Tunnel Boring Machines

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Abstract: Tunneling in hard rock with tunnel boring machines is one of the most mechanized construction processes. Mechanization also applies to the installation of the temporary excavation support and the final lining. Computer-aided process systems have been developed, including: (1) sensor-supported gathering and computer-aided storage of all relevant tunnel operational and survey data; (2) computer-aided visualization and control of the most important boring machine systems; and (3) computer-aided, process-oriented control of all operational processes. Presented here are recent tunneling developments related to gripper and shielded boring machines. In the case of gripper boring machines, particular focus is directed to innovations such as the installation of ground stabilization directly behind the cutter head and adequate logistics to the excavation by engineered ''back-up'' systems. The back-up system requirements necessary to maintain the high performance of shielded boring machines are enumerated.

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Introduction

The use of tunnel boring machines (TBMs) is governed by economic considerations pertaining to multiple variants of costs and schedule deadlines. A minimum project tunnel length as well as the possibility of recovering the capital investment by using the TBM in subsequent tunnel projects are essential for an economic application of these machines. It is not possible to cite a fixed minimum tunnel length, as this depends on a myriad of conditions that are site specific to the project. Tunnels that are several hundred meters in length are excavated by conventional means—drill and blast. TBM applications become practical starting with a length of approximately 2 km, but this depends on the machine diameter.

The demand for increased economy in driving tunnels has led to considerations that foresee applying TBM excavation in increasingly difficult ground. However, TBM systems provide only limited flexibility as far as their ability to cope with variable ground conditions. As a consequence, the following technical problems must be evaluated and carefully resolved for each project:

- Difficulty of the ground,
- Ground gripping capacity of the TBM, and
- Stability and deformability of the ground.

Along the tunnel route these conditions must be carefully investigated to minimize both technical and economic risks. The machine, including its back-up system, must be geared to surmounting the entire range of ground conditions that will be encountered along the tunnel profile.

A TBM excavates a full-face circular cross section. The machine's mechanical excavation process minimizes disturbance of the rock and accurately follows the plan tunnel profile. Presently, tunnel boring machines are constructed with diameters varying from approximately 2.5 to 12 m. There are a few larger diameter machines. In Japan they used a 14.14 m machine to drive the Tokyo Aque-line Tunnel, and they are using a 13 m machine on part of the Tokyo Metropolitan Expressway. There are multiple types of TBM systems, as follows:

- Gripper,
- Enlargement,
- Shielded, and
- Telescopic/double cylinder/gripping jacket.

The gripper TBM (Fig. 1) and the enlargement TBM belong to the category of open full-face gripping machines. These machines are suitable for all ground classes that possess the minimum ''stand-up'' time necessary to install the ground support behind the cutter head. The placing of shotcrete should be carried out in the back-up area in order to avoid causing undue wear and tear to the machine's movable hydraulic equipment. In the case of ground conditions that are prone to collapse, the gripper TBM can be buried behind the cutter head. Usually, when this happens, the ground has to be consolidated by additional grouting and the ''buried'' machine can only be freed by manual excavation. Most significant in a buried TBM situation is the loss of construction progress for several months.

The shielded cylinder can also become stuck when swelling ground is encountered. The possibility of swelling ground requires that an extremely careful site investigation be conducted so that the correct excavation concept can be developed. Where slow deformation processes are the concern, the problem can be resolved by overcutting tools, which create a larger excavation than the shield diameter (the dust shield in the case of a gripper TBM or the shield jacket of a shielded TBM). However, given such ground conditions, it is in many cases preferable to use conventional drive drill and blast excavation techniques.

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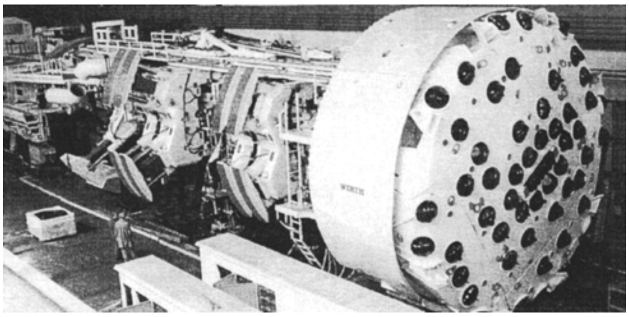

Fig. 1. Gripper tunnel boring machine in factory (courtesy of Wirth GmbH)

The enlargement TBM system provides an additional technical alternative. This system consists of the following two separate machines:

- A pilot tunnel gripper TBM and
- An enlargement TBM.

The two machines are used in sequenced excavation steps. First, a pilot heading is driven along the entire length of the tunnel by the pilot gripper TBM (Machine 1). Afterward, the enlargement TBM (Machine 2) is used. The enlargement machine is equipped with an advance gripper system that stabilizes itself on gripper plates in the previously created pilot heading. The back-up system is attached to the enlargement TBM, as in the case of other TBMs.

Geotechnical Factors Affecting Selection of Different Tunnel Boring Machines

Tunnel boring machines are suitable for cutting hard rock of average to high strength (50–300 N/mm^2). However, the rock should not be too highly abrasive. Abrasiveness relates to the wear sustained by the cutting tools. Minerals, which possess a high degree of hardness (quartz, for instance), are highly abrasive.

Gripper/Enlargement Tunnel Boring Machines

Gripper TBMs work best driving headings and tunnels in ground that is stable and fault free. As a rough guide, it can be stated that approximately 80–90% of the total length of the tunnel must be stable; e.g., temporary ground support for the machine area is required only to a limited degree. The rock compressive strength should lie between 100 and 300 MN/m^2. Strengths in excess of 350 MN/m^2, high rock toughness or tensile strength, and a high proportion of minerals with an abrasive effect (CAI index = abrasiveness according to Cerchar) represent the economic limits for these machines. To assess whether an application is feasible, the rock-splitting strength and the rock quality designation (RQD) index are used as indicators. The rock-splitting strength should amount to $25 \pm 5\ MN/m^2$. The RQD index expresses the ground's degree of separation. The RQD index is described as the ratio $L10/L$ in percent, with $L10$ relating to all of the bore core samples in excess of 10 cm in the bore probe length L

$$\mathrm{RQD} = \frac{\Sigma_n L10_i}{L} \times 100$$

where $L10i$ = length of i-10 bore sample in excess of 10 cm; N = number of bore samples in excess of 10 cm; and L = length of bore section.

