SLURRY, HYBRID AND LARGE TBMs

Werner Burger, Herrenknecht AG Schwanau

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Slurry, Hybrid And Large TBMs

- General Principles - Slurry / EPB
- Slurry TBMs & Slurry Circuit
- Multi Mode (Hybrid) TBMs
- Large Diameter TBMs
Face Pressure Regulation
Flow Based and Independent Face Pressure Regulation

- Soil
- Bulk head
- Screw conveyor
- Bentonite suspension
- Bulk head
- Hydraulic transport circuit
- Without air bubble
- EPB Shield
- Bentonite suspension
- Bulk head
- Hydraulic transport circuit
- With air bubble
- Slurry Shield
- Bentonite suspension
- Air bubble
- Bulk head
- Hydraulic transport circuit
- Mixshield
Face Pressure Control
Pressurized Chamber Fill

\[ \gamma \times h \]

- Earth pressure
- Water pressure
- Chamber fill pressure

\[ P_w \]

\[ P_b \]

\[ \gamma \times h \]

\[ h \]

- Chamber fill
- Air bubble
- Air bubble pressure \( P_b \)

\[ P_b \]
Application: EPB / Mixshield.

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- **EPB Methods**
- **Mixshield Methods**
Face Pressure Control
Slurry Shield / Mixshield

- Face pressure controlled by compressed air bubble
- Face pressure controlled by slurry pumping rates.

Design Pressure

Time (seconds)

Face Support Pressure (bar)

0 1 2 3
Slurry, Hybrid And Large TBMs

- General Principles - Slurry / EPB
- **Slurry TBMs & Slurry Circuit**
- Multi Mode (Hybrid) TBMs
- Large Diameter TBMs
Mixshield System – General Layout

Compressed Air Plant

Bentonite Mixing Plant

Slurry Treatment Plant

Muck Discharge

Feed Line

Discharge Line

Slurry Circuit

Compressed Air Regulation

TBM
The Two Models for Transmitting the Confinement Pressure to the Tunnel Face (Slurry Shields).

Membrane model

Filter cake formed

Penetration model

Pure penetration
From “Star Type” to “Disc Type” Cutterheads
Smart Tunnel, Malaysia
Slurry Flushing System – Possible Percentage of Total Volume for Each Individual Inlet Position
East Side Access, NY – Queens Bored Tunnels
Bentonite Cake Tunnel Face
Disc Cutters for Mixed Face
17“ Monobloc Cutters, Portland ESCSO
Jaw Crusher for Slurry TBMs

Crusher Capacity (Grain Size)
Shield Dia. < 20ft: 20"
Shield Dia. 20ft – 33ft: 32"
Shield Dia. > 33ft: 47"
Closed Slurry System ➔ High Face Pressures Possible
Face Pressure Lake Mead, Istanbul
Slurry, Hybrid And Large TBMs

- General Principles - Slurry / EPB
- Slurry TBMs & Slurry Circuit
- Multi Mode (Hybrid) TBMs
- Large Diameter TBMs
Multi – Mode / Convertible TBMs

### EPB / Mixshield Range

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- **Clay**: Fine, Medium, Coarse
- **Sand**: Fine, Medium, Coarse
- **Gravel**: Fine, Medium, Coarse

Sieve Size: 0.001, 0.002, 0.006, 0.02, 0.06, 0.2, 0.6, 2.0, 6.0, 20.0, 60.0
Motivation for Multi-Mode TBMs.

- Long sections of different ground conditions along the alignment
- Best suitable mode of operation for each single section
- Best suitable mode of operation $\Rightarrow$ optimized economy
- Best suitable mode of operation $\Rightarrow$ increased safety
Three Different Shield Machine Types for Full Face Excavation.

1. open single shield for stable and usually non water-bearing ground conditions with excavation under atmospheric pressure and dry muck removal with belt conveyor

2. closed earth pressure balance machine (EPBM) for fine-grained and usually unstable and water-bearing soils with excavation under controlled positive face support pressure and thick-matter-type muck removal from the excavation chamber with screw conveyor

3. closed slurry machine (STBM) for coarse-grained and usually unstable and water-bearing soils with excavation under controlled positive face support pressure and muck removal from the excavation chamber with slurry circuit and above ground slurry treatment plant
Convertible Machines

