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Soft Ground Tunnelling

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Abstract
The practical application of closed shells as a construction element in tunnelling by the New Austrian Tunnelling Method and the increasing utilisation of microelectronics in mechanical engineering to construct tunnel boring machines have accelerated the development of tunnelling technics especially in soft ground during the last years.
Report will be given about the state of these technics particulary on the application in machine tunnelling.

1. Introduction

In Berlin a section of metro has once again been driven with a Hydroshield, that is a slurry shield. Three years previously the same crew with the same shield drove another section of the Berlin metro very successfully only a few kilometers away.
However this time it was not in the sand strata, but in boulder clay deposits of the glacial geologie with enclosed sand lenses and many boulders.A strata very similar to that on the Great Belt crossing in Danmark.
The same tunnelling machine which had been a thoroughbred in sand was suddenly a stubborn old mule in boulder clay.
Satisfactory advance rates could only be achieved with a new design especially constructed for the particular ground conditions.
This example once again confirms that there is no universal tunnelling machine for soft ground. The machine and components must be matched to the specific geological conditions and these are very diverse in soft ground.

2. Ground Conditions

The ground conditions which influence the tunnelling work in soft ground are mainly determined by the consolidation, the shear strength, the grain size distribution, the water content and the pore water pressure.

The soft ground spectrum encompasses the rock hard marl of West German metro construction sites, the grey Chalk Marl of the Channel tunnel as well as the river mud in the bed of the Huang Po in Shanghai.
So it is not surprising that the methods to drive tunnels in soft ground are very diverse.
Mechanical tunnelling methods are adapted to the particular geological conditions if the tunnel is long enough and the crossection does not vary. The geological conditions are adapted to the tunnelling method when the tunnel is short or the cross section frequently changes.

3. Tunnelling Methods

3.1 NATM

Today short or varying tunnels are also driven in soft ground using the NATM. The ground conditions must ensure that the exposed ground in the crown during an excavation sequence does not collapse, that is be stable , for 1 hour over a cycle depth of about 1.5 m.
If this is not the case, the ground must either be mechanically supported with rammed or bored steel spiling or forepoling sheets, as on the Fort Totten Station at Washington Metro; or the soil properties must be improved with cement or chemical grouting.
With very fine grained ground, particularly in ground water, ground freezing is used. This is expensive and therefore only applied in special cases. During metro construction in Germany ground freezing was used in Munich, Stuttgart, Frankfurt, Essen and Nürnberg.

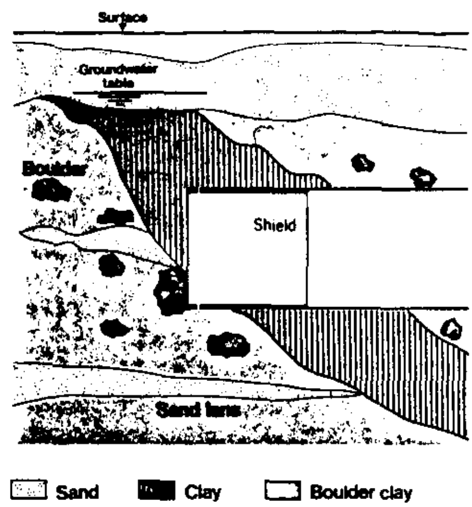
Compressed air can also be used to increase the unsupported period of the ground, because the compressed air not only balances the pore water but supports as well the ground. Many sections of metro have been driven in Germany with the NATM under compressed air, particularly in the tertiary strata with enclosed water filled sand lenses of Munich.

The NATM can not only follow easily varying tunnel profiles but with additional support procedures also remains operational under unfavourable geological conditions. The investment required for the necessary equipment is small. This has hastened the rapide success of this method.
However the disadvantages are the poor working conditions. Dust is formed when applying the shotcrete. And the techniques employed to compensate for unfavourable ground conditions either affect the environment or have detrimental influence on the working conditions, such as the use of compressed air.
Deformations of the temporarily unsupported exposed tunnel wall leads to loosening and ravelling and consequently to settlements at the surface of the ground. Their extent is dependant upon the ground characteristics. The area of the face which is temporarily or permanently unsupported is also determined by the soil properties. In Frankfurt clay for example an unsupported circular face was stable at 7 m but not anymore at 8 m diameter.
In comparison with it, in the crategeous P2 sand in Washington, we had to expose an unstable face of 30 m2 in 12 incremental steps.

3.2 Mechanical Drives

The increased public interest in environmental protection and the demands for improved working conditions promotes the application of mechanical tunnelling methods. Electronic elements are increasingly being used to guide and operate tunnelling machines. TBMs can therefore perform considerably more tasks reliably, if the operating key personnel is familiarized with the advanced technology.Tunnelling methods are now feasible which in the days of mechanical control and steering devices, belonged to the realm of fantasy. Tunnels can now be driven under very difficult ground conditions.
By difficult ground, we mean geological conditions in which , during the tunnel drive, the face is only partly or not stable, where the tunnel lies in ground water, the ground conditions often change and the strength of the excavated material is very variable.