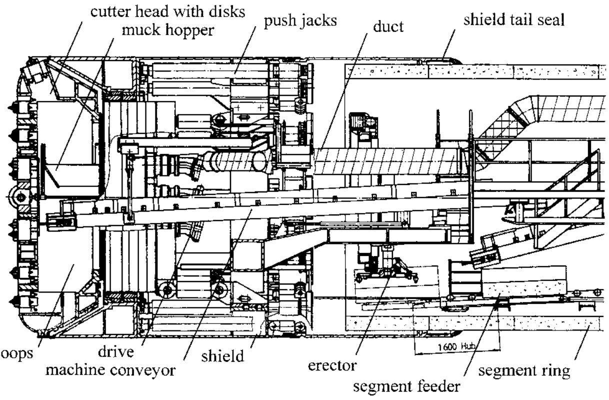

Fig. 2. Shielded tunnel boring machine schematic (courtesy of Herrenknecht AG)

Given an RQD index of 50–100%, a fissure gap of >60 cm and the further criteria mentioned previously, the application of a gripper TBM appears justified at first appraisal. The stability of the ground can become a problem in the event of a higher degree of disaggregation (lower RQD values). Separately, ground having low compressive strengths, less than 100 MN/m^2, can limit the holding capacity of the grippers and can, in turn, reduce the machine's maximum axial thrusting force.

Shielded Tunnel Boring Machine

The rock strength limits are roughly the same as in the case of gripper TBMs. However, the bonding strength is considerably reduced as far as such rocks are concerned. This becomes evident through the fissure gap of 55–65 cm and an RQD index of 50 ± 10%. Even given a relatively low uniaxial rock compressive strength of $50 \pm 5\ MN/m^2$ and a low rock-splitting strength of $5 \pm 0.5\ MN/m^2$, a shielded TBM can be utilized. In the case of ground classes that tend to collapse, shielded TBMs (Fig. 2) represent a suitable operational solution. The shielded TBM or telescopic TBM with segments installed in the shielded cylinder is bound to gain in application, particularly with regard to major diameters.

Gripper Tunnel Boring Machine

A typical modern gripper TBM setup is shown in Fig. 3. The machine's operations are divided into the two major functions of (1) excavation/driving and supporting; and (2) haulage and installation assembly.

The cutter head is the machine's primary functional component. It is rotated by either hydraulic or electric motors, which are usually arranged in a circular pattern around the center free main bearing on the shaft of the machine. The cutter head is separated from the driven cross section by a steel cutter head jacket with dust shroud. The cutter head jacket protects the cutter head from intruding material during the excavation process. This jacket sometimes extends to the rear as a roof shield. The extended roof shield is actually a set of gapped steel strips. It is not a complete cylinder structure. The gapping of the shield strips allows drilling of ground support measures to take place in a protected area. The dust shroud protects the TBM's rear working area against dust and fragmented rock material. The muck (excavated rock) is transferred to the center of the TBM via bucket scooping devices

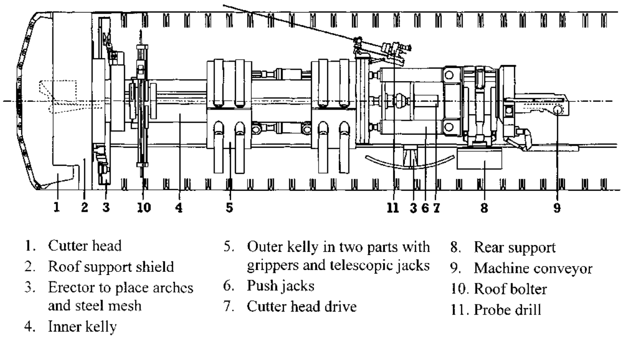

Fig. 3. Gripper tunnel boring machine schematic (courtesy of Wirth GmbH)

on the cutter head and via muck guide plates on the interior (rear) side of the cutter head. At the center it falls into a muck hopper, which passes the fragmented material to a transfer conveyor. Usually, the conveyor is located on the machine's central axis. In the case of hydraulic cutter head driving motors, the electric motors for powering the hydraulic pumps are positioned on the back-up system.

The immediate installation of the initial ground support occurs behind the face of the TBM's dust shield. The shield has drilling equipment probe openings for investigating the ground ahead of the TBM. The installation of initial ground support measures includes

- Setting of steel ground support arches in the excavated tunnel section directly behind the cutter head jacket,
- Steel mesh and/or roof bolts in the roof area as overhead protection, and
- Rock bolting from within the roof shield protection.

Apart from these mechanical and hydraulic securing aids, material-handling equipment is required for transporting the steel arches and rock bolts from their intermediate storage location on the rear section of the TBM to the point of installation. The rock bolting equipment is mounted on a circular cradle. This allows for radial maneuverable installation of bolts at any point on the tunnel circumference. Additionally, a maneuverable drilling arm is available for drilling probe holes and grouting ahead of the excavation face. This is fixed to the outer kelly. This drill can be positioned radially via a revolving cradle for drilling at any desired position on the periphery. In extremely fissured and friable ground, advance injection (grouting) umbrellas can be created using these drilling and grouting units in order to prevent any postexcavation collapses behind the TBM. These installations are usually only suitable for securing minor disturbance sections, as the related special measures that are necessary are extremely time-consuming.

The systematic installation of the ground support system is undertaken roughly 15 m behind the machine, on the TBM's back-up support platform. Conventional support methods (steel arches, shotcrete, roof bolts) are used, but the work is accomplished by mechanized means. Should extensive fault zone areas, in which cave-ins are anticipated, have to be penetrated, then a shielded TBM and immediate use of segmental linings for ground support are appropriate.

Base invert segments, should they be used, are temporarily stored by means of a hydraulically driven transport and hoisting unit on the backup's support platform. Base invert segments are put in place at a rate to match that of the TBM's forward advance. During the installation process a hydraulic hoisting and transport device transfers the base invert segments to the segment erector, which is located on the underside of the outer kelly. The transfer of the segments takes place beneath the rear section of the outer kelly. The erector is fitted with a centering pin and vacuum suction plates to pick, position, and lay the base invert segments. The invert segments serve as a track upon which the back-up platform advances.

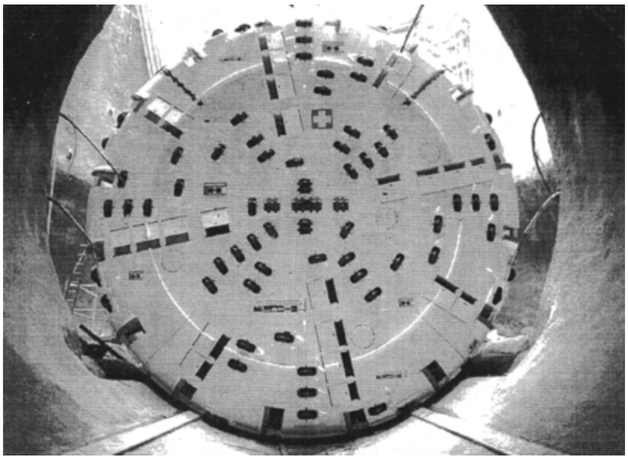

Fig. 4. Tunnel boring machine cutter head with muck bucket scraper slots (courtesy of Herrenknecht AG)

The excavation process at the tunnel face results in the creation of small-size rock fragments (chips) and a corresponding amount of dust. Consequently, there is the necessity for equipment that both controls dust development and removes dust before it becomes mixed with the air that is breathed by the tunneling workforce. The following alternatives are available for coping with the dust:

- The installation of a dust shield behind the cutter head and dust exhaust at the cutter head with a dust particle collection and removal fan located on the back-up platform and
- Spraying of the excavation face (close to the cutter head) with a mist of water. Care must be exercised when applying this option, as some rock is sensitive to water.

