  – Cuttinghead Torque is reduced
  – Screw Conveyor Torque is reduced
  – Power Consumption is reduced
  – Component Wear Rates are reduced
    » Cutting Tools
    » Screw Conveyor
Main Components of an EPB TBM
Cuttinghead

Soft Ground Cuttingheads: Unstable Ground - Closed Mode Excavation

Cuttinghead Features

• Includes ripper housings only
• May include face isolation doors
• Center nose cone or fish plate at center
• Typically used for Clays, Silts and flowing geology
• Large percentage opening ~ 30%
• Rotary Fluid Joint & Injection Ports
• Copy Cutter

Tool Configurations

Center: Fish Plate (Nose Cone)
Face: Rippers & Spades
Gauge: Rippers & kenrocs

Face Isolation Door
EPB Cuttinghead – Mixed Face

**Mixed Ground Cuttingheads:**
Stable/Unstable Ground – Open/Closed Mode Excavation

**Tool Configurations**
- Center: Fish Plate
- Face: Twin Disc Cutters, Rippers & Scrapers
- Gauge: Twin Disc Cutters, Rippers & Scrapers

**Cuttinghead Features**
- Includes housing for disc cutters
- Rippers are installed with adaptor boxes
- Option of full face of disc cutters
- Fish Plate at center interchangeable with disc cutters
- May include face isolation doors
- Large percentage opening ~ 30%
- Rotary Fluid Joint & Injection Ports
- Copy Cutter
**Rippers**

- Used in soft ground
- Three styles for everything from clay, limestone, and abrasive gravels
- Main tool for EPB type TBMs.
Disc Cutters

- Single tip and Twin tip type disc cutters used for mixed ground conditions containing boulders & hard rock.
- Different disc cutter tip spacing are used to cut the rock efficiently.
- 12.0”, 15.5”, 17” and 19” Single tip, Twin tip and Center cutters with replaceable rings.
EPB Cuttinghead – Cutting Tools

Scrapers

- Used as collection tools
- Scraper Profile sits below the Ripper & Disc Cutting Profile to prevent scrapers from excavating
- Various styles have been used (i.e. bottom bolting, face clamp, cross bolted)
EPB Cuttinghead – Cutting Tools

Copy Cutters

• Used to increase the nominal over-cut on soft & mixed faced cuttingheads
• Typically used to help negotiate curves
• Can be integrated into the PLC to cut particular patterns (i.e. top only, left or right, etc.)
MAIN DRIVE COMPONENTS

- **Main Bearing**
  - Triple Roller Design (Most Common)
  - Internal or External Design

- **Motor**
  - Variable Frequency Electric Drive
  - Hydraulic Drive

- **Gearbox**
  - Planetary Type
  - 2 or 3 Stage
  - Water Cooled
  - Integral Pinions

- **Seals**
  - Single/Double Lip
  - Endless Type (no joints)

- **Motorplate**
  - Houses main bearing and gearboxes
Main Drive System
Hydraulic vs. VFD Main Drive

**VFD ADVANTAGES:**
- More efficient – lower power consumption
- Improved working environment
  - Noise reduction
  - Less heat generation
  - Cleaner (reduced oil leaks)
- Less maintenance of electric motor vs. hydraulic motor
- No risk of hydraulic oil contamination
- Reduced cooling water requirement
- Fewer consumables (ie. hydraulic oil, filters, etc.)
- Less manifolds and valve blocks required in Stationary Shell
- Higher break-out torque available
- Quick site start-up time, more modular (ideally plug and play)
- Torque monitoring on each drive unit

**HYDRAULIC ADVANTAGES:**
- Soft system – spike loads are cushioned
- Troubleshooting can be performed by less skilled technicians where as PLC Techs are required for VFDs
- Torque limiter not required
- Space claim in Stationary Shell is not mandatory, electric motors and pumps can be mounted on the Back-Up

Lovsuns Tunneling Canada Ltd.
Main Drive Sealing System

PURPOSE
To protect the main bearing and the drive against contamination.