Shield drive in difficult ground



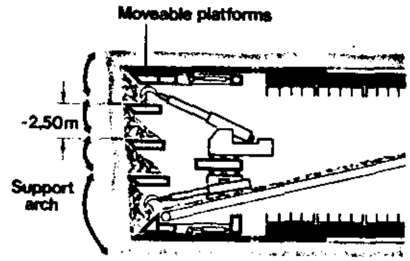
When tunnelling with a machine in soft ground, the face must be reliably supported during excavation and the surrounding ground, behind the shield tail, must be held in balance by grouting during the erection of the lining.
An account will now be given of the achievement of these two objectives with current technical systems

3.21 Face Support

Open Face

If the shear strength of the ground is sufficient to provide a stable face during excavation, then a shield or TBM can be driven with an open face. However, it must be noted that the span width of the ground arch over the face and thus the shield diameter are far more important parameters for the deformation of the face and its stability.
A Memco shield with an open face and a diameter of 12.2 m was used in 1973 to construct the Seelisberg tunnel, Switzerland, in fissured rock.
However open face shields have also been used in soils with low shear strengths and even in sand or gravel. Here the face is supported by the ground itself, ramped back below the natural angle of repose. On shields diameters above 2.5 m the face is divided by platforms so that the ramps do not reach too far back into the shield. Otherwise the thrust required to advance the open shield, in any case very high, would become so large that it could not be sustained by the tunnel lining.

Open platform shield with ramped face



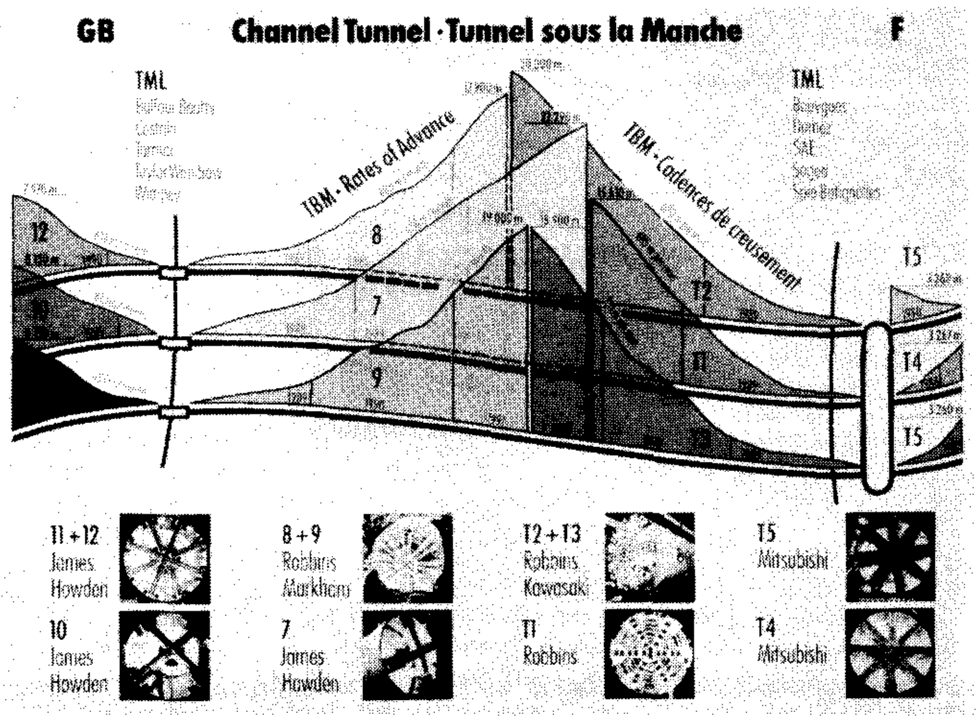
This design concept was developed by Brunel, who drove with a platform shield the first Thames tunnel in 1826-1841. In 1979-1980 the Suez Canal tunnel was also driven with a platform shield, diameter 11.8 m.

Even with extrem care it is hardly possible to avoid excavating more than is theoretical necessary in unstable ground. In addition, the ramp which supports the face cannot prevent deformation and relaxation of the face. This results in settlements at the surface and loosening of the soil around the tunnel. This has led to settlements of more than 20 cm during a drive with a 11.5 m shield passing the banks of the river Elbe in Hamburg in 1972.

When the face is stable, as in the case of the grey Chalk Marl at Channel tunnel, a TBM can be used with an open cutting wheel. Given appropriate geological conditions, the best advance rates can be achieved with such a machine.

The advance rates achieved on the Channel tunnel are an instructive example. They show

- that the favourable ground conditions and a TBM developed for these conditions permit a very high performance
- that, however, a learning period of about a year is required before the optimum performance is reached and
- that the advance rate does not depend on the length of the transport track, provided that an adequate transport organisation has been installed.

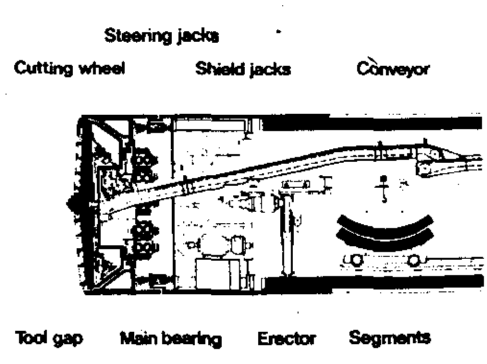


Mechanical Support

When the face is not stable, it can also be mechanical supported during excavation. But this is only possible when the ground water can be kept away from erodible soil.

