Global Experience with Soft Ground and Weak Rock Tunneling under Very High Groundwater Heads

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ABSTRACT:
Several tunnel projects under very high groundwater heads have been started recently or are currently under design, such as the Hallandsås tunnel in Sweden (up to 13 bar), the Brightwater project in Seattle (7 bar) and Lake Mead Intake No. 3, Las Vegas (12 bar). This paper summarizes experience with pressurized face tunneling in soft ground and weak rock on nine completed projects that encountered groundwater heads ranging from 4 to 11 bar. For each project, both the effectiveness at achieving suitable face stability and at completing excavation chamber interventions for cutter-cutterhead-mucking system work are examined. Finally, conclusions are given on approaching the key challenges faced when planning pressurized face tunneling at very high groundwater heads (over 4 bars).

1 INTRODUCTION

High groundwater head is a major challenge for tunnelling in soft ground and weak rock. It has a strong impact on design and operation of Tunnel Boring Machines (TBMs) in order to prevent excessive groundwater inflow, to ensure face stability and to enable access to the cutterhead for maintenance, which can lead to an increase of the required construction period and budget. Designers should keep this in their mind when planning a tunnel alignment.

The enormous technical progress of pressurized TBM tunnelling, especially within the last 10 years, made tunnel projects possible which were not previously constructible. Now, new tunnels are being designed or proposed at deeper depths, higher groundwater heads and longer drives than previously attempted. One of the Brightwater tunnels in the Seattle area will be mined within abrasive glacial and interglacial soils at depths exceeding 130 m and under groundwater heads exceeding 7 bar with a drive length over 6 km. The Arrowhead tunnels in California are being driven through rock under heads over 10 bar and at design pressure for the tunnel lining of 22 bar. The Hallandsås tunnel in Sweden will be driven through a weak fault zone with heads of approximately up to 13 bar. A 4 km long tunnel is proposed near Las Vegas within soil and weak rock at depths over 140 m under heads ranging from 10 to 12 bar.

This paper discusses global experience with tunneling in soft ground or weak or highly fractured rock under groundwater heads exceeding 4 bar. Projects which are discussed include San Diego South Bay Ocean Outfall (7 bar), experience on European projects such as the French Side Channel Tunnels (10-11 bar), Storebaelt Tunnel (8 bar), 4th Elbe River-Tunnel (4.2 bar), Wesertunnel (4.3 bar), Westerschelde-Tunnel (6.4 bar) and the Red Line in St. Petersburg (5.5 bar) and also summarizes two Asian projects, the Nara Prefecture Water Conveyance Tunnel (11 bar) and the Tokyo Wan Aqua-Line (6 bar groundwater pressure).

2 TUNNEL PROJECTS UNDER HIGH GROUNDWATER HEAD

2.1 *South Bay Ocean Outfall, San Diego*

The 5.8 km long South Bay Ocean Outfall tunnel was completed 4.3 km into the Pacific Ocean at invert depths reaching 70 m below sea level (Fig. 1). The tunnel was bored with a 3.98 m diameter Mitsubishi EPB-TBM (earth pressure balanced) under groundwater heads ranging from 6 to 7 bar. The tunnel has a one-pass lining consisting of 3.35 m inside diameter, 30 cm thick, 3.81 m long precast concrete segment rings.

The tunnel zone was within the San Diego Formation – a Plio-Pleistocene age poorly indurated fossiliferous marine siltstone (Navin et al., 1995). Overall, approximately 12 percent (701 m) of the bored ground was cobbly-bouldery sand and gravel (Table 1) while 32 percent (1,847 m) was slightly to moderately cemented silty sand to sandy silt, and 56 percent (3242 m) was cohesive stiff to hard silty clay to clayey silt (Kaneshiro et al., 1999). Unconfined compressive strength (UCS) of the cohesive soil ranged from 80 to 658 kPa averaging 291 kPa. Mass permeability (k in m/sec) ranged from:

- 1×10^{-4} to 3×10^{-5} for gravel with cobbles and boulders
- 3.7×10^{-7} to 1.5×10^{-5} for silty sand-sandy silt
- 2.5×10^{-6} to 2×10^{-9} for silty clay to clayey silt

Actual ground conditions for the four tunnel reaches (Fig. 1) are summarized in Table 1 (Kaneshiro et al., 1999).

Table 1. Summary of actual SBOO ground conditions

Reach/Length	Gravel Cobbles Boulders	Silty Sand	Sandy Silt	Clay/ Cohesive Silt
I / 927 m	5.3%	26.4%	51.4%	16.9%
II / 2728 m	5.8%	4.5%	13.5%	76.2%
III / 1112 m	41.3%	33.0%	16.1%	9.6%
IV / 1023 m	2.9%	5.6%	3.8%	87.0%
Total /5790m	12.1%	13.6%	18.3%	56.0%

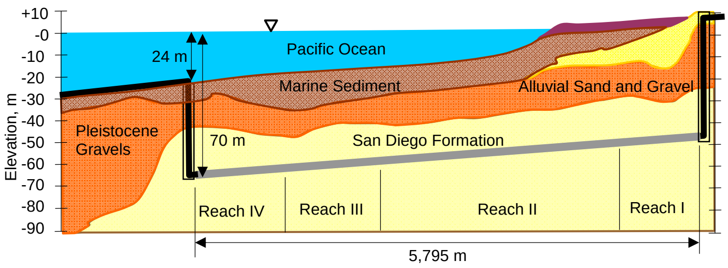

Figure 1. Profile - San Diego South Bay Ocean Outfall

The Mitsubishi EPB-TBM had two screw conveyors and four guillotine gates for dissipation of face pressure and discharge of muck into boxes on cars (Robinson and Jatczak, 1999). Screw No. 1 was 8.9 m long and was a shaftless ribbon type screw to maximize the size of boulders it could pass to a boulder gate for removal. It had 12 pitches (flights) capable of dissipating 0.1 bar each and was limited to 1.2 bar of total pressure dissipation. Screw No. 2 was a 38.3 m long shaft type screw with 4 ribbon flights and 65 shaft flights capable of dissipating 0.2 bar each or a total pressure dissipation of 13.0 bar resulting in a theoretical combined pressure dissipation capability of 14.6 bar (Burke, 1997).

During tunnel excavation (active mining) the applied face support pressure (measured within the excavation chamber) ranged from 3.0 to 7.3 bar and typically ranged from 5.5 to 6.5 bar (Robinson and Jatczak 1999, Williamson et al., 1999).

Most (about 88 percent) of the alignment was completed in fine-grained soil consisting of relatively low permeability cohesive silts and clays or moderately cemented silty sand to sandy silt.

A foam conditioner consisting of 9 to 11 percent surfactant (Soilax-S) plus water and cellulose and 89 to 91 percent air was used to form a proper paste for pressure control and minimization of abrasion (Williamson et al., 1999). Foam ratios within the fine-grained soil varied from 25 to 35 percent.

When the EPB-TBM entered an approximately 600 m long zone of cobbly sand and gravel within Reach III, the previously effective conditioner mix failed and several “washouts” or uncontrolled flows (blow-ins) of soil and water developed. Mining was suspended and conditioner modifications were made. Through experimentation, the contractor found that conditioners consisting of foam (with a foam ratio of 45 percent), bentonite slurry (0.5 m^3 per m^3 soil excavated), and acrylic polymer (Soilax-P) were necessary to form a paste that would allow proper face pressure dissipation. In addition to conditioner modifications, the four guillotine gates along the double screw conveyor were used for additional pressure dissipation within the gravel zone in Reach III.

