1. Introduction

Earth pressure balance technology (EPB) has undergone crucial development in the last ten years. The classical application range of EPB Shields could be broadened by the addition of additives in cohesive soil conditions up to less cohesive grainy soils and in mixed geology such as soft ground and rock.

EPB technology is fundamentally based on the use of the excavated ground as supporting medium in the excavation chamber. Under normal conditions, this requires a cohesive soil with stiff to soft consistency (IC = 0.5-0.75), which extrudes through the openings of the cutterhead towards the screw conveyor during machine stroke and closes the connection between pressurized excavation chamber, conveyor and atmospheric conveyor during stand still of the machine.

Fig. 1: Ideal soil consistency for the EPB operation (Metro Taipei)

The existing soil is a full face excavation with the rotating cutterhead of the earth pressure balance shield. The rotating speed and direction of the cutterhead is - in most cases - changed during the excavation to accomplish the best mixing and conditioning of the ground and to counter a rolling of the shield. Inside the excavation
chamber, between the cutterhead rear and the stators of the pressure wall, the excavated material is kneaded into a plastic mash with the support of agitators.

In contrast to the Hydro-Shield, this type of machine has the technical advantage that a separation plant is not required, hence – space and cost for these systems are unnecessary.

Due to the balancing of thrust speed of the machine and rotation of the conveyor screw it is possible to establish a controlled volume balance and/or controlled support pressure. This provides control of the pressure ratios at the tunnel (s. fig. 2).

![Fig. 2: Earth Pressure Balance Shield: principle of the earth pressure support](image)

The increase of thrust cylinder speed and/or the reduction of the revolutions of the conveyor screw cause an increase of ground pressure. The reduction of the thrust cylinder speed and/or the increase of the conveyor screw revolutions leads to a reduction.

The support effect of the soil mash is accomplished by the transmission of thrust forces via pressure wall onto the mash. Respectively, depending on the existing ground and water pressure, the soil mash is strengthened, until it reaches a balance with the applied pressure of the thrust cylinders. A balance is reached, if the soil mash in the excavation chamber cannot be conditioned any further by ground and
water pressure. If the support pressure of the soil mash is increased beyond the equilibrium, the compression of the mash in the excavation chamber as well as the existing ground may cause displacements of the area in front of the shield. During a reduction of the earth pressure, the existing ground can penetrate into the earth mash and produce settlements on the surface.

Afterwards, the earth mash is transported via screw conveyor out of the pressurized excavation chamber into the atmospheric tunnel. To transfer the material from the screw conveyor exit onto the conveyor belt without a flood gate, the material must have plastic stability and provide a small water permeability to avoid a lowering/dropping of the ground-water level. The material transfer must be controlled to prevent inadmissible reductions of the earth pressure in the excavation chamber and the resulting settlement.

![Fig. 3: Range of application for EPB-technology](image)

The continuous transport through the tunnel is done by muck cars, conveyor belt or muck trains.
The excavated material, which is transferred from the screw conveyor onto the conveyor, is controlled by a belt scale, in order to ensure a muck control between excavated and transported soil.

Innovative solutions by application of special additives further enable expansion of application of EPB technology in the non binding soft ground and/or hard rock area. Foam-supported EPB technology has continued its development in the last years and fulfills highest ecological as well as structural requirements.

The application range of EPB technology could be successfully extended into conditions such as rolling soils by adding soil conditioning features (s. Fig. 3).

2. Operation Modes

Depending on the geological conditions 4 fundamental operation modes can be applied with an EPB Shield:

- open mode (Fig. 4a),
- pressurized mode with compressed air admission (Abb.4b)
- closed EPB mode (Abb.4c)
- a world-wide unique mode, Slurry mode via slurry pumps, was used at the Botlekspoor Tunnel in the Netherlands for the first time (Abb.4d)

For all operating mode, the basics of the machine, i.e. Shield coat, cutterhead with drive unit, erector and backup-system, remain similar.

