NORDSEETAUCHER GmbH

(N-Sea-Divers)

Hyperbaric Tunnel Construction and Diving®

Work under Hyperbaric Conditions
Diving and Compressed Air Work in Tunnel-Boring-Machines

Below a depth of 40 metres (which equals 4.0 bar over pressure) compressed air technicians enter a zone where it is no longer effective to carry out compressed air work under conventional conditions. However, because the next generation of tunnels will be longer and deeper than anything we have at present, it can only be a matter of time and opportunity before divers and compressed air technicians start playing a key role in hyperbaric work.

High groundwater head is a major challenge for tunneling 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 4th River 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 4.5 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.

Frequent interventions for cutterhead maintenance were necessary due to presence of abrasive soils. 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. 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 up to 4.5 bar.

In total 10,920 work hours were spent under regular compressed air at pressures up to 4.5 bar during which 2,738 man 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 River Elbe tunnel was the first project where a rescue could be completed by connecting a NATO lock on the TBM to enable transport compressed air pressure to a shuttle surface. Fortunately it was not

flange to the compressed air of injured personnel under for pressurized transport the necessary to use it.

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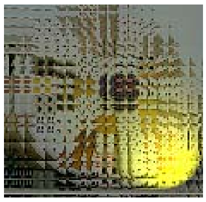
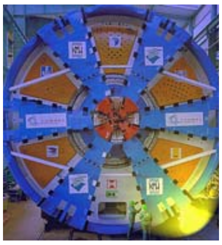


The 1.640 m long twin tube **Wesertunnel** crosses the river Weser north of Bremen, Germany. A Slurry-TBM (∅ 11.71 m) was used to excavate the tunnel in glacial deposits. The glacial soil consists of poorly graded and partly very loose cohesion, less sand with hard granite boulders, and very soft to soft clay and peat in shallow areas. Below the river, plastic clays were found to have mainly stiff to hard consistency reaching shear strength values of weak rock.

The tunnel invert's deepest point was 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. 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.

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 5.000 h of compressed air works and a total of 1.400 man 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.



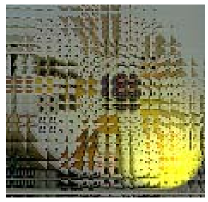
The 6.6 km long **Westerschelde Tunnel** is the first tunnel project where saturation diving technique was used for excavation chamber interventions. The twin tube tunnel was excavated by two Slurry-TBMs (Ø 11.33 m). Ground conditions consist of medium to fine quaternary sands within shallow sections and a massive formation of tertiary stiff clay on a length of approx. 2 km. Dense tertiary sands are found below the clay within the deepest tunnel section.

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.

When Nordseetaucher GmbH was asked to cooperate on this project to build two tunnels under the Westerschelde in the Netherlands, we didn't hesitate a moment, knowing that it would be an ideal opportunity to put to use the skills and expertise we had gained during our 4th Tube of the River Elbe Crossing and the Wesertunnel, Germany contracts. However, the problems we could expect to face were on a slightly different scale. In the 4th Tube of the River Elbe Tunnel we were working under pressures of up to 4.5 bar, while work in the Wesertunnel was carried out at 5.0 bar. The brief for the two tunnels of the Westerschelde Tunnel Project called for us to work at pressures of up to 8.5 bar.

It is impossible to work at 8.5 bars pressure with compressed air, because the nitrogen contained in breath causes narcosis. Accordingly, from the very start we planned to work using mixed gases.

For several decades, a number of methods and procedures have been tested and applied in international commercial offshore diving which can also be used in machine-driven tunnel construction projects carried out in hyperbaric pressure in excess of 5.0 bar.



For instance, the use of mixed gases. These gases are a mixture of oxygen and various inert gases, blended according to the specific pressure spectrum to allow the divers to work for days and weeks under pressurised conditions (saturation method). At hyperbaric pressures of between 3.0 and 6.0 bar compressed air can be used as working gas with the saturation method, and may indeed be the method of preference in future. In order to use mixed gases safely and successfully, meticulous preparations to the tunnel boring machine and logistical processes are necessary.

Due to the relatively thin clearance above the tunnel it would have been dangerous to lower the bentonite level in the cutterhead chamber, the excavation chamber. Accordingly, specially trained diving personnel were on hand to carry out inspections and tool changes in the event of repair and maintenance work becoming necessary.

In total, 6 excursions in saturation were performed with a total saturation time of 40 days. The decompression time was 4 days each time. 10 inspection excursions with mixed gas were performed, in addition to 1.652 hours with compressed air involving 546 man interventions. 5 cases of decompression sickness occurred, all of which were successfully treated in the onsite treatment chamber.

Diving in Bentonite

Preparations

To allow manned interventions to be carried out in the bentonite, special flanged connections were installed in the pressure walls of the tunnel boring machines. These lines supplied the divers with breathing air, reserve air, communication lines, lighting, video and data transmission, and water to flush the breathing regulators in the diving helmets. Those flange connections are also perfect for the new overpressure work helmet.

The Diving Helmets

Diving helmets normally used for offshore diving were specially modified to allow them to be used for diving in bentonite. To make it easier for the divers to breathe in the bentonite, which is a clay suspension, and to reduce breathing resistance, the helmets were fitted with a water flushing system for the air regulator. The constant supply of fresh water also prevents the breathing membranes from sticking together.