The South Bay Ocean Outfall experience demonstrates that EPB-TBMs with proper conditioning and screw conveyor-discharge gate design can handle 7 bar of groundwater head in mostly fine grained cohesive soil-weak rock.

A total of 16 excavation chamber interventions were attempted to check cutter-cutterhead wear, replace worn cutters and remove boulder accumulations at the base of screw no. 1 (Robinson and Jatczak, 1999). Ten successful interventions were completed which correlates to an average intervention interval of 527 m.

The Mitsubishi EPB-TBM was equipped with two airlocks rated up to 3 bar for use during interventions. After the cutterhead doors were closed and the earth paste was substantially removed from the chamber, a free air entry was attempted. If excessive inflows or indications of face instability were observed 3 bars of air were applied and another intervention attempted. During six or 37 percent of the attempts, the intervention was cancelled due to unstable conditions (Jatczak, 2004) The EPB-TBM was then advanced to more favorable ground and an intervention was attempted again.

For 8 of the 16 attempts, the pressure was successfully reduced to zero and free-air interventions completed. The heading ground at these locations was generally low permeability, strong silty clay or clayey silt. When stable ground and groundwater conditions were encountered at 3 bar pressure, the groundwater pressure was progressively reduced and face conditions observed. For 2 of the 16 attempts, 1.5 to 1.8 bar of air pressure was required to maintain adequately stable conditions.

Within the approximately 600 m long reach of abrasive high permeability, cobbly sand and gravel in Reach III, an intervention was not attempted. The 3 bar of air pressure capability was not sufficient to stabilize this soil and counterbalance the groundwater pressure. This abrasive gravelly soil interval was nearly too long - significant cutter changes and cutterhead-screw conveyor maintenance were required after stable cohesive soil was finally encountered – the TBM barely advanced past this zone of granular soil to reach better (stable) ground, where repairs could be performed under less than 3 bar of air pressure. If the high permeability-high pressure zone was much longer than 600 m, an intervention would have been necessary and either high air pressure of 6-7 bar, which the TBM and the compressed air equipment were not designed for, or thorough ground treatment (grouting or freezing) at the heading (which were available on the TBM) would have been required, which might have led to major delays and higher costs.

2.2 *Channel Tunnel, French Side, France*

The Channel Tunnel, French side had three marine tunnels that were bored from 1988 to 1991 using TBMs (Table 2) that were designed for both open mode and pressurized mode tunnelling at heads up to 11 bar (Dumont 1991). The tunnels were lined with 4.8 and 7.6 m inside diameter bolted and gasketed precast concrete segments (1.4 m long and 32 cm thick) erected within the TBM shields (Barthes et al., 1994).

Table 2. Channel Tunnel French Side Tunnels

French Side Tunnel	TBM Manufacturer	TBM Type	Tunnel Length
T1 (Marine Service Tunnel)	Robbins-Komatsu	Double shield (∅ 5.72 m), single 11 m long screw with two piston discharge pump	15.6 km
T2 (Marine Running Tunnel North)	Robbins-Kawasaki	Double shield (∅ 8.72 m), double screws (7 and 10 m long)	20.0 km
T3 (Marine Running Tunnel South)	Robbins-Kawasaki	Double shield (∅ 8.72 m), double screws (7 and 10 m long)	18.9 km

The tunnel zone ground consisted of occasionally faulted, Cretaceous age chalk marl with mass permeability ranging from $3x10^{-6}$ to $5x10^{-7}$ m/s (Barthes et al., 1994). Invert depths below sea level ranged from approximately 30 m at the launch shaft to a maximum depth of 107 m. Ground cover ranged from 22 to 90 m.

The T1 Marine Service Tunnel was bored first using a Robbins-Komatsu EPB-TBM. It was operated in pressurized mode for the first five km with face pressures ranging from 3 to 4 bar (Vandebrouck 1989). The remaining 11 km were mostly mined in open-mode with occasional pressurized mode operation (< 10 bar) at fault zones. Advance probing and grouting was also utilized to reduce permeability and inflows at fault zones. The chalk marl was generally less permeable than expected. Groundwater inflows at the heading and tail seals resulted in a maximum pumping rate of 80 l/s during Open-Mode operation. Interventions for cutter inspection and changes were made in Open-Mode without the use of compressed air.

The T2 and T3 Marine Running Tunnels were bored with Robbins-Kawasaki EPB-TBMs. Higher permeability (fault) zones were grouted from the service tunnel in advance of tunnelling. As a result of the grouting and otherwise low permeability of the chalk marl, both running tunnels were advanced in Open Mode and no face support pressure was applied (Robbins, 1995). Groundwater inflows at the heading and tail seals resulted in a maximum pumping rate of 103 l/s (Barthes et al., 1994). Interventions for cutter inspection and changes were made in Open Mode without the use of compressed air.

The three Channel Tunnel, French side marine tunnels proved that pressurized face tunnelling was not necessary in the generally low permeability chalk marl that was encountered (Robbins, 1995). At most locations, small seepage rates at the heading and tail seal were effective at reducing groundwater pressures sufficiently to result in stable heading conditions under free-air. At higher permeability fault zones, advance probing and grouting was effective at reducing the ground permeability and inflow rates allowing sufficient dissipation of groundwater pressure at the headings for Open-Mode operation during advancement of the running tunnels. Even though pressurized face tunnelling was generally not needed, uncertainties on grouting effectiveness and fault zone conditions justified the additional procurement expense for EPB capable machines (Robbins, 1995). The extra TBM cost was worth the risk reduction provided by having pressurized mode capability.

2.3 *Storebaelt Tunnel, Denmark*

The 7,412 m long Storebaelt railway tunnel provides a fixed link across an international shipping channel in Denmark. It consists of two single-lane tunnels which were excavated by four identical EPB-TBMs (∅ 8.75 m). About 10% of the tunnel length was driven in Upper Till (15% clay + 85% sand content), 25% within abrasive Lower Till (sand, gravel, boulders, $k = 10^{-7}$ to 10^{-8} m/s) and about 65% within the underlying Marl (weak to moderately weak calcareous mudstone, highly fractured, clay content 41%, anticipated max. water inflow exceeding 500 m^3/h at 1 bar pressure). The depth of water along the tunnel route varies between 7 and 55 m which at the lowest point of the tunnel (in marl) means that hydrostatic pressure could be as high as 8 bar. A maximum pressure of 6.3 bar was actually measured during the tunnel drive (Darling, 1993).

The EPB-TBMs were equipped with two screw conveyors. A boulder trap, designed to catch up to

60 cm boulders at up to 4 bar pressure was fitted to the first screw.

One of the problems encountered during the tunnel drive was major cutter and cutterhead wear due to the abrasive nature of the glacial till. As a result, frequent interventions were required at intervals of 75 rings (124 m) to change cutter tools.