2.1 Open EPB Mode

Uppermost in the choice of excavation mode is maintaining the stability of the tunnel face, in order to avoid settlements at the surface. In stable ground, face support becomes unnecessary. Due to the low permeability of the stable binding or rocky tunnel face, atmospheric pressure variations in the excavation chamber are possible.
This reduces the ground volume in the excavation chamber, since there is only as much overburden in the chamber to feed the screw conveyor in the invert for a continuous material transport. Herewith connected is a reduction of the necessary torque of the cutterhead by 20-50% as well as a reduction in cutter tool wear, since the cutterhead face is never entirely in contact with the abrasive material.

Entrance to the excavation chamber for maintenance purposes can be managed relatively quickly in the open mode, since personnel have access to the chamber in the upper atmospheric part.

Substantially for the open EPB mode is the muck control of excavated material (s. Fig. 5), since there is no direct support pressure control via pressure sensors in the roof ridges due to atmospheric conditions. This would host the risk of an uncontrolled multi-excavation at the crown with changing geological conditions in less stable soils, with the consequence of settlements at the surface.

Fig. 4. Various operating mode EPB –
Open mode/compressed air mode/EPB mode with ground conditioning/slurry mode
(BOTLEK)
2.2 Semi-closed EPB Mode with Compressed Air Admission

In wide graded soft ground with low cohesive portion or high cohesive ground with enclosed artesian strained sand, the stability of the tunnel face is mainly determined by hydraulic conditions. The stable grain structure can suddenly break down due to flow forces when tunneling, whereby a structure collapse could have fatal consequences for the excavation and the environment. By increasing the pore water pressure, the grain-to-grain pressure is reduced, whereby a liquefaction of the tunnel face (effective tension reduction) is created. In order to maintain the stability of the face, the pore water pressure in the ground must be controlled by compressed air. The effective grain-to-grain pressures cannot be controlled with compressed air. In the semi-closed EPB mode the empty upper chamber area is filled with compressed air to restrain pore water flow. Due to the compressed air application, a optimum material flow to and through the screw conveyor is accomplished, where special attention must be paid to a sufficiently low permeability of the ground to prevent an uncontrolled pressure loss at the screw exit.

Maintenance can only performed in compressed air conditions and require therefore higher time expenditure than in the open EPB mode. One advantage is that the roof area is already cleared of excavated material. Due to the application of compressed air in the roof area, the support pressure can be controlled by pressure sensors.
An important auxiliary material for the access is a limited amount of bentonite, which is applied during tunneling in order to minimize the permeability at the face and/or to increase its stability. The application of bentonite in the excavation chamber must remain below a certain volume, because of the existing risk that the material turns too fluid, which is presenting difficulties with an inclined position of the belt conveyor.

2.3 Closed EPB Mode

The geological application range of semi-closed EPB mode with compressed air can also be excavated in closed EPB mode, whereas it is the only option in unstable soft ground combined with high water pressures and high permeability or jointed rock with high water penetration.

![Fig 5. Slurry compensation device for pressure drop in the working chamber](image)

During the closed EPB mode, the excavation chamber is completely filled with excavated material to support the unstable face. Because of the large soil volume, which has to be moved, this requires high torque and consequentially leads to an increase in wear. Due to the increased compaction of the material in the excavation chamber, there is also a tendency towards increased blockage of the cutterhead,
which requires time consuming cleaning maintenance. In case of accessing the excavation chamber, as the material is lowered and in case of water penetration, compressed air is supplied.

The newest innovative technology is the automated bentonite supply during pressure loss in the excavation chamber (s. Fig. 6). Via an automatic pressure sensor – similar to the air cushion of the Hydro-shield – bentonite is automatically pumped into the excavation chamber, if pressure decreases. This is particularly helpful during down times such as weekends and holidays and to counter uncontrolled tunnel face conditions.

2.4 Closed EPB Mode with liquid mucking

The application of EBP technology is generally limited to pressures around 3.5 bar in the invert area, because the plasticity of the material is not sufficient to decrease pressure in the excavation chamber along the screw conveyor.