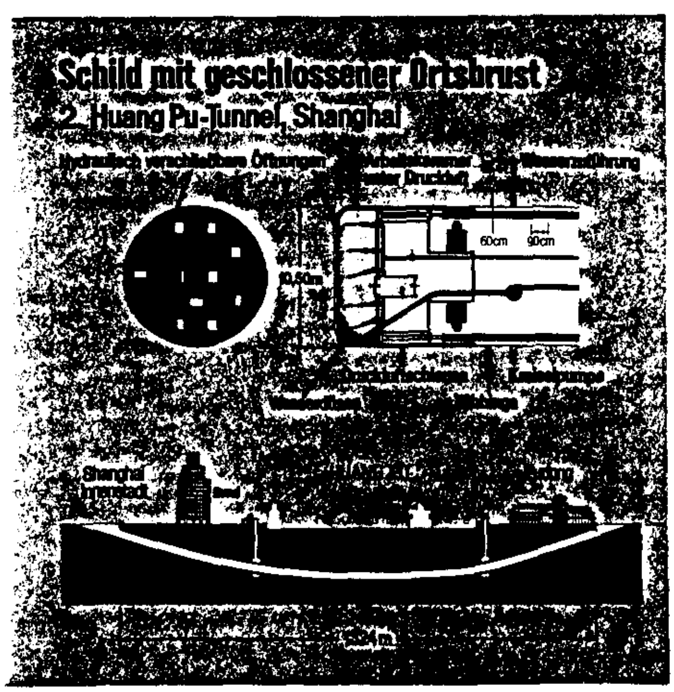
This method was first successfully used in Hamburg in 1965. An elastically supported swinging disc cutter head supported the face during the excavation. The tunnel was driven under compressed air to hold back the ground water. But larger stones which do not pass through the slots in the swinging cutter head had presented insurmountable obstacles.

Tbm with mechanical support



The actual Lovat machines are undoubtedly a further development, particularly in cohesive ground. With closeable flaps the flow of material from the tool gap into the drum like cutting head is controlled. The face is supported by the excavated material maintained in the tool gap. This operates exellently if there is no ground water and the soil is slightly cohesive.

Another application of mechanical support is reported from China. In 1965 a road tunnel of 10 m diameter had to be driven under the Huang Po river in Shanghai. The very soft clay was displaced with a completely closed shield. No ground was excavated. The shield was thrust through the clay with about 10 000 t. The shield was difficult to steer and the river bed rose about 3.5 m. But the tunnel can be driven through to day and the ships can pass after dredging.
Thus for the second tunnel in Shanghai, 1985-88, an 11.3 m diameter blind shield was used with several hydraulically operated apertures in the flat fixed face. The soil flowed into the shield through these variable apertures. When the shear strength was too high the soil was removed with high pressure water jets. The front of the shield was separated from the rest by a bulkhead, and so formed a chamber which could be placed under compressed air. The soil /water slurry was removed from the tunnel by centrifugal pumps. But the settlements of the tunnel summed up to 30 cm.



Compressed Air
Compressed air face support during excavation is suitable because excavation is not delayed and the groundwater is kept away. The disadvantage is that the crew must work under compressed air if the compressed air has not been restricted to the working chamber. This method is also restricted to particular soils.
The face is supported by compressed air because the flow pressure in the ground pores at the surface of the face is greater than at depth. This means that the more impermeable a face is in relation to the deeper zone, the easier it is to support. If this precondition is not met, problems can arise through an unstable face or blow outs.

In order to permit the crew to work under atmospheric conditions compressed air could be limited to the working chamber at the front of the shield. However, there is then the danger that compressed air flows around the shield cutting edge into the the steerage gap, which exists around the shield body due to an overcut at the cutting edge.
As most of the the shield tail seals are not airtight, the air can flow through this seal into the atmospheric part of the tunnel. The relatively small volume of the working chamber is not a sufficient reservoir to compensate for the outflow of air without large pressure drops, which would then endanger face stability.

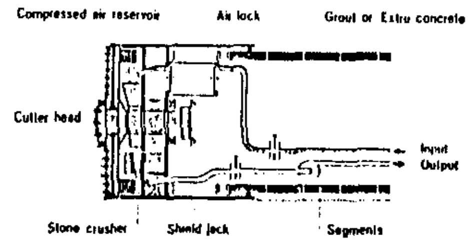
So far, shields with only the working chamber under compressed air have been used only for pipe jacking, for it is only on pipe jacking drives that simple effective shield tail seals can be employed.

Fluid Support

The ideal method of tunnelling in loose ground is to drive the tunnel without altering the primary stress state of the ground and of preventing any overexcavation. An efficient way of approximating this is to support the face with a fluid.

Slurry Shields
In slurry-shields the fluid support medium serves simultaneously as the transport medium for the excavated material. The solid content is about 10 % of the transported volume.
The slurry consists of water mixed with an additive which filters out at the face and forms an impermeable membrane. Over this membrane the support forces from the pressurized fluid are transferred to the face.
In Europe bentonite is usually used as an additive, at about 30-50 kg/m3 suspension in gravel conditions. In Japan natural clay is usually added.

Slurry shield



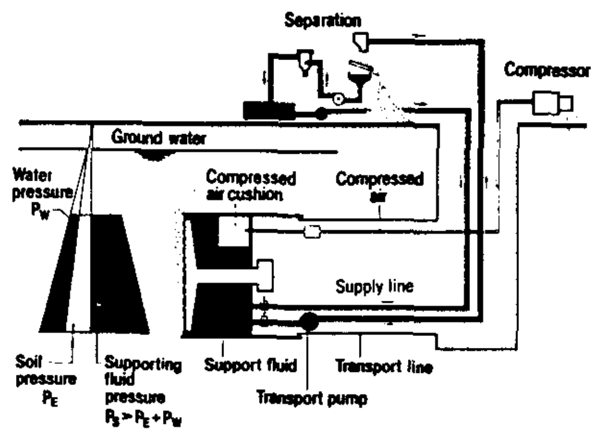
To support the face effectively, the support pressure must be held constant. The dynamic effect of variations in the support pressure causes the face to collaps unavoidably.However, because the support medium is also used for spoil transport this precondition is difficult to achieve. Up to 1 000 m3 of fluid, for example, must be removed each hour from the working chamber of a 6.5 m diameter TBM, and have to be replaced simultaniously with cleaned suspension by an equal volume if no pressure differential is to occur.