Another problem was the inability to form a sufficient tight plug of muck (earth paste consistency) within the screw conveyor to properly dissipate chamber pressure without excessive lost ground. Typically the tunnel was excavated in Open Mode, the excavation chamber was kept about ¾ full and not pressurized. Inflowing water was used to transform the excavated material into a transportable consistency. Generally no additional conditioners were added. In some cases bentonite slurry, polymers or marl slurry were used as conditioners, but could not solve the stability problems at the face and the screw conveyor sealing problems related to the discharge of soil (Zell, 1995).

Inflowing water was used to build up some pressure within the excavation chamber, but the support pressure was typically less than 3 bar, which is lower than required to fully counterbalance water and earth pressure and thus corresponds to Open Mode operation.

High external groundwater pressure called for a counterbalanced water pressure in the excavation chamber during tunnelling, which frequently caused problems with the starting torque. Although the drive motors were powerful, very often the support pressure had to be reduced to make driving possible. However, reduced chamber pressure immediately caused collapses of the soil and excessively high volumes of lost ground occasionally resulting in sinkholes to the sea floor.

As it was not possible to apply the required face support pressure with the screw conveyors, a Putzmeister piston pump was installed on two of the TBMs behind the first screw to enable pressure build up at high pressure sections.

The TBMs were not equipped with saturation diving installations although it was required in the contract specifications. As a result, cutterhead interventions were performed without use of compressed air support or were completed at a low air pressure of less than 3 bar. Poor stand-up time of the till made interventions difficult. Often extensive ground improvement or support works were necessary. Some interventions had to be curtailed.

After 350 m of tunnelling a sudden inrush of water occurred when the TBM had been stopped for 72 hours to perform maintenance on the cutterhead and boulder trap. The face was in Upper Till (15% clay) and was unsupported — no compressed air was applied. Water was pumped out of the excavation chamber to maintain the water level at the heading. Water and electrical hoses were passing through the open manlock doors and a manhole cover on the screw was removed, when the flood occurred. Water and material flowed into the TBM interior, flooding the TBM, the launch shaft, the parallel tunnel and the second TBM as well (Darling, 1993). Fortunately, no one was injured, but the repair works caused an eight month time delay and major additional expenses.

After this incident another 15 similar face collapses occurred, resulting depressions in the seabed, but during these events, the face was isolated, rather than left open as it was when the flooding occurred.

In order to enable tunnelling with the TBMs provided, an extensive dewatering program (called MOSES) was constructed at a cost of US$32m. The dewatering system comprised 43 deep wells (∅ 400 mm, L = 35 to 115 m) at a staggered interval of 200 m. Six power barges (0.5 MW) were in constant use to enable a total nominal pumping rate of 3,400 m³/h (Biggart, 1995). The wells were effective in reducing groundwater pressure at the tunnel zone down to 3 bar enabling unsupported face access during subsequent interventions.

Experience on the Storebaelt tunnel has shown that operation of an EPB-TBM reaches its limits at high groundwater head in unstable abrasive ground, if important features such as muck conditioning and equipment for proper cutterhead interventions (e.g. by saturation diving) are not provided to handle high groundwater pressure.

As face support during excavation was limited to 3 bar maximum, costly additional measures including an extensive dewatering program were necessary to enable Open Mode TBM operation and free air face access. The various tunneling problems ultimately resulted a 2 year delay of completion and a cost overrun of approximately US$550m above the initial contract value of US$520m.

2.4 *4th Elbe Tunnel, Germany*

The 4th Elbe tunnel was a milestone in Slurry-TBM tunneling due to the large TBM diameter of 14.2 m, low cover of as small as 7 m and high groundwater pressure of up to 4.2 bar. The southern section of the 2,561 m long tunnel was excavated in glacial deposits consisting of sand, marl and boulders, while more cohesive ground such as marl and clay with sand lenses and boulders was present on the northern tunnel section (Wallis, 2000).

Due to high required support pressure and low overburden, compressed air support was not possible in certain tunnel sections. Thus excavation tools had to be replaced from inside the cutter head arms under atmospheric pressure, which was a unique feature on this TBM.

Frequent interventions for cutterhead maintenance were necessary due to presence of abrasive soils (Figs. 2 and 3). Severe wear was observed on excavation tools and on the backside of the cutterhead which had to plough through accumulated spoil at the bottom of the excavation chamber.

Figure 2. Welding for repair works due to excessive wear on backside of cutterhead (4th Elbe tunnel)

Figure 3. Repair works on stone crusher, personnel standing within bentonite slurry (4th Elbe tunnel)

The cutterhead structure was ground down from 80 mm thickness to 15 mm (Nielsen et al., 2006). Thus intensive and time consuming repair works (6 weeks) were required under compressed air.

At the deepest point of the river crossing, the crew had to enter the excavation chamber and work under compressed air at 4-4.5 bar for about 80 min maximum to change tools on the centre cutter and to undertake repairs. They then had to spend about two hours in oxygen assisted decompression.

An incident occurred after 750 m of tunnelling just 50 m before reaching the point of lowest cover (Becker, 1999). Here the TBM was stopped due to increased torque.

The gauge cutters (buckets) had to be changed under compressed air, which took about 5 weeks. Just before the repair work was finished, the face collapsed followed by a blow out of the compressed air, creating a 500 m³ sinkhole. This example demonstrates the variability of the face stability (stand-up time), which was typically between one hour and several weeks due to extreme range of ground conditions.

At long periods of compressed air support the face stability decreases as the face dries out and the pore pressure is increased by compressed air penetrating into the face (Babendererde et al., 2000). Particularly problems occurred at sand lenses within surrounding clay when the pore water in the sand cannot be expelled under compressed air support. Although the face may look stable, the water is still in the sand and reduces the pressure difference at the face which determines the stand-up time. During tunneling for the 4th Elbe tunnel, the sand started to collapse without notice after drying occurred.

After face collapse and blow-out, the excavation and the working chamber were both completely full of water. The door within the buffer wall for face access was left open because the personnel had to rush into the compressed air lock when the collapse occurred. To remedy this condition, divers were used to close the buffer wall door within the flooded area, which was a first for such an operation on a TBM drive. The compressed air lock installations had to be changed – electrical controls and oxygen decompression units were taken out and air supply for divers were put in. Two divers with diving suits entered the lock, the lock was flooded with water. The divers removed the obstructed cables and hoses from within the buffer wall door and then closed the door. Within 2 days after the collapse the TBM was ready for operation again. Other time consuming measures such as ground freezing or injections were successfully avoided.

In total 10,920 work hours were spent under regular compressed air at pressures up to 4.5 bar during which 2,738 interventions were performed, 237 of them at pressures > 3.6 bar. In total 21 cases of decompression illness were reported, all of them occurred at pressures < 3.6 bar. The 4th Elbe tunnel is the first project where a rescue could be completed by connecting a NATO flange to the compressed air lock on the TBM to enable transport of injured personnel under compressed air pressure to a shuttle for pressurized transport the surface. Fortunately it was not necessary to use it.

This project shows that tunnelling under high groundwater head in soft ground is possible even with a large diameter TBM. While excavation with a Slurry-TBM under high groundwater head is generally not problematic, a large number of time consuming hyperbaric interventions under compressed air were necessary due to excessive wear. Long periods of compressed air support at one location should be avoided to minimize the risk of sudden face instability.