The conveying speed of the muck becomes faster than the screw rotation, which means, the muck is “shooting” through the screw conveyor uncontrolled. This results in an increased risk of settlements on the surface. As a solution, additional piston pumps were flanged to the screw conveyor exit of an EPB shield in the Netherlands, to mechanically control the excavated muck in unstable pressure conditions in the screw conveyor.

Two conditioning pumps attached to the side of the screw conveyor enable a regulated discharge of the material. The transport generally continues from the screw conveyor onto the conveyor belt and following a so-called slurryfier box. In extreme conditions with high ground and water pressures as well as high water permeability, there is a possibility to transfer the muck via slurry pumps to the slurryfier box, which is located on the backup behind the shield. Here, the muck is mixed with water and transported hydraulically.

Afterwards, the material is pumped by conveyor pumps along the backup and out of the tunnel.
3. Soil Treatment

Earth pressure balance technology has made significant progress in the past 10 years. Especially regarding the expansion of its application towards low cohesive to grainy ground conditions (see Fig. 3).

Soil can be conditioned with
- water
- bentonite, clay or polymer suspension
- foam (surfactant foam)
- foam – polymer mixture (surfactant – polymer – foam)
- polymer (polymer foam)

where the application of the classic tunneling procedure, EPB and Slurry support, are overlapping. This is reflected in specific densities of the excavated material in the excavation chamber.

![Application of full face machines in soft rock](image)

![Bulk density spoil](image)

*Fig. 6. Soil mechanical criteria for different modes*
The density of classic EPB shield without conditioning is between 1.6 t/m³ and approximately 2.0 t/m³ and/or the Hydro shield between 1.1 t/m³ and 1.4 t/m³ (s. fig. 6).

Due to the application of light foam, the material receives a reduction in density in the EPB mode, which can also be in the range of a bentonite suspension. The limit of the density decrease may result e.g. in a blow-out risk underneath the water. In case of an over foaming of the ground in the excavation chamber, the rising air bubbles may cause a structural collapse due to instant reduction of the internal ground friction. Therefore, pressure control in the excavation chamber is necessary, which gives a conclusion to the specific weight of the excavated material.

The soil-mechanical background of ground conditioning via additives is the creation of a temporary artificial cohesion in grainy material as well as a reduction of water permeability. The soil receives almost instantly a cohesive characteristic which is necessary for EPB technology. The introduced foam bubbles also provide an elastic air cushion for the soil, which is compensating abrupt pressure changes at the tunnel face – similar to the Hydro shield principle.

Starting with the pores in the ground, which – in the ideal case – are all filled with tiny foam bubbles, the foam volume for a closed EPB mode, with a completely filled excavation chamber, can be estimated in theory. For a dense to loose middle sand, the value is e.g. between 27% and 47%. The consequential loosening and repositioning of the soil is leading, in practice, to higher values.
The void ratio in grainy soils presents herewith a first indication for the so-called foam injection rate (FIR), which is defined as a quotient of the foam volume flow $Q_{\text{Foam}}$ and muck volume $Q_{\text{soil}}$.

$$FIR = \frac{Q_{\text{Foam}}}{Q_{\text{soil}}} \times 100\%$$

Appearing ground water at the tunnel face is pushed back by the foam, which leads to a reduction in water permeability of the soil. The sand is temporarily integrated into the foam-polymer network, which provides an artificial cohesion, which then allows the sand – depending on the injection rate – a certain amount of expansion (similar to fresh concrete). The suppression of the ground water at the face however, must not be confused with the function of a filter cake used in bentonite technology. This could have fatal consequences for the safety of personnel when entering the chamber, since the “life span” of the foam in dependence of the permeability of the soil is a lot shorter than the lifespan of a filter cake regarding sealing and/or stabilizing the tunnel face.