A dust removal ventilation duct (Fig. 2) passes from immediately behind the cutter head to dust collection/removal equipment found on the TBM back-up train.

Cutter Head

To excavate solid rock, closed rock cutter heads that are fitted with rotating disks or roller cutters, and scraper slots are usually employed (Fig. 4). The cutter head acts structurally as a holder for the cutting tools. The cutter head is fabricated having a slight conical shape. To make certain that the cutter head is sufficiently stiff without employing excessive material thickness, the cutter head usually comprises a conic butt-form element, which is strengthened at its interior by means of radial stiffener plates. Excessive material thickness can result in large internal stresses and, in turn, crack formation. The stiffener plates form conical chambers in the cutter head, into which the loosened material falls via the exterior scraper slots that are arranged in a radial pattern on the cutter head. The stiffener plates direct the material into the middle of the center-free supported cutter head. There, the muck is fed into the machine's muck conveyor collection hopper. The scraper slots (Fig. 4) of the scraper units should be located in a central position as far as possible. In this way, the loosened material is prevented from sliding past all of the disks over the entire face. If the scraper slots are only set at the edges, the cutting rate drops, as the loosened material trickles over the cutting tracks of the disks; as a result, it hampers disk penetration by forming a cushion (barrier) of loose material between the excavation face and the cutter disks.

The disks or roller cutter holding blocks are installed in the cutter head front plate. The disks or cutting rollers are borne by bearing holders, which are attached to the rear side of the cutter head. The holding blocks should be devised in such a way that the disks or rollers can be replaced from either the front or the rear of the cutter head. Safety is enhanced with rear access for replacement operations. The free gap between the face and the cutter head is reduced to a minimum through the installation of the holders on the rear side of the cutter head plate. In this way, the holders are subjected to less strain. The danger that falling blocks of rock might block the cutter head or that the holders might be torn off is largely eliminated with this design. Technical aspects govern the cutter head bearing design.

Usually, the following types of bearings and drives are used in TBMs:

- Central shaft bearing,
- Circumferential bearing, and
- Center-free compact bearing.

The center-free compact bearing is normally used for larger (>5 m) gripper TBMs. This has the advantage that the mucking (removal of cuttings) conveyor can be installed in the center of the cutter head, and the excavated material moved through it. Furthermore, lines and hoses for the TBM's systems are guided through at this point via rotary transmission. Man access into the cutter head interior is also located here.

Personnel access is usually gained through a hatch on the underside of the inner kelly; this requires that the machine's conveyor system be retracted. Man access holes on the dust shroud serve as access to the cutter head interior. Additional man access holes to reach the face are located in the front plate of the cutter head. Removal of a disk or roller cutter holder can also provide access to the excavation face. Furthermore, there is sufficient space, thanks to the center-free main bearing, to arrange either the multiple-hydraulic or electric (E)-frequency conversion motors around the periphery so that the necessary total working torque can be exerted on the cutter head. Unlike the hydraulic motors, the E-motors are not usually attached directly to the main bearing, but are set up at the rear end of the inner kelly. The rotation (driving moment) is transferred to the main cutter head bearing via a kelly bar. The kelly bar/driving rod's torsional stiffness provides the motor with a certain degree of elasticity with regard to sudden increases in cutter head resistance.

To ensure smooth operation and optimal adjustment to varying ground characteristics, it is essential that the cutter head be started gently and operated vibration free. As a consequence, most TBMs are fitted with infinitely variable hydraulic or variable-frequency controlled electric motors. The drive train should be capable of being switched to bypass operation by manual means and arranged with the ability to provide a temporary breaking torque equivalent to 1.5–2 times the nominal torque. The drive control must be constructed in such a way that the machine parts are not overloaded. It is important for maintenance purposes that the drive is capable of clockwise and counterclockwise rotation. The cutter head should be secured by means of a locking safety brake. The following alternatives exist for driving the cutter head rotation:

- Electric drive with friction coupling, usually two different speeds,
- Electric drive—frequency controlled, variable speed,
- Hydraulic drive, variable speed, and
- Electric drive with auxiliary hydraulic drives for a high starting torque.

The electric drive is normally fitted with two speed stages. As a result, the motors are not particularly flexible. The starting torque required to start the cutter head is approximately 1.5 times as high as the operating or driving torque. This breakaway torque is limited in terms of time. It is attained by starting all of the motors and then activating the clutch. The jammed cutter head breaks away and starts rotating or the slip clutch relieves the motor. The E-motor's efficiency amounts to roughly 95%. Electric motors with frequency-controlled converters operate in a variable fashion. They are capable of attaining a temporary starting torque equivalent to about 1.7 times the driving torque. A heat switch regulates the starting torque in order to prevent damage to the motor and to restrict strain on the cutter head tool holders. To effect breakaway, the frequency-controlled motors are revved to full power from a standstill. The efficiency amounts to around 90%.

Hydraulic motors are frequently used because of their simplicity and robustness. Extremely high starting torque can be attained by means of hydraulic motors, which are rated between two and 2.5 times in excess of the driving torque given nominal cutter head speed. In the case of lower speeds, the driving torque can be increased to 1.5–1.8 times the torque at the nominal cutter head speed. However, the efficiency only amounts to 75%. In the case of the customary electric drive with two speed stages, the breakaway torque can be increased to 1.8–2.2 times the driving torque, thanks to a small hydraulic auxiliary motor with very low speed.

The advantage of electric motors is that they have a high-energy development rate. Given the extremely high-energy consumption of TBMs, the cost of power can be significant over the period of use. Today, the price of new electric motors is not that much higher than that of hydraulic ones. However, qualified staff is needed to maintain electric motors. Frequency-controlled electric motors are particularly demanding. Hydraulic motors, on the other hand, are very robust and easy to maintain. Additionally, an extremely high starting torque can be achieved with hydraulic motors. When it comes to the maintenance of hydraulic motors, only hoses or seals have to be replaced under normal circumstances—something that can be performed by a shift mechanic. A relatively high amount of heat is created in the tunnel in the vicinity of the pumps and motors as a result of their low efficiency, and supplemental cooling may be required. A variable speed is advantageous for a TBM with an extremely large cutter head diameter for the following reasons:

- Best possible adjustment to different rock and ground conditions along the tunnel profile through a variable speed [revolutions per minute (rpm)] cutter head and
- Capability to control the starting torque and machine vibrations.