2.5 *Wesertunnel, Germany*

The 1.64 km long twin tube Wesertunnel crosses the river Weser north of Bremen. A Slurry-TBM (∅ 11.71 m) was used to excavate the tunnel in glacial deposits (Babendererde et al., 2000). The glacial soil consists of poorly graded and partly very loose cohesionless sand with hard granite boulders, and very soft to soft clay and peat in shallow areas (Fig. 4). Below the river, plastic clays were found to have mainly stiff to hard consistency (UCS > 400 kPa) reaching shear strength values of weak rock.

In contact with water, such as in fissures and on their surface, the stiff clays softened to a soft to medium consistency.

The tunnel invert's deepest point is 40 m below sea level. Due to tidal influence of the North Sea the water level of the river was typically between +/-2 m above/below sea level and reached in maximum +5.2 m above sea level (Fig. 4). Along the tunnel route, groundwater head encountered at tunnel invert was typically in a range of 2.5 to 4.0 bar and reached a maximum of 4.5 bar at storm tide. The tunnel cover of 12 to 20 m was relatively low, corresponding to 1 to 1.7 times the TBM diameter, which resulted in a high blow-out risk.

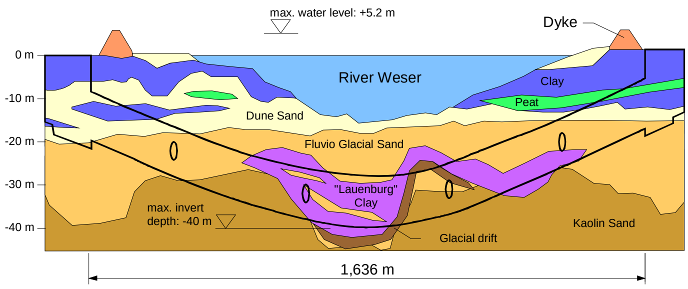

Figure 4. Longitudinal section of the Wesertunnel

During tunnel excavation, the applied face support pressure of the bentonite slurry was typically about 0.3 to 0.5 bar larger than the groundwater pressure according to calculations for various tunnel stations. Face pressures were adjusted by 0.1 bar steps to account for tidal variations within each 12 hour tidal interval.

In the deep tunnel section, clogging occurred during excavation of the first tube due to adhesive and cohesive properties of the clay which restricted material extraction from the excavation chamber. The average progress rate reduced to approximately 4 m/day. Before start of the second drive modifications on the TBM were performed, which separated the slurry pressure control from the function of spoil extraction and improved slurry flow conditions (Wirtz, 2004). In response, advance rates doubled to 8 m/day (including all maintenance work).

Maintenance under compressed air was performed at up to 4.5 bar air pressure for works at the cutterhead and up to 5 bar for works at the stone crusher. Additionally divers were used to work within the bentonite slurry under pressure of up to 5 bar. Regular compressed air (no mixed gases) and oxygen decompression were successfully used. In total 5000 h of compressed air works and a 1400 total interventions were performed while 600 of them were under pressures exceeding 3.6 bar. Only 15 minor cases of decompression illness were reported, all of them under pressures less than 3.6 bar.

2.6 *Westerschelde Tunnel, Netherlands*

The 6.6 km long Westerschelde Tunnel is the first tunnel project where saturation diving technique was used for excavation chamber interventions.

The twin tube tunnel was excavated by two Slurry-TBMs (Ø 11.33 m). Ground conditions consist of medium to fine quaternary sands within shallow sections and a massive formation of tertiary stiff clay on a length of approx. 2 km (Fig. 5). Dense tertiary sands are found below the clay within the deepest tunnel section (Braach et al., 2003).

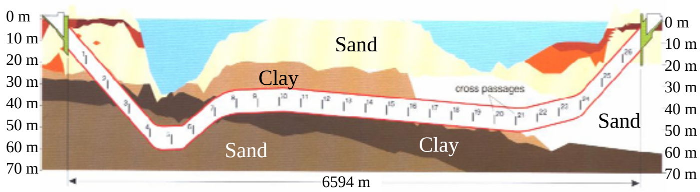

Figure 5. Longitudinal section of the Westerschelde Tunnel

At the deepest point the tunnel invert is at a depth of 60 m below sea level. The water level was typically within a range of +/- 2.5 m above/below sea level and reached about +4.0 m in maximum. The tunnel cover was in a range of 28 m to 40 m.

Due to very high water pressure, deformations of the shield up to 53 mm occurred at the deepest point of the tunnel alignment and reduced the available ring space for ring construction. As a remedial measure, lifting cushions were installed on the inside of the shield tail on one TBM. The cushions were filled with water and pressurized to stabilize the shield tail by using the stiffness of the erected ring within the shield tail.

Additionally, the excavation tools were changed in order to create a larger overcut which partly relieved the earth pressure on the shield tail. Saturation diving was required to perform this work as normal work under regular compressed air was no longer possible due to water pressure of up to 6.4 bar.

Saturation diving generally consists of progression of divers from compressed air habitats (regular compressed air < 3 bar) into high pressure (> 6 bar) with breathing mixtures consisting of either Heliox (helium and oxygen) or Trimix (helium, nitrogen and oxygen) with the proper composition depending on the type of operation and the pressure of exposure (Mayer, 2001).

The divers have to wear a special helmet which is light and enables breathing of mixed gases (Fig. 6). The helmet allows them to wear regular work suits and includes a cooling system as temperatures of up to 50 °C can occur within the excavation chamber. After approximately 4 hours of work in the excavation chamber, the saturation divers return to a compressed air habitat.

Figure 6. Special helmet for breathing mixed gases, used on the Westerschelde Tunnel

In total 6 excursions in saturation were performed with a total saturation time of 40 days at pressures of up to 6.9 bar within the excavation chamber. The decompression time was 4 days each time. Additionally 10 inspection excursions with mixed gases were performed, in addition to 1652 hours of work within compressed air involving 546 transfers. In total 5 cases of decompression sickness occurred, all of which were successfully treated in the onsite recompression chamber.

After saturation diving work, the personnel were transferred from the TBM to the habitat at the surface, by use of a shuttle, which could be connected to the backside of the compressed air lock on the TBM (Fig. 7) and to the habitat.

Maintenance work within the excavation chamber was able to be performed at atmospheric conditions at only one occasion, and even than additional support measures were necessary. After approximately 3.8 km of tunnel drive the main bearing had to be inspected and repaired. At this location the TBM was full face within stiff clay, that was self supporting and almost watertight (UCS 450 kPa; clay content 35 to 60%). The tunnel invert was about 45 m below sea level. A mortar seal, which was supported by the cutterhead and supporting plates, had to be installed at the face as an additional support and sealing measure before start of the repair work.

The Westerschelde tunnel project shows, that use of mixed gases and the saturation method is a very successful approach for hyperbaric interventions at very high groundwater pressures exceeding 5 bar. At such pressures use of regular compressed air is no longer possible due to the fact that nitrogen within compressed air is narcotic, also known as “rapture of the deep” or nitrogen narcosis.

Figure 7. Shuttle connected to the comprresed air lock on the TBM by NATO-Stanag flange (Westerschelde Tunnel)

2.7 *Red Line St. Petersburg, Russia*

An 800 m long twin tube TBM tunnel was driven to rebuild an existing metro twin tunnel in St. Petersburg which was build in the early 1970s using ground freezing, an open face shield, reinforced in situ lining and an inner welded steel casing. These first two tunnels had about 6.5 bar external water pressure and were closed in 1995 due to heavy water inflow of up to 800 m³ per day on each tunnel causing substantial sand inflow of some 30 m³/day and surface settlements reaching 300 mm. This caused the tunnel section to be closed (Wallis, 2002).