*Fig. 8: Good condition of the cutting knives after tunnel excavation*

The liquid phase of foam as well as polymer create a grease film around the angular soil grains and metal surfaces, which significantly reduces the abrasiveness of the soil and therefore also the wear on the excavation tools. This results in less time consuming and less difficult entrances into the excavation chamber for cutter changes and such, which, on the other hand, results in higher tunneling performance of the machine. For both 1.84 km sections of the Botlekspoor Tunnel/Netherlands, one set of cutter tool each was sufficient due to a sophisticated soil treatment. The
cutting knives, which were in very good condition after the completion of the tunnel, are shown in Fig. 8.

The reduction in the friction coefficient between ground and steel – due to the grease film – also leads to a drastic conservation of thrust torque for the cutterhead. This can range from 30-50 percent.

**Fig. 9: Foaming system for an EPB-shield**

The quality of the foam is significantly influenced by the foam expansion rate (FER), which is depending on machine and technology as well as the utilized foam product. The expansion rate reflects the increase in volume of the starting liquid (water plus additive) by mixing it in the foam generator:

An expansion factor of 14 has shown to be sufficient in sandy ground. The foam consists of one volume portion of water and 13 portions of air. In accordance, the diameter of the liquid lines in front of the generator are kept small, while the foam lines behind have to transport 14 times the volume.
Dry and/or wet foam is created by higher and/or lower expansion rates, which, depending on the geological conditions, are adapted to the existing conditions such as water sensitive, high tendency to stick pressured ground.

Ideal are tiny and therefore stable, closely positioned foam bubbles (diameter of 0.5 – 2 mm), which are adjusted to the pressure in the excavation chamber. Feed locations for the foam should be in front of the cutterhead, such that the mixing process of foam and soil can start as early as possible. In addition, additional foam can be fed from the stator in the excavation chamber as well as the screw conveyor.

During transfer from the pressurized excavation chamber to atmospheric conditions of the screw exit, the foam bubbles pop due to the equalizing pressure. The major part of the foam is eliminated already during this transfer. The rest of the foam disintegrates due to the high biodegradability of surfactants in fresh air.

4. Jobsite Experience (worldwide application of Herrenknecht Earth Pressure Balance Shields)

4.1 Botlekspoortunnel / Netherlands

Beginning of December 2000 was the successful breakthrough of the „Botlek-EPB. After 18 months of excavation, two 1.835 m long railway tunnels under the river „Oude Maas“ were completed.

The Botlekspoort tunnel was excavated with a Herrenknecht EPB Shield with a diameter of 9.755 m. Highest safety requirements due to the under crossing of important cable and pipelines of the petro-chemical industry at the Rotterdam harbor were successfully implemented. The Botlek EPB Shield is an exceptional proof of technical innovation in the EPB sector. Machine technical innovation allowed the expansion of application for this EPB shield into the medium to rough sand and with permeability of $10^{-2}$ m/s.
At the lowest point under the „Oude Maas“ the top of the tunnel is approximately 20 m underneath Rotterdam’s level, which means, a maximum support pressure of 3.6 bar was accomplished.

**Fig 10: Earth Pressure Balance Shield Botlekspoor Tunnel (⌀9,775 m) Rotterdam, Netherlands**

The EPB shield is equipped with a complete ground conditioning system for surfactant foam conditioning. Two transport procedures were installed based on the special geological conditions. Two conditioning pumps, mounted to the side of the screw conveyor enable a controlled discharge of the material at support pressured above 3 bar.

The ground is continuously conditioned during the excavation of the Botlekspoor Tunnel. The transport is performed via screw conveyor onto the conveyor belt and
later into the Slurryfier-Box. In extreme areas with high ground and water pressures and simultaneous high water permeability, the possibility arises to pump the muck via slurry pumps directly to the Slurryfier-Box.

Fig.12: Foam Generator, Backup 1, Conditioning pump on screw conveyor, Project „Botlekspoor tunnel“

In the Slurryfier Box, located in the backup area approximately 40 behind the shield, the muck is mixed with water and transported hydraulically. Afterwards, the material is transported via feed pumps along the backup and out of the tunnel.