The Umbilical

As the name indicates, the umbilical is the diver's lifeline. The umbilical consists of a variety of differently coloured tubes and cables, which pipe in air, reserve air and fresh water, and also contain communication lines, light, video and data transmission lines.

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Diving and Working in Saturation Conditions

The Living Chamber

Saturation diving means living and working under hyperbaric conditions for long periods of time, i.e. anything up to 28 days, although the limits have never been fully tested. To enable divers and engineers to survive and work under these conditions requires a pressurised living chamber consisting of a number of rooms outside of the tunnel zone. Up to 9 divers and engineers can live in this system, and it contains all the necessary facilities, from berths to showers and toilets.

The Transport Shuttle

Due to technical and hygienic reasons, it is not as a rule feasible to locate the saturation habitat in the tunnel zone and link it to the tunnel machine. This makes it necessary to use a mobile transportation system – a shuttle. The shuttle collects the divers from the habitat outside the tunnel zone and takes them to the tunnel, where they dock on to the tunnel machine. Each pressurised shuttle can take up to 4 divers, technicians and engineers. Once it docks on to the tunnel machine, the passengers disembark and go to their stations in the control room and the excavation chamber to carry out all necessary inspection, maintenance and repair work to the cutterhead.

Hyperbaric Helmets

Unlike in the 4th Tube of the River Elbe Tunnel and Wesertunnel projects, where the pressure was in excess of 4.5 and 5.0 bar, we were unable to work with compressed air under the Westerschelde. Instead, we used mixed gases, consisting of helium, nitrogen and oxygen. The equipment used by the divers was identical to that used in the other tunnel projects. Partially submerged work under the Westerschelde was carried out with the aid of a new, lightweight type of helmet used in the chemical industry. These helmets, which are not available on the free market, were specially refitted and adapted for the task. All tests and trial runs prior to the start of the project were carried out at the Belgian Navy's Hyperbaric Centre in Zeebrugge. This special helmet has two breathing regulators and a controllable cooling system, the latter being essential, as temperatures in front of the tunnel face can reach up to 50° Celsius.

This new helmet design of Composite Beat Engel, Switzerland is the construction of an overpressure helmet. It has been realized in close cooperation with Nordseetaucher GmbH. This type of helmet - that with an additional kit can be transformed within one hour into a breathing controlled helmet - is now operational in extreme hazardous environment like tunnel machines and gives full satisfaction to the user. Every helmet is provided with connections for surface air/gas supply, an independent emergency air/gas connection and communications equipment.

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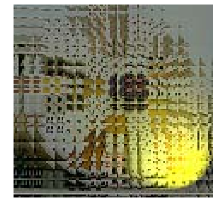


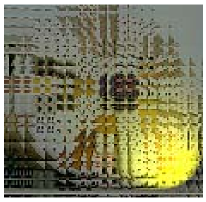
The **Nanjing Yangtze River Crossing Tunnel** is a 2.990 m long twin tube crosses the river Yangtze in Nanjing, China. Two Slurry-TBMs (∅ 14.96 m) are in use to excavate the tunnel in soft alluvium strata. The strata are mainly silt and fine sand.

The tunnel invert's deepest point is 65 m below sea level. Due to tidal influence the water level of the river is typically between +/-1.5 m above/below sea level.

On this project, welding in compressed air was the major task to carry out. From our experience and research of welding in compressed air and under water we knew that it is not a real problem. But this time it was very extreme. The buckets of 6 arms of the TBM had to be renewed. Therefore we welded new supports on the side arms of the cutterhead. The total time of this work took more than 12 weeks, day and night. The pressure was up to 5.4 bar overpressure in air. To keep the support pressure stable we used bentonite with a special mixture of high density and viscosity.

Maintenance and repair under compressed air was performed at up to 5.4 bar air pressure for works at the cutterhead and up to 6.5 bar for works at the stone crusher. Regular compressed air (no mixed gases) and oxygen decompression is successfully in use. In total more than 4.000 h of compressed air works and more than 850 total man interventions are performed. Only 3 minor cases of decompression illness are reported.

For the welding operation we used the first time a new special designed compressed air helmet with triple air supply, two regulators and one free flow, communication and an integrated welding shield with sensors.



Summary

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.

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.

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.

The experience gained in the projects proves that the saturation method is a very successful approach to hyperbaric tunnel constructions. It also shows us that work in compressed air is possible up to 6.5 bar overpressure, but not very efficient.

The cooperation between the tunnel construction companies, the manufacturer of the TBM's, the Herrenknecht AG, the Hyperbaric Medic Dr. Faesecke, the Hyperbaric Training Center, Germany, the Classification Company Germanischer Lloyd, the Design and Manufacture Company Composite Beat Engel and the Nordseetaucher GmbH is very rewarding and productive, and we hope that it can be intensified in future co-operations. The excellent training of the diving personnel, engineers and hyperbaric construction technicians involved in this ground-breaking projects, the continual training and the adaptation of the tunnelling machines to the existing conditions open up a highly promising perspective on the future of tunnel construction:
deeper, larger and longer.

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