The new tunnel was excavated using a refurbished 7.4 m diameter Slurry-TBM (Voest Alpine Polyshield) which was used previously on the EOLE-Project in Paris in the mid 1990s. The tunnel drive was started within impermeable, hard claystone, then passed into a valley filled with softer/looser low plasticity clays, silts and fine sands under high groundwater pressure and then back into the claystone. The tunnel invert lies about 65 m below the surface and imposes a hydrostatic head of up to 5.6 bar within the soil section which is in close proximity to the river Neva. The maximum applied slurry pressure was about 6.4 bar at invert level while the TBM was designed to handle a max. slurry pressure of up to 8.0 bar. Cutterhead interventions were performed at atmospheric conditions (no compressed air pressure) within the claystone, which is a competent rock and was completely dry. Within the tunnel section in high permeability soil, interventions were performed under compressed air support. At pressures reaching 5.5 bar, mixed gases were used for breathing air while workers had to wear breathing masks. A transfer shuttle was able to connect to the compressed air lock on the TBM for transfer to a decompression chamber.

At 5.5 bar, the gross working period was about 1.5 hours followed by approximately 5 hours of decompression. This slowed down the tunnelling progress significantly as only 4.5 gross working hours under pressure were possible per day. Approximately 15 to 25 minutes of time was needed for each entry to apply the pressure, open the bolts and brackets of the bulkhead hatch door, and prepare and clean the excavation chamber. After accounting for this time, the net daily working time for tool changes was only about 3.5 working hours when the crews worked 3 shifts per day. Thus a stoppage for a cutter changes, which usually takes about 5 days under atmospheric conditions, took about 1 month under 5.5 bar air pressure.

The St. Petersburg project showed that the equipment installed for use of mixed gases was able to handle the groundwater pressure of up to 5.5 bar, but allowed only very limited working periods and required time consuming decompression periods. Based on their experience at this site, the TBM personnel recommended use of a saturation diving technique for a future projects under similar conditions rather than mixed-gas diving back and forth from atmospheric pressure.

2.8 *Nara Prefecture Water Conveyance Tunnel, Japan*

The Nara Prefecture water conveyance tunnel with a length of 1151 m that was excavated by an EPB-TBM (ϕ 3.95 m). The TBM was assembled underground within a cavern at the end of an 860 m long drill and blast tunnel.

The EPB-TBM tunnel started within a short zone (<10 m) of foliated crystalline schist (Zone 1 in Fig. 8), then passed through mixed-face ground into soil.

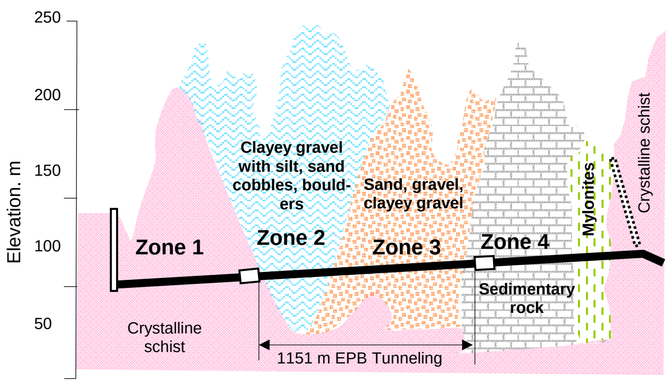

Figure 8. Nara Prefecture ground profile

The initial soil unit (Zone 2 in Fig. 8) extended to approximately Station 6+20 m of the EPB-TBM drive. Zone 2 was described as gravel (10 to 50 percent gravel) with cobbles and boulders in a matrix of cohesive sand, silt and clay. The cohesive soil matrix was apparently very stiff to very hard and had a fines content (< 0.074 mm) ranging from 25 to about 45 percent. Within the last 18 m of Zone 2, the fines content decreased and the soil became more permeable and unstable.

The second soil unit (Zone 3 in Fig. 8) was a higher permeability sandy stratum with a gravel with occasional zones of very hard (UCS = 2.2 MPa) sandy clay with gravel.

The EPB-TBM holed through into Zone 4 rock, a Cretaceous age sedimentary rock that had been premined by drill and blasting methods.

A maximum groundwater head of 11 bar was measured about 85 m after launch with the TBM at rest in Zone 2. The groundwater pressure typically dropped 2-3 bar during tunnel advance. External groundwater pressure decreased to about 7 bar near Zone 3. External water pressures during tunnelling through Zone 3 sands generally ranged from about 6 to 8 bar. This pressure data suggests that active earth paste pressures typically ranged from 6 to 9 bar during tunnel advance.

The TBM was equipped with 3 screw conveyors for pressure dissipation. The initial screw was 500 mm diameter and approximately 7.2 m long. The second and third screws were each 600 mm diameter and approximately 4.3 m long. Mud (bentonite slurry) was pumped into the excavation chamber for ground conditioning. Volume, density and viscosity of the injected mud were adjusted to the ground conditions.

Problems developed when high groundwater inflows occurred. The excavated soil (muck) generally degraded into a thin sludge. To compensate, the openings at guillotine gates along the screw conveyors and discharge gate at conveyor 3 were reduced in size. The restricted gate openings reduced the tunnel progress rate.

At about station 900 m, cutterhead torque significantly increased and the progress rate decreased when a zone of very hard cohesive soil was encountered. To compensate, the cutterhead teeth (pin type) were replaced from the backside of the cutterhead. A sample of cohesive ground was taken from the face and tested. Its unconfined compression strength was 2.2 MPa which indicates a very hard, low permeability soil, similar to the properties of a mortar or lean concrete.

Interventions for replacements and repairs were provided 3 times in total. Kawai & Tanabe (1988) did not report if compressed air or other gases were used during cutterhead interventions. The TBM profile did not show or identify an air lock, which suggests that compressed air capability was not provided and that the interventions were completed in free air.

The tunnel lining consisted of high water pressure resistant steel segments (DA 3.65 m, width 1.0 m) and a secondary steel pipe lining (DA 2.4 m, t = 18 mm). The steel segments were equipped with a 5 x 20 mm water-swelling seal. About 100 m behind the TBM the segment bolts were further tightened and the caulking groove was filled with epoxy resin to prevent leaks. The seals were effective as hardly any leakage was observed, even at 11 bar external water pressure.

The 15 cm thick annular tail gap outside of the segments was filled with a two component backfill grout. The gel time was generally 4 to 8 seconds and after 28 days unconfined compression strength of about 2.5 MPa was achieved. Grouting pressure was generally equal to external water pressure plus 3 bar. Grouting pressures as great as 15 bar were reached. The average grout volume rate was about 130% of the theoretical annulus volume. No major problems were reported related to backfill grouting. Occasionally, some grout found its way past the tail seal and into the excavation chamber when advancing through the more permeable sand and gravel zones. This problem was solved by decreasing the gel time.