- **Open Mode**

- **Conversion**
  - integrated
  - modular

- **Closed Mode**

- **Single Shield TBM**

- **Slurry Shield**

- **EPB Shield**
Change Between Open Single Shield and EPB Modes Of Operation

Closed Mode - Earth Pressure Balance
- regular mode of operation
- positive face support
- max. 6-8 bar depending on soil condition(ing)

Closed Mode - Compressed Air
- exceptional mode of operation
- control of water inflow
- max. 2,5 bar depending on soil condition(ing)

Open Mode
- stable face conditions
- atmospheric excavation chamber
- rapid chamber isolation possible (discharge gate)
- muck pile in chamber required (cutterhead wear)
Change Between Open Single Shield and EPB
Katzenbergtunnel, Germany

- Screw conveyor for primary mucking system
- No modification for open – closed mode change
- Short individual closed mode sections along the alignment (approx. 10%)
- Moderate soil abrasivity
Change Between Open Single Shield and EPB
Center Belt Conveyor And Screw Conveyor As Primary Mucking System

Closed Mode - Earth Pressure Balance
- Screw conveyor in forward position for full capacity
- Center belt and muck hopper retracted, rotary installed
- Cutterhead muck transport channels partially removed

Open Mode
- Screw conveyor in retracted position (limited capacity)
- Center belt and muck hopper in forward position, rotary removed
- Cutterhead muck transport channels installed
Change Between Open Single Shield and EPB
Tunnel de Saverne, France

- Screw conveyor and center belt / muck hopper for primary mucking system
- Approx. four days required for open – closed mode change
- Two short closed mode sections along the alignment (approx. 5%)
- Very high rock/soil abrasivity
Change Between Open Single Shield and Slurry Center Belt Conveyor And Slurry Circuit As Primary Mucking System

**Closed Mode – Slurry machine**
- Submerged wall gate open
- Center belt and muck hopper retracted and sealed
- Slurry circuit and treatment plant in operation

**Open Mode**
- Submerged wall gate closed
- Center belt and muck hopper in forward position
- Closing / Mode change within 2 - 4 hours
Change Between Open Single Shield and Slurry
Weinberg Tunnel, Switzerland

- Slurry circuit and center belt / muck hopper for primary mucking system
- Approx. one week required for open – closed mode change
- 10% of the tunnel length in closed slurry mode at the end of the drive for Limmat river crossing (transition from molasse rock in gravely material)
Change Between Slurry Shield and EPB Shield

Slurry Circuit or Screw Conveyor as Primary Mucking System, Different Method of Face Pressure Control

**Closed Mode – EPB Machine**
- Screw conveyor for primary muck discharge
- Advance speed and / or discharge volume regulation for face pressure control ➔ muck volume based face pressure control

**Closed Mode – Slurry Machine (Mixshield)**
- Slurry circuit for primary muck discharge
- Air bubble for face pressure control ➔ independent face pressure control
Change Between Slurry Shield and EPB Shield

Modular Concept for Change of Operation Mode

- Exchange / installation of system specific modules or subassemblies in intermediate shaft (e.g. slurry circuit – screw conveyor, air bubble regulation system…)
- Common modules for not system specific functions (e.g. ring erection, cutterhead drive, air lock systems…)
Change Between Slurry Shield and EPB Shield
Integrated Concept for Change of Operation Mode

- Slurry and EPB specific modules or subassemblies permanently installed
- Change of operation mode in the tunnel
- Chamber interventions for “activation” of mode specific equipment required
Change Between Slurry Shield and EPB Shield

SOCATOP Tunnel Project, France

- Long tunnel (10km)
- Long single stretches within the alignment with clear preference for operation mode
- TBM size of 10m sufficient to install parallel systems
Change Between Slurry Shield and EPB Shield
The Herrenknecht “Variable Density”® Concept

- Transformation between EPB face support and slurry face support in the tunnel without the need of modification or chamber intervention
- Full size and quality face support systems for EPB and slurry operation
- Safe and fully controlled conditions for face support during mode change
The Herrenknecht “Variable Density”® Concept
Modes of Operation

Open Mode

EPB Mode

High Density Slurry Mode

Slurry Mode
The Herrenknecht “Variable Density”® Concept
Typical Layout for a Mid-Size TBM in Full Multi Mode Configuration
Slurry, Hybrid And Large TBMs

- General Principles - Slurry / EPB
- Slurry TBMs & Slurry Circuit
- Multi Mode (Hybrid) TBMs
- Large Diameter TBMs
Motivation for Large Diameter Tunnels