4.2 Paris Socatop / France

A double story 5.5 km car and 4.5 km truck long tunnel is currently under construction southwest of Paris. This tunnel is the final link in the second freeway ring A86. The tunnel boring machine (11.565 m diameter) utilized in this project is so far the largest ever operating in France. Herrenknecht AG received the order to manufacture this Mixshield. The mechanical concept of the Mixshield is a very unique tunnel boring
A complete conversion of the tunnel boring machine is possible in only 16 hours (2 shifts). During the EPB mode, the excavated material is transported via screw conveyor to the conveyor belts with a maximum volume of 1000 m³/h. Operating the Hydro shield, the material transport is hydraulic with a maximum volume of 2000 m³/h. The conversion option allows the fastest possible tunneling in varying geology. The excavation leads through chalk, sand, clay and lime. The tunnel boring machine
is currently the largest in the world to operate in the EPB mode with a cutterhead torque of 31,232 kNm and total thrust force of 150,000 kN.

4.3 Guangzhou / China

Since spring 2001, the subway network of the south Chinese city of Guangzhou is being expanded using 4 earth pressure balance shield made by Herrenknecht.

![Earth Pressure Balance Shield](image)

*Fig.15: Earth Pressure Balance ShieldMetro Guangzhou Northe Tunnel (Ø 6,250 m), Guangzhou, China*

The shown EPB shield is tunneling though the 3,900 m long section in saturated clay and slight to extreme weathered rock and conglomerates of densities of up to 70 Mpa. The mixed equipment, cutting knives and cutters, on the cutterhead are precisely adapted to the anticipated ground conditions. The screw conveyor is equipped with an additional exchangeable wear protection. To master the blocking tendencies of the binding ground, and to accomplish a plasticity of the muck in hard rock, as well as to achieve an improved support behavior, a foam conditioning system in installed.

4.4 Singapore

A total of 5 Herrenknecht AG EPB shields are operating in the new sewage system (DTSS) in Singapore. The machines have diameters ranging from 4.5 m to 7.2 m. The excavation includes sections of loose rock as well as very hard granites with stabilities of 300MPa.
Each of the cutterheads of the EPB machines can be exclusively equipped with disk cutters. Depending on the geological conditions, the cutting tools can be changed. In the center, disk cutters can be replaced by cutting knives and the other way around.

The maximum tunnel section is 12.5 km

All EPBs have ground conditioning features available.

One innovation is the segment crane of the Züblin EPB shield, which can move forward to the tail shield and transfers the segments directly to the erector. A segment feeder is not required any more.

4.5 Madrid / Spain

An earth pressure balance shield with conversion from closed EPB-mode open mode to open TBM-mode was developed for the expansion of the subway system in Spain’s Capital Madrid.
The EPB for the Metro Sur project is designed for a torque of 20,000 kNm and a break away torque of 24,000 kNm as well as total thrust capacity of 8,000 tons. The approximately 7,000 meter long tunnel runs through a geology consisting of crystalline plaster with clay and SCHLUFF.

### 4.6 Heathrow / England

Only minute settlements are allowed in the construction of the 2 x 1240 m long transport and supply tunnels between terminal 5 and the already existing terminals of London’s International Airport Heathrow.

An English/French Joint Venture ordered an EPB shield with an outer diameter of 9.160 m from Herrenknecht AG. The machine can produce a torque of 17,195 kNm and is pushed forward by 14 thrust cylinder pairs with a total of 6927 tons capacity. Planned is a semi-open and pressurized tunneling mode. Installed as an option, is a complete ground conditioning system for the use of foam.
A unique feature is the double piston pump (Putzmeister AG) installed behind the screw conveyor. This pump is capable to thicken approximately 2 m³ per stroke. Two 250 kW water cooled electric motors drive the pump with a theoretical maximum material flow of 400 m³/h Softground material and/or 200 m³/h of solid material.