The Nara Prefecture tunneling experience shows that screw conveyors and the earth pressure balance method can be used for excavation chamber pressure dissipation in both cohesive and granular soils under heads up to 11 bar. Three cutter change interventions were required in the abrasive soil at an average spacing of 288 m. Sufficiently low permeability and high soil strength were encountered at the headings to allow free air interventions.

2.9 *Tokyo Bay Wan Aqua Line, Japan*

Tokyo Bay Wan Aqua-Line is a toll road across Tokyo Bay that includes two tunneled legs each with parallel 13.9 m inside diameter tunnels at depths of 60 m below sea level. The two Kawasaki leg tunnels have drive lengths of 2.30 km each while the two Chou leg tunnels have drive lengths of 2.26 km each (Funazaki et al. 1999).

The tunnels were bored using eight slurry shield TBMs (3-Kawasaki Heavy Industries, 3-Mitsubushi, 1-Hitachi, and 1-IHI) having 14.14 m outside diameters (Wallis, 1994). The ground cover and tunnel zone varied from soft sedimentary marine silty clay and sandy clay to denser cohesionless to weakly cemented sand. Cover over the tunnels ranged from 15 to 20 m and averaged approximately 16 m. Groundwater pressure varied from 5.1 to 6.0 bar and slurry pressure at the heading was slightly more (0.2 to 0.5 bar estimated), but actual pressures were not reported.

The Slurry-TBMs were capable of applying 9 bar pressure at the heading (Smith 1995) and were also equipped with air locks, capable of applying 3 bar of air pressure during interventions, if necessary.

Due to concerns with compressed air blow-outs through the soft sediments during excavation chamber interventions to inspect and change cutters, the eight tunnel drives were kept relatively short and the cutters and cutterheads were designed to be abrasion resistant without need for repair or changes during the design drive lengths.

Interventions would have required ground freezing of the heading (Wallis 1994), but fortunately no interventions were needed. The TBMs were furnished with 40-50 ports through the shield bulkhead for drilling, grouting or freeze pipe installation, if needed.

The tunnels were initially lined with 11+1 key bolted and gasketed precast concrete segments, 65 cm thick and 1.4 m long. The segments were designed to withstand all anticipated loads, including 6 bar of groundwater pressure. The final lining consisted of a waterproofing membrane and 35 cm of cast-in-place concrete (Wallis, 1994).

After cutterheads from opposite drives met, the slurry TBMs were stripped of equipment and the shields abandoned. The undersea junctions were completed using ground freezing to allow cutterhead removal and permanent connection of the tunnel linings (Funazaki et al. 1999).

The Tokyo Bay Wan Aqua-Line tunnelling demonstrated that large diameter slurry TBM tunnelling can be successfully completed through weak clays and non abrasive sands under 6 bar groundwater head with low cover (16 m) without need for compressed air interventions.

3 COMPARISON OF TBM PROJECTS WITH HIGH GROUNDWATER HEADS

A comparison of the previously discussed TBM projects in soft ground and weak rock with high groundwater heads is presented in Fig. 9 and Table 3. Fig. 9 shows the encountered groundwater head, the applied support pressure during excavation (EPB- or slurry pressure), and the applied air pressure during compressed air interventions.

It turns out that on some of the projects, such as the Storebaelt tunnel and the Channel tunnel the encountered groundwater head was much less than anticipated due to dewatering or ground of very low permeability, respectively.

During excavation, the applied face support pressure was generally maintained slightly above the groundwater pressure on all selected projects in order to provide face stability.

During interventions, there was a wide range of applied pressures. On some projects the applied compressed air pressure was much lower than the groundwater head and interventions were executed only in stable, low permeable ground such as on the South Bay Ocean Outfall project and on the Nara Prefecture tunnel. On all other projects the applied

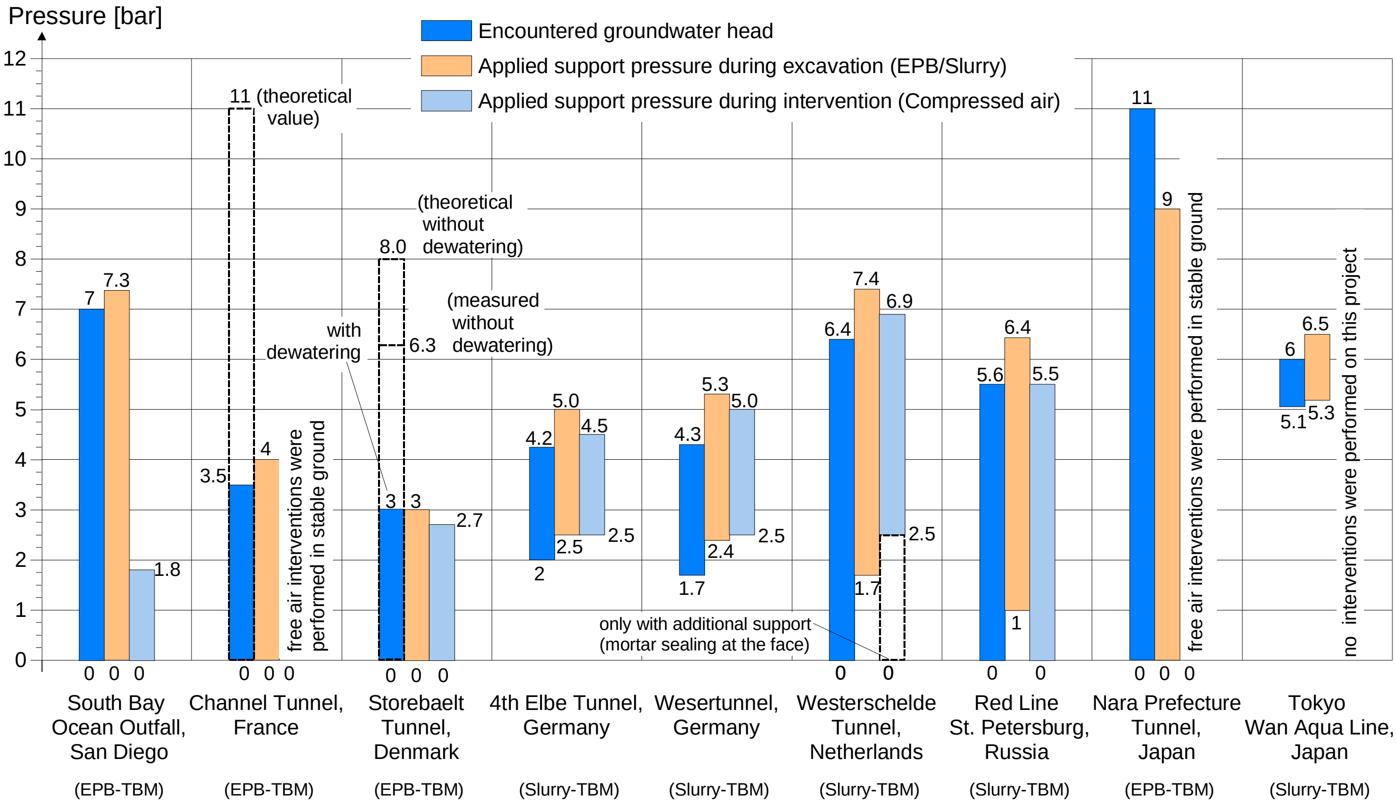

Figure 9. Encountered groundwater head and applied face support pressure (EPB/Slurry and compressed air respectively).

compressed air pressure was in the same order as the ground water pressure.