These attributes can be attained by both frequency-controlled electric and hydraulic motor drives. The electric drive with auxiliary hydraulic drive is used if stable ground containing a number of fault zones has to be excavated. This allows a high starting torque should problems develop. In addition, the advancing speed and the contact pressure of the cutter head can be infinitely adjustable so that the most efficient penetration rate can be accomplished, given the ground conditions prevailing at the excavation face and in conjunction with the optimal working drive torque.

The most efficient penetration rate is interpreted as the most economic boring rate. During excavation, the cutter head rotates evenly.

Normally, the cutter head consists of a standard rectangular or square core, around which custom-fabricated outer segments are attached so that the TBMs can be custom-built for a range of project-specific diameters. When a TBM is built to a specific diameter, appropriate outer cutter head segments are added, and only the shield jacket and the dust shield are custom-built. The rotation, stabilizing, and thrusting components must be designed to the specific (maximum possible) diameter.

Normally, the main bearing of the TBM constitutes a high-performance axial-radial roller bearing designed to sustain the high cutter head load. A multiple lip seal with confining grease protects the oil chamber on the front inner and outer side of the bearing. The oil is removed separately from each of these chambers and carried to pressure filters, which are equipped with solenoids. The oil is cooled by heat exchangers. The cleaned and thermally controlled oil is then recycled under pressure to the periphery of the main bearing (controlled oil supply). An interlocking control between the lubrication system and cutter head drive is intended to preclude dry operation.

Cutter Head Jacket

The cutter head protective rolled steel plate jacket surrounds the rotating cutter head in the area where the outer scrapers are located. This rolled steel shell is designed to protect the cutter head against any ground that should collapse, and prevents jamming of the cutter head rotation. It is connected to the dust shield at its rear side. It is frequently utilized for steel arch setting operations or serves to provide overhead protection behind the dust wall. The foot (bottom) of the cutter head jacket can serve as a forward TBM structural support during the relocation of the machine grippers, and as additional cutter head support during boring. The jacket's steel construction is made up of conical plates and ribs. Because of the additional stabilization it provides to the machine, vibrations are reduced. Should the ground conditions (squeezing ground) necessitate it, the cutter head jacket consists of individual segments and orthogonally arranged hydraulic cylinders. Compared to the nominal diameter, the stroke in a radial direction amounts to between 50 and 200 mm, which enables the external diameter to be modified. This is to ensure that the machine does not become stuck due to ground convergence—particularly at those times when the machine is not moving (advancing).

Inner/Outer Kelly with Gripping

The inner kelly comprises a box or cylinder construction that rests on slipways in the outer kelly. The inner kelly forms the gripper TBM's central guide element. The thrusting forces are transferred from the outer kelly via the thrusting cylinders to the inner kelly. The front inner kelly zone is kept open as much as possible, so that this area can be reserved for ancillary equipment (e.g., for a setting unit for installing the steel support arches). The rear inner kelly area contains the rear TBM support. In most cases, the interior of the inner kelly houses the transfer conveyor with hydraulic or electric drive. The conveyor belt can be removed in its entirety for repair purposes. It moves the excavated material in the cutter head muck hopper onto the transfer conveyor.

The outer kelly can be made up of one or two separate constructions. However, it makes sense in operational terms to utilize two separate box constructions for the outer kelly, in the event of the need to install continuous steel arch ground support. It is possible to compensate for assembly inaccuracies through mutually altering the gaps in the two gripping levels through changing the relative distances of the two kelly box constructions.

When ground conditions dictate that steel arches are to be set close together, the gripping plates must be divided so as to form two separate ''feet.'' These are set farther apart than the spacing of the steel support arches so that the gripping plates do not press against a support arch. That would result in the arch being destroyed (crushed). A gripping unit comprises the following elements:

- Gripping shield (gripper, anchor pad),
- Normally two hydraulic gripping cylinders, and
- Telescopic guide piece for accepting and transferring lateral forces resulting from the torque and the thrusting force.

The TBM can grip the excavated tunnel section either at one or two locations along the TBM's longitudinal centerline (a single set or two sets of grippers). Observed in cross section, the gripping takes place horizontally or in an X-shaped manner. A TBM with only a single set of grippers has more space behind the dust shroud. Two X-form grippers spaced some distance apart along the length of the TBM are usually employed for ensuring positional stability during the boring process in varying stratified rock of different hardness and strength, and in order to save space in the case of machines with diameters less than 4.00 m.

Thrusting Components

The thrusting components are normally divided into two pressure cylinder groups in order to ensure that the thrusting forces are safely distributed into the one-part or two-part outer kelly construction, as well as in the interest of compact fabrication and operation. One end is attached to the inner kelly and the other, to the outer kelly. The path of the boring stroke is measured at the thrusting cylinders. In the case of two separate outer kellies, each of them can be driven individually with the relevant gripping and thrusting cylinders should there be locally restricted ground faults or fractures causing low-strength ground conditions. Following the conclusion of a boring stroke and the lowering of the machine onto the front and rear supports, the thrusting cylinders are retracted until they reach their contracted position. The rear inner kelly area is surrounded by a frame, which is supported during the relocation phase by hydraulic props on the tunnel floor. During this relocation phase, the inner kelly rests on the vertical frame support cylinders. When the gripping cylinders are released, the rear end of the TBM can be raised and lowered by means of the vertical support cylinders. Horizontal cylinders are employed to move the rear end of the TBM transverse to its longitudinal axis. These movements are necessary to steer the TBM by altering the direction of the thrust cylinder stroke. The rigid guidance of the inner kelly by two sets of grippers possesses the following advantages:

- High contact and thrusting forces in hard rock can be readily transferred.
- The gripping forces can be distributed to a large area of the tunnel wall to ensure favorable adaptation to difficult ground conditions.

The inner kelly's rigid guidance by two sets of grippers prevents undesired deviations in the position of the cutter head during the boring process.

Mechanical Ancillary Device

The entire TBM should be accessible for personnel via platforms and ladders. The standing height in the main working zone should not be less than 1.8 m. The setting of steel roof arches and steel mesh for overhead protection, in the case of friable ground, as well as the installation of all-around support steel are carried out directly behind the cutter head. A structural frame is welded to the inner kelly; it serves as a guideway for the hydraulically operated steel arch installation unit. The steel arch setting unit has

- A storage carousel with hydraulic drive for preassembly purposes and
- A working platform that can be moved longitudinally. The platform has integrated steel arch hoisting and steel arch expanding cylinders, which remain standing in relation to the tunnel during the boring process in order to install and expand the steel arches.