- Multi lane road tunnels
- Multi deck designs
- Combined tunnels
- Alternate safety concepts (cross passages)
25 Years of Very Large Diameter TBMs, $\varnothing > 14,0$ m

- **Mixshield / Slurry Shield**
- **EPB**
- **Gripper**
- **Herrenknecht AG**

Data: TunnelTalk / Herrenknecht 2016
Boundary conditions for parameter variation of the shield diameter

- Ground water level: -4.0 m
- Surface load = 10 kN/m²
- Ground: friction angle = 30°
- Unit weight = 19 / 11 kN/m³
- Necessary overburden for blow-out safety $\gamma = 1.2$?
- Variable diameter: 5, 10, 15, 20 m

Thewes 2010
Required air pressure for various shield diameters and different levels of chamber fill level for face access

- Ø 5 m, required overburden 5 m, full chamber evacuation (invert access) → 0.8 bar
- Ø 15 m, required overburden 24 m, full chamber evacuation (invert access) → 4 bar

Thewes 2010
Diameter – Required Overburden – Face Pressure

- Deeper tunnel alignment (increased soil overburden) for larger diameter required for safe face access
  - Higher face pressure required for safe chamber access
  - Higher tool consumption due to larger excavation volume
  - Increased need for chamber access for tool replacement
  - Increased effort for chamber preparation works (temporary platforms etc.) for cutter head / cutter maintenance

- Increased need for implementation of high pressure chamber access technology and “non exposure maintenance” features for large diameter TBMs
  - Preparation for high pressure compressed air work
  - Accessible cutter head for atmospheric tool change on slurry TBMs
  - Remote face inspection techniques, cutter tool monitoring systems …
Accessible cutter head, atmospheric cutter change at 12 bar face pressure (Istanbul Strait Crossing Project)
Diameter – Tool Speed Limitation – Advance Speed

- Tool speed limitation:
  - 180 m/min for Rock TBM
  - 40 m/min for Soft Ground TBM

- Typical tool penetration rate:
  - 8 mm/rev for Rock TBM
  - 25 mm/rev for Soft Ground TBM
Diameter – Tool Speed Limitation – Advance Speed

- Reduced cutter head rotation for larger diameter
  - Tool speed limitation at cutter head periphery (rim speed)
  - Technical limitation of achievable tool penetration
  - Multiple tool per track at outer face and periphery positions can compensate tool penetration limits
  - Center area with only single tool per track due to space restrictions as decisive factor
  - Mixed face conditions of rock – soft ground combine low rock penetration limits with low soft ground speed limitation limits

- Concentric dual cutter head concept for higher center cutter speed
  - Higher center tool speed, better center mixing dynamics
  - High mechanical effort in TBM design (double drive system)
Diameter – Tool Speed Limitation – Advance Speed

- 15.4 m EPB for M30 Project in Madrid with concentric dual cutterhead
Cutter Head Drive System – Torque / Power

JSCI Standards*

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

$T$ = cutter torque
$D$ = outer diameter of shield machine
$\alpha$ = torque factor

* JSCI Standard Specification for Tunneling - 2006
Cutter Head Drive System – Torque / Power

- Exponential increase of installed cutter head torque and power with larger diameter
  - Technical manufacturing limits for single piece main bearings approx. Ø 8 m
  - Larger diameter bearings and drive cartridges require split multi piece designs for handling and transportation
  - Adjacent structures of the TBM like cutter head, cutter head support and shield structure have to address the possible extreme operational loads
  - Real site experience suggest increased gap between EPB and Slurry TBM torque requirements at larger diameters

- Besides increased power “smart” concepts are required for very large diameter
  - Increased importance of muck conditioning for EPB operations
  - Increased importance of chamber muck flow for Slurry and EPB operations
  - Increased importance of bentonite distribution and flushing systems for slurry TBMs
  - TBM data processing systems to support the optimization of the operational parameters
14.4 m EPB Auckland Waterview Project, second tunnel - typical power demand for excavation – ring build cycles with optimized operation parameters
Tuen Mun – Chek Lap Kok Link (TMCLK), Hong Kong
TMCLK – Northern Landfall
TMCLK – Starting Shaft S-880 & S-881
Arrival of S-880 (17.6m) at Ventilation Shaft Northern Landfall
TMCLK – TBM for Cross Passage Excavation
THANK YOU FOR YOUR ATTENTION.

burger.werner@herrenknecht.de