Volume flow is monitored by flow meters and controlled by pumps and valves, However, pumps and valves are sluggish control elements, and cannot compensate for momentary volume differentials, which in a fluid lead to immediate pressure changes. An elastic spring element is required to absorb the pressure changes from volume imbalance due to the input and extraction of support fluid.

Containers filled with gas can serve most effectively as the spring element when they form part of the working chamber or are integrated close to it in the fluid circuit. Volume changes in the gas result in relatively small pressure changes.

The German Hydroshield has proved itself to be a reliable design. The working chamber is divided by an immersed wall and in the upper section to the rear of this wall an air cushion, whose pressure is regulated, compensates for volume changes in the flow of fluid. Pressure variation in the support fluid can thus be generally held to +- 0.05 bar.

Hydro - shield

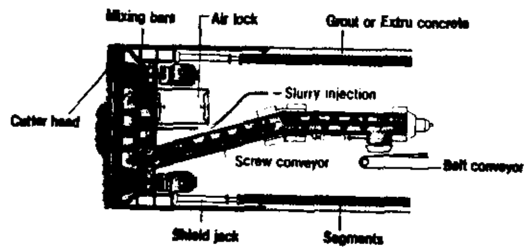


Other designs control the pressure without an elastic spring element and employ only pumps, valves and computers. Limited pressure variation is absorved by the momentum of the pressurized fluid flowing in the circuit. With such a design pressure variation is more extensive than with a Hydroshield.
But with both designs, tunnels with large diameters have been performed; by a Hydroshield the Grauholz tunnel in Swizerland with almost 12 m of diameter and by a shield with monitoring devices the Tokyo Bay crossing with almost 14 m of diameter.

Earth Pressure Balanced Shields
TBM's with earth pressure support have been developed in Japan to simplify or avoid separation of the excavated material from the transport fluid.
In these TBMs the face is supported by a pressure-regulated earth slurry, which consists of excavated material and inflowing water.
The earth slurry have to have the properties of a viscosious fluid to achieve the pressure transfer. High shear resistance of the soil or dry consistency are the obstacles which have to be removed for an successful operation.
In cohesive soil fluidity is improved by injection of a high density slurry of water and bentonite or natural clay.
As in no-cohesive soil an additional agent have to be mixt to the excavated material. At several sites a foam has been applied which consist of polymere and water, blown up by compressed air.

In general polymere as an additive to improve fluidity will be an element to expand the application of EPB-shields under adverse soil conditions in the future.
The earth slurry is mixed in the working chamber, if it has not already been scraped off as an homogenious material. Mixing paddles are mounted on the back of the cutting wheel and on the fixed pressure bulkhead. Mixing tools which operate independently of the cutting wheel are also mounted in the working chamber.

Earth pressure balanced shield



The pressure of the earth slurry on the face is controlled by regulating the speed of the shield advance, dependent on the rate of the screw conveyor which removes the slurry from the working chamber. Sensors on the bulkhead and on the cutting wheel monitor the support pressure.
Additional agents improving the fluidity of excavated material should be pumped into the tool gap in front of the cutting wheel to avoid imperfections in the pressure transfer to the face due to high viscosity of the support medium. In the working chamber the pressure drop between the rear pressure bulkhead and the cutting wheel was measured on some occasions with 1 bar.
In practice the method of support pressure control, which is not as simple as on slurry shields, leads to greater relaxation of the face than with slurry shields. However, experienced crews can compensate for this disadvantage by sensitive operation.

Sealing the working chamber
The pressure on the face can only be kept constant if the extraction points for material from the working chamber are equipped with reliable and controllable

sealing units. In EPB-shields the material reconstituted in the working chamber is generally removed from there by screw conveyors.
In Japan, two conveyors are often mounted one behind the other, using different diameters and different speeds to interrupt in between the transport of material. in the intermediate screwless section, the material should compact and form a bung, a so called sand plug. This seals the pressurized working chamber from the atmospheric area behind the second conveyor.
In the design of the T1 for the Channel tunnel Robbins has adopted another solution. Instead of the second screw conveyor he has installed a double reciprocation pump behind the first screw conveyor and so achieved a reliable sealing system for the working chamber.

3.22 Excavation

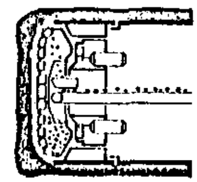
The manner in which the material is excavated, and the associated equipment are very largely responsible for the rate of advance and the economic success. In soft ground we often have a heterogenious geology with, for example, large hard stones which are embedded in a soft ground strata. This ground can then only be excavated with a combination of tools. or the strata tends to stick. This requires a special cutterhead. Also the dumping requirements for the spoil place are increasing demands on the tunnelling method.