The steel support arches are fabricated in segments (approximately three to seven per arch). The segments are transported in stacks to the point of installation by the TBM transport system on the upper side of the kelly. The steel arch segments are fed into the storage carousel one after the other and are bolted together, except for the section in the base area. Once the carousel has been rotated to reach the correct position, placement continues from the working platform. The preassembled ring is maneuvered along the inner kelly into the setting position by two lifting and two adjusting cylinders. Finally, the arch is adjusted and closed by a bolted plate.

A hydraulic drilling unit (Fig. 3) is employed for setting rock bolts (approximately 3.0–4.5 m in length) around the tunnel periphery, and for the attachment of support and overhead protection arches. The drilling unit is set on an assembly with a swiveling device; this, in turn, is installed on a circular base frame attached to the inner kelly by means of a cradle that can be moved in a longitudinal direction. The mechanical action of the hoisting device for the support and overhead protection arches combined with the drilling unit makes for rapid and efficient setting and bolting of these ground support elements. All of this work takes place directly behind the dust shield.

Usually, a separate exploratory drilling unit for 50–80 mm bores and lengths of 30–50 m is available. Drilling is undertaken mostly in the roof area (upper 120° arc) with the TBM at a standstill. This drilling unit can also be utilized for the drilling of grout holes for ground-stabilization umbrella grouting.

In the floor area, a miniexcavator with an omnidirectional rotating hydraulic arm is normally required for disposing of the small-size material resulting from falling rock or shotcrete rebound; this unit transfers the material to a skip or an additional conveyor belt. The material is finally discharged onto the muck conveyor.

Working and Maintenance Cycles for Gripper Tunnel Boring Machine

The working and maintenance cycles of TBM operation are

- Repetitive working cycle—boring, relocating (shifting and gripping) and
- Repetitive maintenance cycle—maintenance of TBM systems (electrical, hydraulic, conveyor, utilities) and changing of cutters.

Gripper TBMs have a cyclic operational sequence involving boring, securing, and shifting. To advance the machine following the boring phase, the inner kelly is lowered onto the front and rear supports. Subsequently, the outer kelly grip is released. The machine axis is aligned, in keeping with any necessary direction correction for the boring, by means of the rear support cylinders.

Machine inspection and maintenance are carried out during each shift. To avoid interfering with the machine advance, these tasks are undertaken collectively on a daily or weekly basis and are allocated to the nonadvancing standstill periods in the day's schedule. Cyclewise, these maintenance operations are executed separately from the hours worked by the TBM driving crew. In this way, the driving and maintenance crews are optimally deployed. The daily or weekly inspection and maintenance are undertaken to ensure a high operational availability of the machine. This applies generally to all of the equipment that is used underground.

Control

There are distinctions between the gripping and control systems used with gripper TBMs. First, there are gripper TBMs with two sets of grippers using the kelly principle to support the cutter head. The inner kelly is guided by the two outer kellies, with each kelly stabilized by two gripping elements.

Second, there are gripper TBMs with one set of longitudinally spaced grippers, also serving as the abutment reaction for the TBM's inclined axial thrusting cylinders. These axial thrusting cylinders that are inclined to both sides of the TBM push the inner kelly of the machine forward. With this arrangement, a ''steel shoe'' bearing against the tunnel floor together with two side guides provides support for the TBM.

The advantage of the TBM with only a single set of grippers is the increased space available between the dust shroud and gripper set. During the boring operation (phase), the TBM is like a cantilever fixed by one set of grippers. The disadvantage of a TBM with only a single set of grippers relates to the possible change of position, with the machine veering away from its intended path when cutting horizontally layered rock of varying strengths. The TBM can sink or rise as a result of gripper slippage caused by eccentrically acting contact pressure on the cutter head. Furthermore, the thrusting forces must be provided by only one set with two grippers. This leads to either extremely large grippers or high localized compressive stresses beneath the side grippers. In addition, it is difficult to bridge local fault zones of low strength with only a single gripping level. A TBM fitted with two levels of grippers is not as adversely affected in low-strength ground as a TBM with only a single level of side grippers.

The advantage of the two sets of grippers is the control of the position of the tunnel boring machine in two planes via the hydraulic cylinders of the anchor pads (grippers). The thrusting force is provided by two gripper sets having two grippers each; this allows higher thrust force and lower contact pressure. The steering of a gripper TBM equipped with two sets of grippers takes place via the rear thrust cylinder support after the advance process and prior to the grippers being repositioned for the next push. During the tunnel excavation operation the machine is supported like a rod by the two sets of grippers, and thus retains its alignment very accurately during the thrusting process. As a result, these machines are particularly suitable for nonhomogeneous ground. The machine is steered polygonally along the driving path using lasers plus survey controls. Additionally, the two gripper set arrangement is effective in eliminating machine vibration, which can often be a problem for TBMs when excavating very hard rock.

During the entire drive, a real-time recording of the actual and desired position is necessary so that corrections can be undertaken immediately following each boring stroke. Compared to mobile roadheaders, the kinematics is much more straightforward. The position and direction of the TBM are governed by

- The *x*-, *y*-, and *z*-coordinates of the cutter head and
- The φx-, φy-, and φz angles (pitching, rolling, and yawing angles) of the inner kelly.

Varying the pitching and yawing angles facilitates the steering process. This correction is integrated through the central shaft rotating around the center point of the cutter head—namely, through changes in the gripper Axes 1 and 2, through Δx_1 and Δx_2, and Δy_1 and Δy_2. Both the gradient (and vertical curves) and the horizontal alignment positioning are simplified with the polygon form. The length of the individual polygon sections depends on the profile deviations defined in the project. Depending on the length of the dust shield around the cutter head, these machines are more or less sluggish to steer/control. Permanent monitoring of the actual TBM position is essential so that timely and accurate steering corrections can be made. Survey laser units are used to ascertain the machine's real-time position. Monitoring can be accomplished as follows:

- Position in keeping with coordinates by means of automatic laser theodolites,
- Pitching and rolling angles by means of inclinometers (deflections of the plumb line), and
- Yawing angle by means of laser beams using two target panels located one behind the other or through gyro units.

The location data are collected by electronic means and transferred to the control computer in the control cab. If the TBM is found to be within a previously defined excavation tolerance range, there is no need for steering adjustments to be undertaken. Should this tolerance range be exceeded, an optical and acoustic signal warns the operator to initiate countersteering by manual means. In the case of a partly robotized system, the computer calculates the optimal polygonlike correction as well as the location along the drive at which countersteering should be accomplished. All engineering technically relevant data are gathered, displayed, and checked in the control cab of the TBM. These include active jacks, temperature of bearings, hydraulic pressure, contact pressure, cutter head rpm, and conveyer belt speed. The individual system controls are provided upper and lower limits to avoid overloading. The relevant excavation cycles must be checked in accordance with material quantity flows in order to be able to trace operational disturbances in the system.