There are only two projects where mixed gases were used — the Westerschelde tunnel and the Red Line in St. Petersburg. There is only one project so far, where saturation diving was used (Westerschelde). On all other projects compressed air support was used for cutterhead inspections or free air face access was performed in single cases of very strong, low permeability ground conditions that did not require face support.

4 WORKING RANGE FOR USE OF COMPRESSED AIR, MIXED GASES AND SATURATION

There are typical working ranges for use of compressed air or mixed gases and saturation diving respectively for cutterhead interventions, as presented in Fig. 10. It shows that applicable pressure ranges overlap for the three types of intervention methods.

Compressed air is recommended for pressures up to 3.6 bar which is the upper limit according the German regulation for compressed air works. A lower 3.0 bar upper limit exists in the United Kingdom and most of the United States. Certificates of exemption were applied and issued for single projects, such as the 4th Elbe tunnel and the Wesertunnel to allow use of compressed air up to 5 bar in exceptional cases at single locations and with specific additional requirements. In the United States, an variance was obtained on the Portland West Side CSO project to allow regular compressed interventions up to 4.8 bar (Burke 2004).

Slightly longer working periods compared to what is possible with compressed air can be achieved by using mixed gases for short term interventions such as for inspections at up to 8 bar pressure.

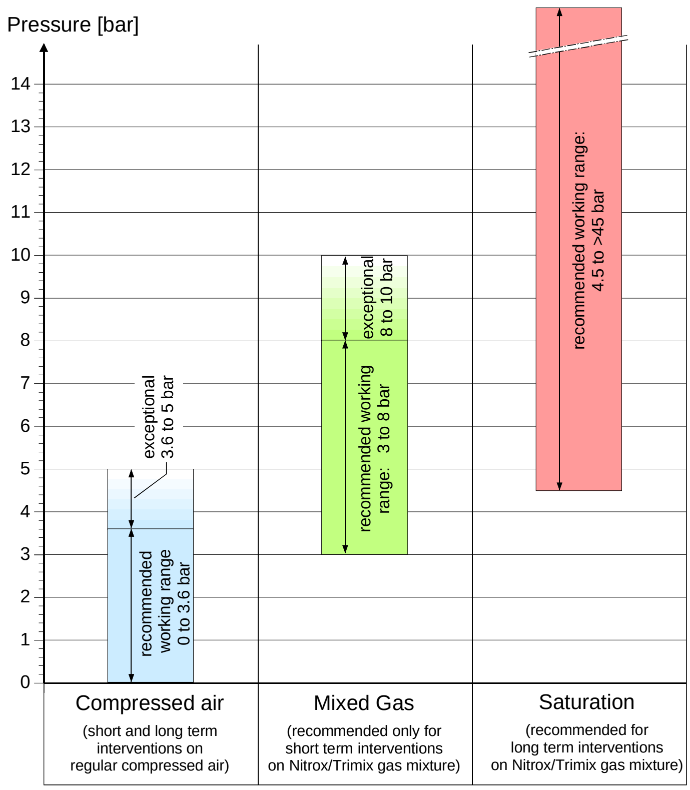

Figure 10. Recommended pressure working range for use of regular compressed air, mixed gases and mixed gases under saturation for hyperbaric interventions on TBMs