Tools

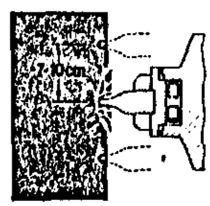
Hard rock

Single disc roll cutters have generally established themselves for breaking hard rock. They are forced against the rock by a load up to 320 kN per disc. Under the linear load pressure the rock is destroyed and following shear failure individual segments or "chips" are broken out. The disc cutters are spaced between 7 and 10 cm apart. The disc cutters can also break up hard stones embedded in soft ground. The secret is merely that they must continue to turn in the soft material so as not to wear out asymmetrically. The fragments of rock fall into the cutter head or, in a shield with fluid support, into the working chamber. They can be too big to be pumped away. A stone crasher must therefore be installed in shields with fluid face support to reduce the fragments to an edge length of about 10-12 cm, which can then be handled by centrifugal pumps.
Stone crashers can not be installed in front of the screw conveyor in EPB-shields. Here the screw conveyor must be designed to cope with larger fragments. Screw conveyors with diameters up to 1,40 m are already being used.

Tbm with disc cutters



Detail
Hard rock
disc cutters



Cohesive soil
Cohesive soil tend to stick with a clay content of more than 25%. According to experience definite plastic clays tend more to stickiness with a water content between the Atterberg limits.This can paralyse the performance of a TBM. Only the choice and positioning of tools to remove material in small pieces and the design of the machine to permit a direct and unimpeded flow can ensure a satisfactory advance rate in sticky cohesive soil. Tests with application of polymere injection result promissing to reduce the adhesion between pieces of clay.
To get small pieces scraper blades are fixed on the sides of the spokes of the cutting wheel which shaves off 2-4 cm layers of ground; while small hoes on the front of the spokes in advance of the scrapers limit the width of the shavings.In mixed ground with embedded stones the disc cutters positioned 2-4 cm in front of the scraper blades act instead of the hoes to limit the shaving width.

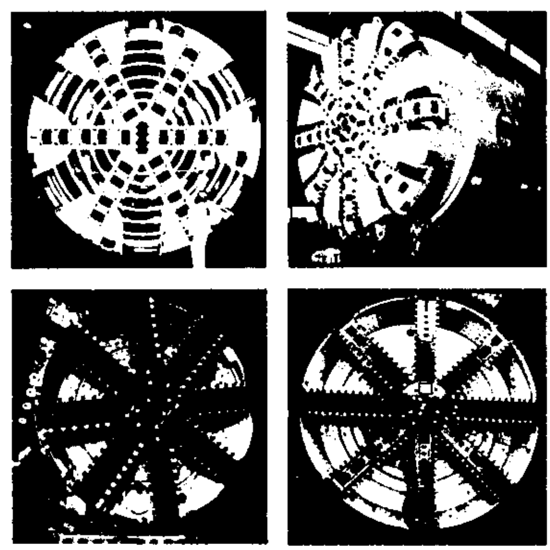
Non cohesive soil
In non cohesive soil simple square bar picks suffice as excavation tools.

Cutter Head

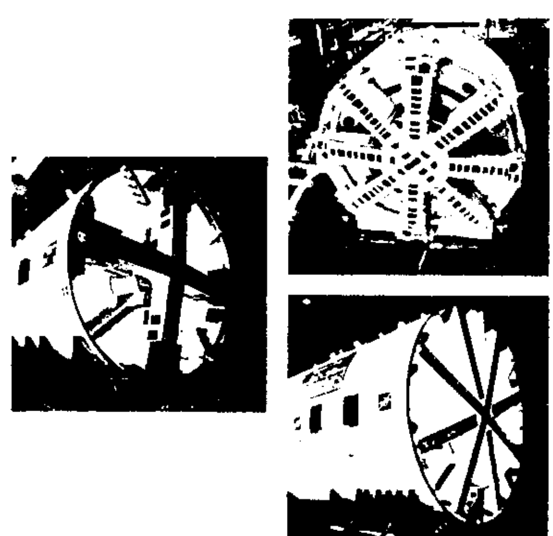
The construction of the cutting head often determines wether a TBM can be used succsessfully. The requirements are varied and depend upon the geology. The considerable forces which are necessary to break up the rock require on the one hand a strong and solid construction, on the other hand it must be possible to remove the broken material simply and quickly. Which requirement be given the higher priority depends upon the design engineers. So it is very interesting to see the different cutting heads on the Channel tunnel machines, all designed for the same ground.

Channel Tunnel TBM

French side



British side



Hard Rock

In hard rock machines there are tub shaped steel constructions, mounted on the open rim with the tools attached to the base of the tub. The rock spoil drops down in the tool gap and is transported through slits in the cutting head to the interior. Here scoops load the spoil via a shoot onto the conveyor. The spoil is only passed through the cutting head via scoop shaped openings on the circumference of the cutterhead. This ensures a rapid spoil extraction without grinding to fines.

Cohesive Soil

Cutter heads for stable cohesive soft ground are preferably open. They can be spoked cutting wheels with a rim, as on the Mitsubishi machines for the Channel tunnel or, as on the James Howden machines, largely open drum like cutter heads with cutting beams.

The cohesive material must be passed as far as possible unimpeded through to the inside of the cutter head to avoid sticking.

Non Cohesive Soil

A tunnel face in non cohesive soil is not stable and is therefore supported with slurry or earth pressure. However to change cutting tools or carry out repairs men have to enter the working chamber generally under compressed air support of the face.

In order to ensure a stabilized face also under adverse geological conditions and to prevent the crew being endangered by falling stones, closeable flaps are installed between the spokes of the cutting wheel. A rim at the circumference of the cutting wheel facilitates the construction.

With varying conditions these units however can increase the effects of stickiness in cohesive ground.

3. 23 Muck Shifting

Dry Transport

If material is excavated and transported dry, then it is the least difficult to dump. This method of transport is favored if feasible. The removal of the material from the pressurized working chamber with face support by compressed air requires special equipment such as the piston discharge pump used by Robbins on the T 1. Rotary cell locks have not proved satisfactory as the pockets tend to clog.