PRESSURISED OIL SEALING SYSTEMS
High pressure (EPB) applications up to 6.5 bar
EPB Sensors

Optional 2 EPB Cells on top of Forward Shell

2 No. EPB Cells Inside Screw Conveyors

6 No. EPB Cells Inside Cuttinghead Chamber
Airlock

AIRLOCK - INTEGRAL

AIRLOCK - BINOCULAR
Segment Erector

**Radio Remote Control**
- Heavy duty joystick control
- Color display for cylinder selection and pressure indication
- Dead man switch
- All 6 DOF control
- Emergency stop

**Notable Features**
- Rotary hose track ("no mechanical rotary union")
- Axial hose track
- Vacuum pad and tank
- 6 no. powered degrees of freedom (DOF) control

Lovsuns Tunneling Canada Ltd.
Trailing Shield

- Structure
- Passive Articulation Lug
- Torque Linkage
- Grout Line
- Grease Line
- Brushes Tail Seal
- Invert Grout Flap
Tail Seal Grease Injection Distribution

- Tail Seal Grease is injected into each chamber through an array of distribution pipes
- Qty is dependent on diameter of TBM
Grout Injection

SEGMENT vs. TAIL

GROUTING THROUGH SEGMENT

GROUTING THROUGH TRAILING SHIELD
Screw Conveyor

- TUBE ASS’Y
- EPB CELL
- SLIDE SUPPORT
- PERIPHERAL DRIVE
- SLEEVE
- AUGER ASS’Y
- GUILLOTINE

Lovsuns Tunneling Canada Ltd.
Automatic Face Control System

Rapid Replacement Bentonite Injection System

**EPB SENSOR**
Monitors Cuttinghead Chamber Pressure

**PLC CONTROL SYSTEM**
Reads information from EPB Sensor and sends command to Bentonite Tank

**PRESSURIZED BENTONITE TANK**
Receives command from PLC and injects bentonite into Cuttinghead Chamber
EPB machine future trends

EPB machine has a history over 50 years.
-Lovat first EPB was manufactured in 1987 (UK)
-3.6 m diam 4.5 km long tunnel 6.5 bar.
Mechanized tunnel technology is continually developing.
Modern EPB TBMs design characteristics:
• increasing advance rate and TBMs diameters
• Dual mode TBM “Crossover” type

In the 1990s a 12 meter diameter TBM was consider to be a size limit for TBM
EPB machine future trends

In last 15-20 years many very large TBM project has been completed successfully.
Larger EPB TBM torque and thrust

Cutter Head Drive System – Torque / Power

JSCI Standards*

- Cutter head Torque: \( T = \alpha \times D^3 \)
  - Slurry TBM: \( \alpha = 8 - 20 \)
  - EPB TBM: \( \alpha = 10 - 25 \)

\[ T = \text{cutter torque} \]
\[ D = \text{outer diameter of shield machine} \]
\[ \alpha = \text{torque factor} \]

* JSCI Standard Specification for Tunneling - 2006
EPB machine future trends

EPB TBM technology improvements:

• Main drive motors have become more powerful
• Drive motors (VFD) controls allowing large TBM can operate in more complex ground.
• Modern TBMs can collect and process a vast amount of data in real time
• Increased scientific understanding of Ground condition (foams/additives)
• TBMs to be designed to suffer less wear and increase in reliability.
• Improved design of the cutting tools
• Improved design of seals in bearings
• Improved design of seals between TBM and the tunnel lining
Today solution for variety of geologies:
Dual mode TBM “Crossover” type:

**Hard Rock/ Epb** (open /close mode -hard/soft ground)
-screw conveyor for closed operation.

**Slurry/ Epb** (tunneling in high pressure condition)
Slurry system (used to when is not possible to create a “plug” in the screw)

**Rock/ Slurry**
Thank You!
References