Table 3. TBM projects under very high groundwater heads

Project name	South Bay Ocean Outfall, San Diego	Channel Tunnel (French Side), France	Storebaelt Tunnel, Denmark	4th Elbe Tunnel, Germany	Wesertunnel, Germany	Westerschelde Tunnel, Netherlands	St. Petersburg, Red Line, Russia	Nara Prefecture Water Conveyance Tunnel, Japan	Tokyo Wan Aqua Line Tunnel, Japan
TBM type	EPB-TBM	3 EPB-TBMs	4 EPB-TBMs	Slurry-TBM	Slurry-TBM	2 Slurry-TBMs	Slurry-TBM	EPB-TBM	8 Slurry-TBMs
TBM manufacturer	Mitsubishi Heavy Industry	1 x Robbins-Komatsu; 2 x Robbins-Kawasaki	Howden/Wirth	Herrenknecht	Herrenknecht	Herrenknecht	Voest Alpine	Japanese	3-Kawasaki Heavy Industries, 3-Mitsubishi, 1-Hitachi, 1-IHL = 8 total
TBM diameter	3.98 m	5.72 m (1x) 8.72 m (2x)	8.75 m	14.20 m	11.71 m	11.33 m	7.40 m	3.95 m	14.14 m
Tunnel length	5,795 m	15.6 km; 20 km; 18.9 km	2 x 7,412 m	2,561 m	2 x 1,645 m	2 x 6,600 m	2 x 800 m	1,151 m	2 x (4.6 km + 4.5 km)
Ground type at tunnel depth and above	12% cobbly sand + gravel, 14% silty sand, 18% sandy silt, 56% stiff-hard silty clay and clayey silt	Chalk and calcareous marl, UCS 6-9 MPa, $k<10^{-7}$ m/s	Marl (highly fractured mudstone, $k=5\times10^{-4}$ m/s) and glacial Till (very abrassive sandy material with gravels and limestone/granite boulders)	Glacial soils: sand and marl with boulders, clay with sand lenses and boulders	Poorly graded, loose sand with granite boulders; soft clay and peat; stiff to hard clay	Medium to fine sands; stiff clay, dense sands in deep sections	Saturated glacial deposits: fine loam + sands	25% cohesive silty-clayey gravel with cobbles and small boulders, 75% compacted gravelly sand	soft marine silty to sandy clay overlying denser cohesionless to weakly cemented sand
Max. ground cover	58 m	90 m	45 m	35 m	20 m (below dyke)	35 m	55 m	135 m	20 m
Max. groundwater pressure at tunnel invert	7.0 bar (measured)	11.0 bar (theoretical)	8.0 bar (theoretical) 6.3 bar (measured)	4.2 bar (measured)	4.3 bar (measured)	6.4 bar (measured)	5.5 bar (measured)	11.0 bar (measured)	6.0 bar (measured)
Max. TBM shield design pressure	8.5 bar	11 bar shield, 18 bar tail seal	8.0 bar	6.0 bar	6.0 bar	8.0 bar	8.0 bar	11 bar	9 bar
Max. tunnel external lining design	7 bar	10 bar	8.0 bar	5.5 bar	6.0 bar		6.0 bar	11 bar	6 bar
Max. applied support pressure at tunnel invert during excavation	7.3 bar	~3.5 bar (mined in open-mode)	typically < 3 bar	5.0 bar	5.3 bar	7.4 bar	6.4 bar	11 bar	6.5 bar
Number of interventions for cutter/cutterhead work	16 attempted, 10 completed	at average spacing of 1.2 km	not reported	2738	1400	approx. 817	not reported	3	none
Number of interventions under free air	8	not reported	not reported, but used	not used	not used	1	not reported, but used	3	none
Number of interventions using	2	not used	not reported, but used	2738	1400	approx. 800	not reported, but used	no report of compressed air	not used
Number of interventions using mixed gas	0	not used	not used	not used	not used	10	not reported, but used	not used	not used
Number of interventions using mixed gas + saturation diving	0	not used	Saturation diving was specified in the specs, but not installed on TBMs	not used	not used	6	not used	not used	not used
Max. applied compressed air pressure during intervention	1.8 bar	0 bar (free air)	max: 2.7 bar typically: 0 bar	4.5 bar	5.0 bar	6.9 bar	6.0 bar	no report of compressed air use	no use of compr. air
Special TBM features	Capability for advance probing and grouting or freezing of heading. Screws had four guillotine gates.	Double shield, single 11 m long screw with two piston discharge pump on TBM 5.72 OD and double screws (7 and 10 m long) on TBMs 8.72 m OD	2 screw conveyors + Putzmeister piston pump; four rows of brush seals	accessible cutterhead arms to change cutters under free air; rescue compressed air shuttle could be connected to the TBM air lock	isolated invert area: separation of slurry pressure control from spoil extraction (2nd drive)	Mixed gas and saturation equipment including shuttle and habitat	compressed air shuttle could be connected to the TBM air lock; four sets of tail seal brushes	4 wire brush seals	Advance grouting and ground freezing capability, tail seals have 4 wire brush rows rated at 12 bars
Tunnel lining	5 + 1 bolted-gasketed concrete segments (ID=3.35 m, t= 30 cm, L= 3.81 m; rebar reinforced)	5 + 1 bolted-gasketed concrete segments (ID= 7.6 m, t= 40 cm L=1.6 m; rebar reinforced)	6 + 1 bolted-gasketed concrete segments (ID 7.70 m; t=40 cm; L=1.65 cm; B35; rebar reinforced)	8 + 1 bolted concrete segments, 2 gaskets (ID 12.35 m; t=70 cm; L=2.0 cm; rebar reinforced)	6 + 1 bolted-gasketed concrete segments (OD 11.30 m; t=50 cm; L=1.50 cm; rebar reinforced)	7 + 1 bolted-gasketed concrete segments, (OD 10.10 m; t=45 cm; L=2.0 cm; rebar reinforced)	5 + 1 bolted-gasketed concrete segments (t=35 cm; L=1.40 cm; rebar reinforced)	Steel segments, 3650 mm OD, 1.0m long. Final lining 2400 mm ID welded steel	11+1 bolted-gasketed precast concrete segments (ID= 11.9 m, t= 65 cm L=1.5 m; rebar reinforced)
Notes / incidents	Screws jammed due to boulders; temporary uncontrolled inflow of water + soil through screw conveyor in gravel before conditioners adjusted	Mainly open mode TBM operation due to presence of low permeability chalk	excessive wear on cutterhead; massive water inflow during excavation; inundation of two TBMs and two tunnels; extensive dewatering scheme (Project Moses) to reduce groundwater head to 3 bar; Resume: 100% cost	Face collapse and blow-out at 4.5 bar. Use of divers for underwater saervice on TBM and in river Elbe.	Use of endoscope inspection with remote-controlled camera; installation of isolated invert area improved significantly tunnel progress rate	1st time use of divers for cutterhead works under mixed gas; 1st time use of a shuttle transfer system for compressed air technicians	long stoppage periods due to short working periods at high compressed air pressure up to 5.5 bar using mixed gases without saturation	3 screw conveyors, mud supply into excavation chamber, water inflow into tunnel	Underground docking of 8 TBMs at two tunnels with four headings with ground freezing for groundwater cutoff.
Construction period	1995-1999	1988-1991	1990-1994	1995-2000	1998-2002	1998-2001	2002-2004	1984-1988 (including D&B)	1994-1997
Contractor	Traylor Brothers	JV Bouyges, Dumez, SAE, SGE, Spie Batignolles	JV Monberg & Thorsen, Campernon Bernard, Dyckerhoff & Widmann, Kiewit Construction, Sogea	JV Bilfinger+Berger, Dywidag, Heitkamp, Hochtief, Philipp Holzmann, Wayss & Freytag, Züblin	JV Hochtief, Philipp Holzmann, L. Freytag, Hecker, Oetken	JV Bredero Infrabow, Franki, Heijmans, Voormolen, Philip Holzmann, Wayss & Freytag	JV Impregilo/ NCC	JV Okumaragumi + Obayashigumi	24 companies including: Kajima, Taisei, Nishimatsu, Tobishima, Obayashi, Maede, Kumagai and Shimizu

If longer interventions are required such as for repair works or multiple cutter changes, use of mixed gases under saturation conditions are recommended at pressures exceeding 4.5 bar. For long term saturation interventions, the same helmet is used as for short term mixed gas intervention, but additionally a shuttle and a habitat are required.

As pressure increases, the allowable working period decreases significantly. For a total decompression period of 2 hours, which should not be exceeded for workers sitting in the relatively small TBM airlock, use of compressed air and decompression with oxygen results in a gross working period under hyperbaric pressure of 2:45 hours at 3 bar, 1:35 hours at 4 bar and only 50 min at 5 bar. Additionally, the net working time at the face is about 15 to 20 minutes shorter, as safety bolts and brackets on the hatch door in the buffer wall have to be opened and closed and the excavation chamber has to be prepared and cleaned for inspection. This means that at 5 bar pressure compressed air can be used for a quick inspection but is not suitable for major maintenance or repair works, which would significantly increase the required stoppage time.

If mixed gases are used instead of compressed air at 5 bar pressure and a 2 hours decompression period, the gross working period increases by 50%, being 75 min in total. This enables short term maintenance work to be done.

For long term maintenance or repair work, saturation is recommended, which enables 4 hours working period per team. By using two teams per day this would allow a constant 8 hour working period per day, which is major benefit.

5 CONCLUSIONS

Based on the experience from nine completed tunnel projects in soft ground or weak rock under groundwater heads ranging from 4 to 11 bar, the following key points can be summarized for these and future projects:

- High groundwater pressure (above 4 bar) makes tunneling much more difficult and requires special knowledge of cutting edge technologies during design and construction.
- TBM, tunnel equipment and tunneling procedures should be designed to enable reliable application of adequate support pressures at all times during excavation and hyperbaric interventions to counterbalance the acting groundwater head.
- If adequate primary components and backup systems are not installed on the TBM, major problems including cost overruns and time delays can occur, as happened on the Storebaelt tunnel.
- Tunnel excavation in strong, fine grained cohesive soils and rock under high groundwater pressure is generally not problematic for Slurry- and EPB-TBMs, as typically the face is stable and the amount of inflowing water is low due to low permeability of the ground.
- In coarse-grained soil or unstable rock, tunnel excavation requires a reliable active face support to provide face stability and prevent excessive lost ground during tunneling and interventions. Suitable active face support is easier to achieve with Slurry-TBMs. On EPB-TBMs, adjustments to the muck conditioning needed for pressure control takes time and EPB-TBMs are often not responsive enough to abrupt ground condition changes to be effective at controlling water inflow and ground loss such as happened on the San Diego, Storebaelt and Nara Prefecture tunnels.
- Depending on the level of the groundwater pressure, abrasiveness of the ground and the length of the corresponding tunnel sections, the TBM should include provisions for hyperbaric interventions using regular compressed air, mixed gases or saturation diving, depending on pressure level and duration of intervention time expected.
- Only in very strong, low permeability soils or in competent rock are risks of attempting cutterhead interventions under free air reasonable (if not otherwise restricted), but there should always be provisions available to apply adequate compressed air support or ground treatment if needed.

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