In terms of civil engineering automation TBMs are among the most advanced excavation equipment. In the case of partly robotized machines, the geometrical position of the machine is defined via a control computer. In addition, the thrust jacks are steered automatically to provide the desired directional correction during the next advance. Further, the simultaneous performance of both the TBM excavation and mucking is automatically controlled and synchronized.

Enlargement Tunnel Boring Machine

Enlargement TBMs (Fig. 5) supplement the application of the full-face cutting machine in technical and economic terms. Enlargement TBMs are especially suitable for ground conditions in which special risk factors must be determined through exploratory headings.

In a typical Phase I, the pilot TBM with a diameter of 4.0–4.5 m drives the pilot heading. After completion of the pilot heading, the enlargement to final diameter is made in Phase II using the enlargement TBM. The enlargement TBM is equipped with a spoked wheel. Thanks to the ample room on the spoked wheel's cutting arms, it is possible to install disks one behind the other per cutting path. This is not possible in the central area of the gripper and shielded TBM with full-face section cutter heads. This can, however, be accomplished with the enlargement TBM, as the smallest cutting arms are between 3.5 and 4.5 m in size. The speeds of enlargement TBMs are comparable to those of gripper TBMs, but the penetration per cutter head revolution can be increased through double disks mounted per cutting path (e.g., with two disks located one behind the other). The enlargement TBM's concept thus possesses a potential to achieve project-specific economics. In the case of projects that do not require an exploratory heading, the application of an enlargement TBM is no more economic with respect to construction duration and cost than the use of a gripper TBM. The enlargement TBM permits more straightforward modification of the machine in adapting to different tunnel diameters on subsequent projects. The machine's spokes can be modified to provide a relatively large range of excavation diameters. The machine does not require extensive conversions when used on later projects.

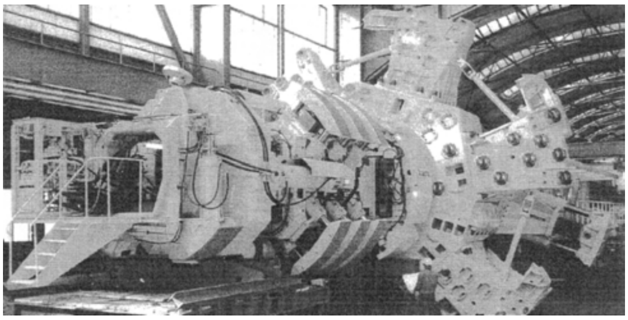

Fig. 5. Enlargement tunnel boring machine (courtesy of Wirth GmbH)

With regard to the enlargement TBM systems compared to full-face cutting machines, there are advantages in terms of both machine transport and assembly as a result of

- The lower weight and smaller size of the pilot TBM and
- The more straightforward dismantling of the enlargement TBM into its basic elements.

The enlargement TBM's gripping element with the inner and outer kellies as well as the thrusting jacks and hydraulic drive motors are anchored in the previously excavated advance pilot bore. Apart from gripping, a stabilizing (supporting) ring with a roof protection shield must be installed at the junction between the pilot heading and the enlargement cross section in order to prevent material that cannot be controlled from falling into the pilot heading. This is necessary, to be certain that the integrity of the ground at the contact point of the gripper plates in the pilot heading is ensured. A constraint of this method is the fact that the diameter of the pilot heading tunnel is relatively small; it is therefore not possible to introduce large gripping forces into the ground. As a consequence, the machine's thrusting force is restricted. For these limitations and for practical considerations, the maximum ratio between the pilot heading diameter and the final diameter can be given as roughly 1:2.5. Only the muck conveyor, and the electrical power and hydraulic supply restrict the excavated tunnel cross section directly behind the enlargement TBM cutter head. Almost the entire cross section is available for securing the ground support systems (steel support arches, roof bolts, steel mesh, shotcrete). This work is carried out from the TBM back-up system.

The pilot bore enlargement method is advantageous in unstable types of ground that are prone to cave-ins (collapse) and in the case where a pilot tunnel has been previously used for exploration purposes. The enlargement TBM machine is suitable for application for tunnel diameters in excess of 7.5 m.

Shielded Tunnel Boring Machine

In the case of shielded TBMs, a steel cylinder protects the entire machine. The shielded TBM is used in average, i.e., crumbling (friable) to unstable ground, for which it is anticipated that the installation of many temporary ground support measures (segmental linings) will be required directly behind the cutter head. The temporary ground support work is installed while protected by the TBM shield. Workers have the protection by the shield of continuously provided temporary ground support. This added measure of safety enhances worker confidence and improves overall TBM performance. The production cycle of the shielded TBM is a two-linked system of boring and segmental lining erection activities. Therefore, boring accounts for only half of the total cycle time.

Segmental Linings

Segmental linings are relatively expensive in terms of required material. Additionally, the use of segmental linings is an inflexible construction process should changes in geology occur. Once it has been decided to use segments, they must also be installed at points where they are not really needed in terms of safety. However, tunnel construction cycles are usually reduced and production performance is improved when segmental linings are used. This is because they can be industrially prefabricated and mechanical systems are available to assist with the installation of the segments. As a consequence, this consideration must be included in reaching a decision on whether a gripper or a shielded TBM should be used. When segments are utilized in tunnels excavated in hard rock, the annular gap between the excavation and the outside of the segment lining should be backfilled with sand. The use of grout has resulted in problems on past projects, including

- Floating of the segments by the fresh annular gap grout when the thrusting jacks squeeze grout that has not yet set and
- Rolling of the shield jacket and segments, as insufficient friction was present for the cutter head driving torque's reaction resistance. Essentially, extremely large driving torques are necessary for the cutter head in rock. However, this problem can be corrected through inclining the thrusting jacks.

Fault Zones

The advantage of a shielded TBM (Fig. 2) is that temporary ground support can be installed in the shield, without any exposure to the ground. This hiding of the tunnel wall surface can, however, cause serious problems when major fault zones and raveling ground, which is not anticipated or discovered immediately, are encountered (e.g., cavern formation outside of the neat tunnel excavation diameter). As a consequence, it is absolutely essential in sections where fault zones are forecasted to undertake systematic investigative drilling during the tunnel excavation. This exploration drilling can be performed using a percussion drill without taking rock/core samples. Normally, all that is needed to evaluate the ground conditions in order to identify fault zones is a comparison of the drilling rate (good rock versus bad rock rates) with respect to the drilling pressure and thrusting speed.

The TBM should be designed in such a manner that, should problematic geological zones be encountered, it is possible to undertake grouting to consolidate the ground mass and/or to apply ground reinforcement with the aid of glass fiber reinforced roof bolts. The TBM should also be designed to include access to the front side of the cutter head, so that incidents at the face of the machine can be inspected and repaired as necessary. ''Caverns'' in front of the face can be stabilized by means of shotcrete from these access points.