Transportation of dry spoil in skips with diesel, battery or overhead wire locos is an established system. A radio control and communication system for all vehiceles is a precondition on long tunnels to achieve satisfactory advance rates.

Recently extendable conveyor belts have been used to remove dry spoil. They are especially economic on large cross sections and long tunnels.

Spoil Transport with Piston Pumps

Spoil is often sent to the surface from EPB shields with piston pumps. The material must be incompressible to be pumped without forming "stoppers". Either the spoil is intrinsically suitable, for example as a homogenious soft clay or, as it is generally the case, it has to be enhanced by additives and homogenizised. Then one can pump a material which consists of 70% solids by volume over long distances. Water lubrication, injected into the pipeline, reduce the friction.

Spoil Transport with Centrifugal Pumps

The excavated material is moved by centrifugal pumps through a pipeline to a separation plant where the spoil is separated from the transported suspension. The cleaned fluid is returned to the TBM working chamber. The solid content during pumping is about 10% and the flow speed about 3 m/s.

On a 6.5 m diameter TBM the diameter of the transport line is 250-300 mm and approx. 800-1000 m3/h of loaded slurry will be transported. The edge length of the transported solids is limited to less than 12 cm for a 300 mm pipeline. For long distance pumping intermediate pumps are required every 600-700 m.

3.24 Separation

Separation of the excavated material from the support and transport medium for liquid transportation is influenced by the geology and in particular the grain size distribution curve of the spoil. If the amount of material of less than 0.06 mm is below 25%, the solids are separated by passing coarse grained material of less than 0.35 mm over a coarse vibrating screen

Finer material of grain size 0.06-0.35 mm is separated by the first stage of a hydrocyclone, and then passed over a dewatering sieve with a mesh size of 0.3-0.6 mm. Even finer material down to a grain size greater than 0.03 mm is removed by a hydrocyclone stage and passed over a high frequency dewatering sieve with a mesh of 0.1 x 0.7 mm.

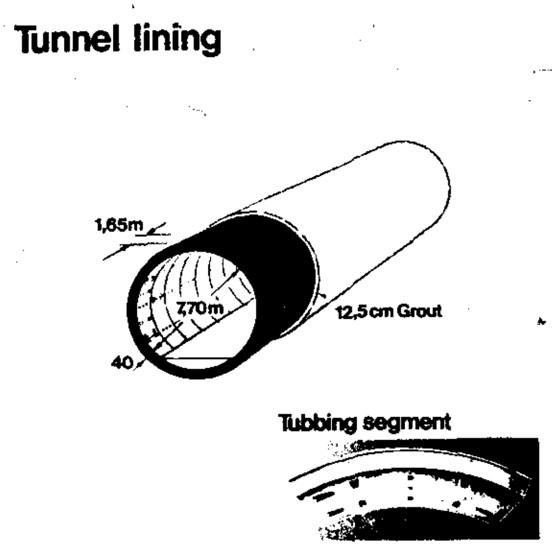
When the amount of material less than 0.06 mm grain size is above 25%, additional centrifuges or filter presses must be used.

With filter presses, the fluid that is to separated is continually fed between two filter belts. The belts and the material which lies between them is passed between several rollers whose radius determines the filter pressure. Solids and fluid are continually separated. The grain size of solids separated is less than 0.01 mm.

Depending on the grain size distribution curve and local conditions, separation can also take place in simple settling ponds. Chemical additives accelerate the process of separation.

3.25 Lining

The stress state of the ground is influenced not only by the method of excavation but also by the way the tunnel lining is built. This stress state act upon the lining and determines the load distribution, size and nature of the loading and thus the cost of maintenance and life span of a tunnel. One must therefore attempt to optimize the bedding of the tunnel, either by stressing the lining directly against the exposed ground with a minimum disturbance or by grouting the gap between the soil and the lining.



Segments
Precast units, segments of cast steel, concrete or reinforced concrete are mounted with erectors to form a lining behind the shield. To attain higher performance rates, sometimes two erectors are used to build a ring. The ring erection time is decisive for the rate of advance. It is not so dependent on the size of tunnel cross section as on the reliability of mechanical equipment. Construction time can be reduced to 15 min but is generally 30 min.
Segments can be installed behind the shield and then expanded against the exposed ground or erected under the cover of the shield tail. The gap between the ground and the back of the segments must then be grouted.

Expanded Segments
In order to be able to construct the lining behind the shield, the exposed ground must be stable for a limited period. There must not be a high water make. In addition , stratified material, which leads to relaxation and local ravelling, hinders lining erection behind the shield. In general the ground should be plastifiable to guarantee a sufficient bedding as is London clay where expanded segments were invented.
High rates of advance can be achieved on a TBM where segments are installed behind the shield and the thrust forces are transferred not to the lining but to a special gripper system. The excavation procedure can then continue without being interrupted by the ring erection. However, the surface of the ground may be destroyed by the forces of the gripper system to fix the TBM in the ground.
The segments which are erected behind the shield form a hinged chain and are expanded against the ground by forcing in a wedge shaped keystone. The segments are not bolted but at the most dowelled without sealing gaskets.
The jointed ring can also be expanded by hydraulic jacks between two segments of a ring. The resulting gap is then concreted.
Expanded segments are not suitable as a single lining system in water bearing ground.