Large Diameter Tunnels

There is evidence of a trend to employ hard rock TBMs fitted with a shield and to utilize segments for tunnel lining purposes in the case of projects having tunnel diameters greater than 10 m. Such large tunnel diameters make the installation of the temporary support (e.g., steel arches) in the case of gripper TBMs directly behind the cutter head extremely difficult. Furthermore, the polygonal curvatures become ever smaller (flatter) as the tunnel radius becomes larger; this results in destabilizing the roof zone (as the roof takes a flat shape instead of that of an arch), and the danger of localized cave-ins (collapse) of the roof zone increases in the case of TBMs without shields. The production performance of the open TBM (nonshielded) is slowed when temporary ground support is required for large diameter tunnels. Shielded machines are fitted with thrusting jacks, which support themselves on the segmental lining.

Telescopic Shield Tunnel Boring Machine

The telescopic shield TBM (Fig. 6) is used in difficult ground, like the shielded TBM. This would be for projects in ground having a tendency to cave-in (collapse) or in friable (crumbling) ground, where groundwater and underground water are absent. Again the segmental lining is installed within the shield. The telescopic shield TBM is also known as a twin-shield TBM or a gripping jacket TBM. The telescopic shield TBM was developed to increase the rates of advance of shielded TBMs when segmental linings are used. The twin-shield system simultaneously provides for the advance and the installation of the segments. The boring/excavation cycle time for a telescopic shield TBM is only interrupted for a short period to allow the cyclical advance of the rear contact shield after each boring stroke. In the case of a shielded TBM, the boring/excavation time is interrupted by the entire time period required to install the temporary ground support ring; this is roughly equivalent to an excavation cutting cycle. This difference in the operation cycle results in the actual net ''cutting'' time per workday with a telescopic shield TBM being almost double that of a shielded TBM.

The telescopic shield TBM system is divided into the following three sections in the longitudinal dimension:

- The front shield with cutter head,
- The telescopic shield in the central section, and
- The rear contact shield with tail shield for installing the segments.

The telescopic shield TBM constitutes two independent shield jackets that overlap one another. The first continuous shield is the

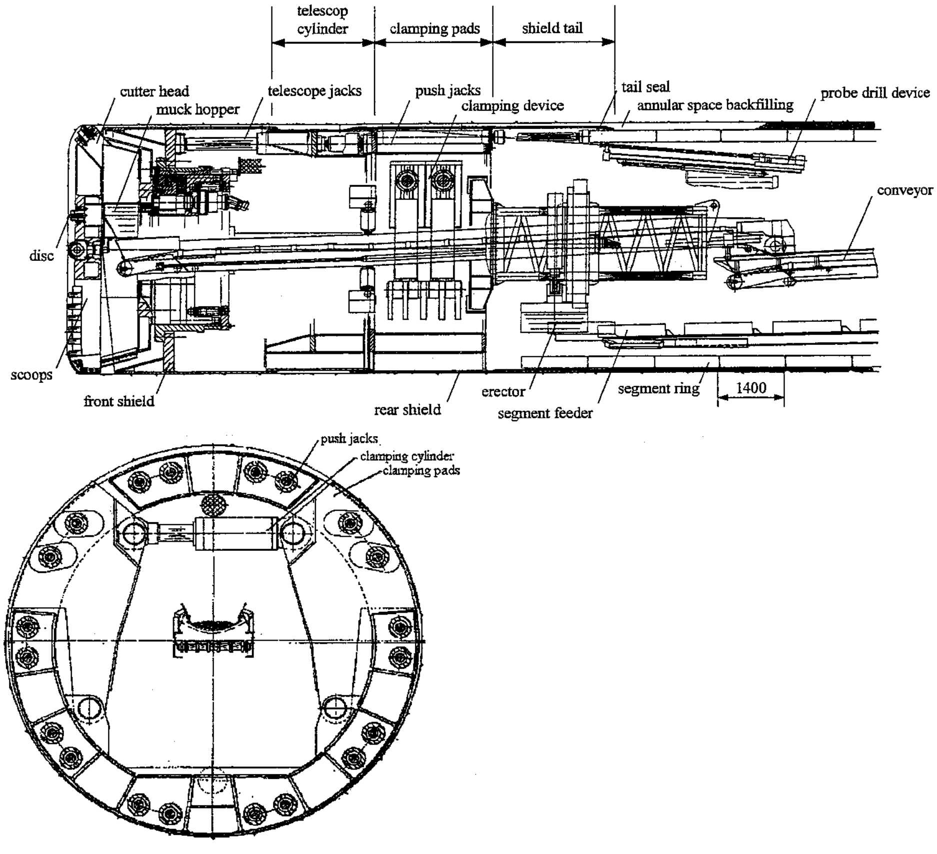

Fig. 6. Telescopic shield tunnel boring machine schematic

front one. The telescopic shield overlaps within it as part of the rear shield jacket. The rear shield jacket is a unit in the longitudinal direction comprising

- A telescopic shield,
- A contact shield (gripping jacket), and
- A shield tail.

The front shield with the cutter head is designed similar to a conventional, extremely short, shielded TBM. The front shield is fitted with longitudinal thrusting jacks arranged at equidistant gaps in the direction of the circumferential ring. Brackets on the front shield and the rear contact shield support these thrusting jacks. The two shield parts advance themselves via the telescopic shield located between the front and rear contact shields. The telescopic shield possesses a rigid jacket. The gripping cylinders with the shield jacket grippers are located in the contact shield, also known as the gripping shield. The contact shield is provided with a shield jacket split in the longitudinal direction. The contact shield gripping jacket diameter can be enlarged or reduced by means of tangentially acting gripping hydraulic cylinders set in the interior. These telescopic jacks are arranged in the upper part of the shield in a crosswise direction. They move a part of the contact shield in the form of a gripper, which is supported on brackets at the sides in the lower part of the shield. In this way, the required contact forces are created. The telescopic shield machine has a two-phase working cycle.

Phase 1—Excavation/Cutting and Segment Installation Process

First the gripping shield is radially anchored with the ground. The cutter head thrusting cylinders support themselves on the contact shield and advance the cutter head during the boring process until the cutter head thrusting cylinder stroke is completed. At the same time in the shield tail of the rear shield jacket the ground support segments are installed.

Phase 2—Advancing Rear Shield

The advancing phase for the rear shield jacket (telescopic shield, contact shield, and shield tail) requires a few minutes. Prior to commencing the shield-advancing phase, all of the cutter head thrusting cylinders are released and then the radial gripping cylinders of the shield jacket grippers are retracted and relieved. After relieving the radial grippers, the rear shield jacket around the cutter head thrusting cylinders is advanced with the aid of the rear shield thrusting cylinders. In the process, the shield thrusting cylinders react against the segmental ring. The rear shield jacket is inserted into the front shield (cutter head shield) in a telescopic fashion in the telescopic shield area. The boring and segment installation process is repeated for each cycle of the tunnel advance.