Bolted Segments
Particularly in loose water bearing ground, the lining is erected within the protection of the shield tail. As the shield is advanced, the resulting gap between the segments and the ground must be simultaneously pressure grouted if ravelling of the surrounding ground is to be avoided. The front of the gap on the shield tail is sealed by a sealing construction.
The segments are very accurately cast with small tolerances and have peripherical gaskets. They are bolted together to form the ring; adjacent rings are usually dowelled together.
Thrust forces of the TBM which are transfered to the segments compress the ring joints with the gaskets. Later the hardened grout holds them in the compressed position.

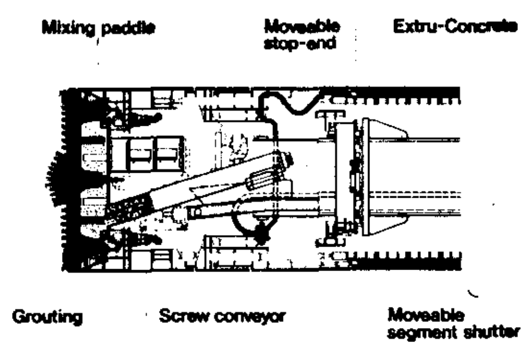
Dowelled Segments
At the Boston Outfall Tunnel and at the Passante Ferroviario in Milano a dowelled segment system with trapezoid shaped segments is in performance with good results. The system works ideally with only two types of segments in a key-stone-like funktion.
This system appears suitable for a automated segment erection procedure.

Extru-Concrete

Apart from the segmental lining, the extrusion method can also produce a tunnel shell within the protection of the shield tail. Concrete is continuously pumped through an elastically supported stop end construction into the ring shaped void formed behind the advancing TBM. This void is bounded on the outside by the surrounding soil, on the inside by replaceable steel shuttering and at the front by the stop end. Control and steering elements ensure a constant pressure in the concrete, so that even in the fluid state it can support the pressure of non -cohesive water bearing ground.

To achieve this, the elastically supported stop end is pushed forward by the pressure of the concrete itself. A special hydraulic linkage ensures a parellel advance of the stop end construction, a gas reservoir combined with the hydraulik system the necessary elasticity and a friction compensation system the correction of jamming or friction of the stop end construction between the shield tail and the shuttering.

Earth pressure shield with Extru-Concrete lining
Lot 32/33, Essen



The Extru Concrete Lining is very economical because normal concrete is used. The reological properties of the concrete merely have to be improved by the addition of a super liquidizer. Instead of steel bar reinforcement, steel fibres are added. Microsilicate improves the bond of the steel fibres in the concrete. But the tunnel lining of extruded concrete is not watertight, and shrinkage cracks in the continuously formed tunnel shell cannot be avoided. Thus a second lining, which can be installed afterwards, is required in water bearing ground.

This system has already proved itself several times, the most impressive of which was in Lyon, underpassing the rivers Rhone and Saone in water bearing

gravel with a distance between shield and river bed of less than 5 m and a shield diameter of 6.50 m.
There it was proven that it was possible to drive a shield in cohesionless ground without relaxing or ravelling the surrounding ground. Settlements of the surface could be completely avoided although the shield had passed under foundations of buildings with distances of 2.50 m.

3.26 Shield Tail Seal

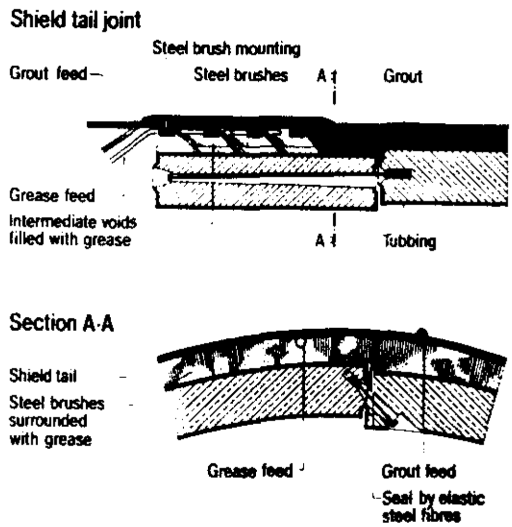
The shield tail seal is a very important design element. It must effectively seal the joint between the shield tail and the back of the segments so that the grout injected behind the segments can balance the surrounding soft ground and ground water.
If the seal fails, grout can flow into the interior of the shield, the pressure in the grout drops down and ground water mixed with soil penetrates immediately the shield tail joint. The ground around the tunnel lining could relax and ravel. The bedding of the lining would be badly affected. Surface settlements are the consequences.
The seal of this shield tail joint is technically difficult, not only because the individual segments can not be positioned accurately enough to avoid steps and ledges of up to 1.5 cm, but because the advance of the shield leaves a void behind the shield tail, which has to be simultaneously filled with an equal volume of grout under a constant pressure to compensate the loads from the surrounding soil and ground water.
These requirements are not always met by current designs. The easiest way to solve this problem is to introduce an elastic spring element which compensates for differences in the volume created by the shield tail and that of the injected grout. To achieve this the shield tail seal construction has to be movable and ellastically supported.

Rubber Seal
Up to now rubber seals, due to their stiffness, were likely unable to close steps between inaccurately placed segments and thus the more inexperienced the crew, the greater the problems they cause.
And at present, a shield tail seal system has not been constructed with rubber seals on a movable and elastically supported basis.

Steel Brush Seal
The steel brush seal developed in Japan, can seal the gaps between inaccurately placed segments. They are arranged in several rows, up to 5, one behind the other. Grease is pumped into the chambers between the individual rows and held at a particular pressure, whereby the pressure in each chamber increased towards the shield tail so that the pressure in the last chamber is about 1 bar higher than that of the grout. The grout is thus prevented from

penetrating through the brushes to the shield interior. The higher grease pressure does mean that grease constantly flow into the grout. On the Channel tunnel it was meassured with 25 kg per running meter tunnel.

Japanese brush seal

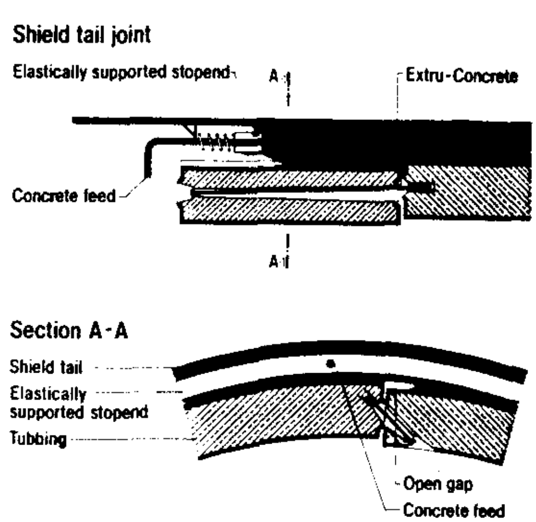


Extru Concrete Seal

A reliable shield tail seal that meets all the requirements, is the seal with Extru Concrete.

A movable , ring shaped steel construction, which closes the shield tail joint, is elastically supported by hydraulic jacks from the body of the shield. The hydraulic jack circuit is linked to a regulated gas reservoir, which provides the elastic spring.

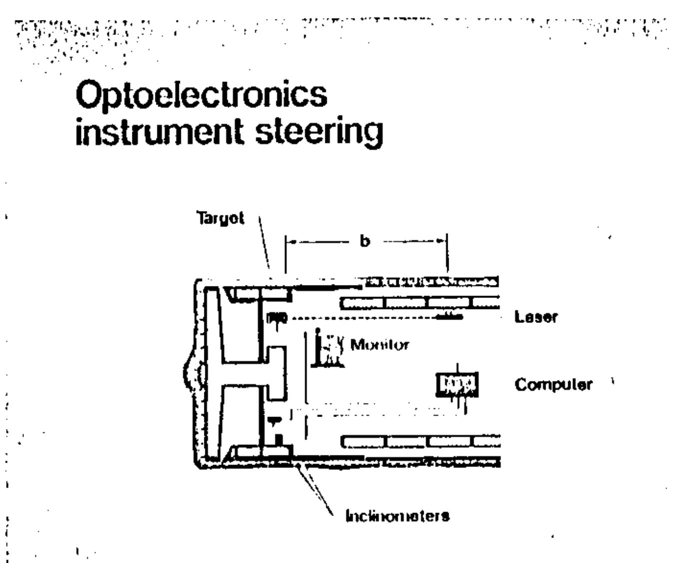
Seal with Extru - Concrete



The steel construction is sealed against the shield tail with a rubber seal and with spring strips against the back of the segments. Extru Concrete is pumped through the movable steel construction into the shield tail joint. With the pressure of the Extru Concrete itself the movable seal construction will be pushed forward.
The gaps between the inaccurately placed segments are sealed by the concrete itself. Initially some of the cement mortar flows out, but a support matrix of coarser material is quickly formed, which even for gap widths of 1.5 cm provides enough support for the finer material. Even at pressures of 8 bar this seal is effective. It has been sucessfully performed on the Passante Ferroviario in Milano.

3.27 Steering

Tunnelling machines today are guided with the aid of electronic equipment, in which a laser beam shines on to a target plate mounted on the tunnelling machine.
The geometrical position and strike angle of the laser beam, as well as the horizontal and vertical deviation of the tunnelling machine axis are the geometrical variables with which the position, inclination and roll of the tunnelling machine are calculated.



These actual values are compared with previously computed design parameters and the deviation from the design position is continuously dislayed on a screen, so that the operator can steer the machine. He can thus immediately recognize what effect his action have on the position of the machine.
This equipment makes it possible to maitain even large tunnelling machines on course with a tolerance of +- 10 cm.
Guidance of TBMs has been developed so far that some are controlled fully automatically with very small deviation from the design alignment.

4. Future Development

Future development of TBMs in soft ground will be accelerated by large projects, such as the Channel tunnel, the tunnel under the Great Belt or the Tokyo Bay crossing.
The increased use of electronics in construction equipment opens up new areas for TBM operations.These machines can reliably perform delicate and constantly changing tasks.Thus the contractor can master even difficult and variable geological boundary conditions.
Today TBMs are already steered automatically. Electronic signals from the survey equipment are not only converted into optical alignment information, but are also directly translated into hydraulic operation commands. As a result, the TBM follows a more even course than with manual guidance. Electronic control systems in future will also enable the face support pressure to be better maintained within tighter limits, possibly by also introducing an elastic spring element.
Certainly, in the not so distant future automatically operated systems will transport and install segments.Also the imperfections to grout the shield tail gap will be remedied.

The development of tunnelling machines has almost reached the point where we can excavate soft ground from the the face without affecting the primary stress state and where we can install an economical and technical high quality tunnel lining with slip formwork in a continuous extrusion process.

But all endeavor in the technical development is wasted, if the operating personnel is not capable to use its advantages. The modern TBM with all the electronic control systems requires an operator with an elevated level of skilfulness steadily trained. Engineers should operate the machines!