The use of conveyor belt transportation for removing the excavated material is particularly suitable for continuous production operations. To ensure that the telescopic shield TBM's performance is maintained, special attention must be given to logistics and to segment supply. A segment storage magazine must be available on the TBM backup in keeping with the transport capacity and the tunneling rate of advance so that when the supply of segments by transport vehicles (train or truck) is interrupted, TBM advance is not affected. The segments must move to the erector from the backup in a robust and speedy manner to eliminate any downtime to the overall advancement cycle of the TBM.

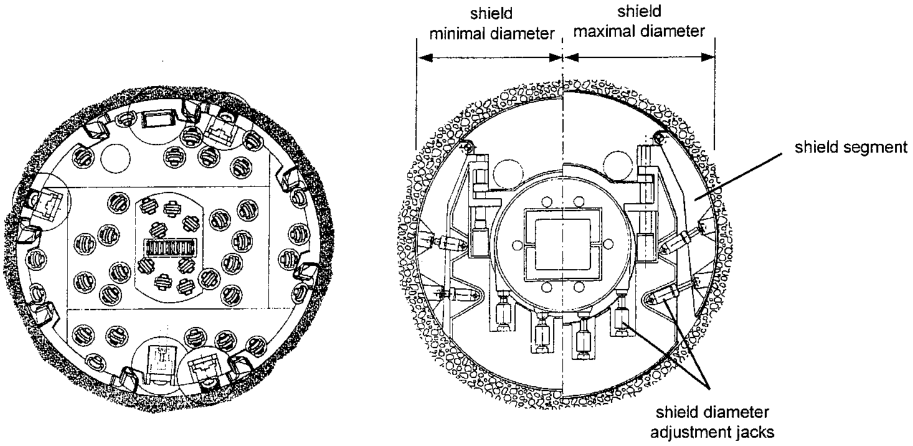

Fig. 7. Adjustable boring and shield diameter TBM schematic

The cutter head and shield thrusting jack stroke must be conformed to the width of the segmental lining pieces. In this way, the machine's maximum boring performance can be exploited without delays caused by awaiting the installation of the segments. The shield jacket overlaps at its longitudinal joint. The telescopic shield TBM has a high degree of flexibility when operating in unstable (friable) ground. Telescopic shield TBM ancillary devices include

- Overcutting tools (disk or roller cutters) at the cutter head, which produce a boring diameter larger than the minimum excavation diameter plus steering tolerance. The telescopic shield jacket supports the overcut excavation diameter until the ground support segments are installed.
- A cutter head that is movable in the longitudinal and radial direction so that overbreak can be created to one side in order to improve the machine's steerability.

Squeezing Rock

If squeezing sections of rock are being excavated by a shielded TBM, the cutter head shield and the cutter head itself must be designed in such a manner that the diameter of each can be altered (Fig. 7). This is done to prevent the TBM from becoming wedged in or trapped by the ground pressure during interruptions in tunnel excavation operations—e.g., work shutdowns (weekends or holidays) or major repair periods.

Squeezing rock is characterized by the fact that the excavated tunnel cross section deforms (becomes smaller) in the course of time. The rock pressure builds up through a corresponding support resistance. Should the rock start to deform during interruptions in excavation operations lasting several days, the cutter head shield or the cutter head itself can become locked in the rock. The radial stresses that are thus created at the cutter head and shield cylinder cause frictional forces so great that the machine is usually not able to free itself of its own accord to continue the process of boring. As a consequence, it is necessary to apply a specifically designed shield cylinder with a corresponding cutter head assembly, which allows the boring diameter to be reduced in such situations. If interruptions in tunnel advancement are anticipated, the cutter head's overcutting rollers and the scraper slots at the outer circumference of the cutter head are extended prior to penetrating such rock conditions so that a larger diameter can be bored (Fig. 8). Given the present state of TBM science, the enlargement can be up to 250 mm. Converting the cutter head diameter does not result in any time being lost in the excavation cycle, but it does reduce the rate of boring advance. The rate of boring advance reduction is roughly 50%.

The cutter head is surrounded by a floating mounted cutter head shield, which protects the head against crumbly rock in the reaming roller zone in order to prevent blockage of the cutter head. The cutter head is supported on the floor by hydraulic cylinders so that the kelly is relieved. During the relocation of the machine's gripping system, the foot of the cutter head shield is employed as the front TBM support. It is also used as an additional cutter head support during the boring process. The cutter head shield comprises a conical cutting shape. This steel fabrication consists of conical exterior wear plates and stiffening ribs. The conical cutting shape serves to clean the floor and serves as a dust shield to ensure that the dust collection system works efficiently.

The cutter head shield is comprised of individual fabricated steel segments, which can be moved radially over the diameter by means of radially arranged hydraulic jacks. If need be, the cutter head shield's diameter can be reduced by 150 mm. The cutter head shield can expand hydraulically to provide an initial support resistance to the squeezing rock at the cutter head. The maximum attainable pressure amounts to 400 kN/m^2. The TBM can still be freed at a rock pressure of 600 kN/m^2, but in this case the cutter head *shield* can be damaged as a result of steel plate deformations. The cutter head is designed and fabricated in such a manner that it sustains no damage when subjected to this pressure. To

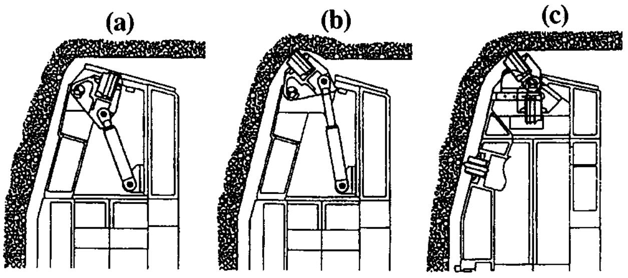

Fig. 8. Phases of cutter head expansion: (a) overcutting rollers retracted; (b) extending overcutting rollers; (c) overcutting rollers fully extended

diminish the danger of wedging the TBM, the cutter head shield is equipped with pressure transducers. Once the maximum pressure of 400 kN/m^2 is attained, the TBM automatically starts to move.

The steel arch storage and assembly device as well as the erector are located directly behind the cutter head. These are in an area protected by the extended cutter head roof shield. The cutter head and the cutter head shield should be as short as possible. The minimum length amounts to 4 m; i.e., the first temporary ground support measures can be installed just 4 m behind the excavated tunnel face.

The cutter head shield's diameter depends on the cutter head diameter. Experience has shown that the free space in the roof between the cutter head and the cutter head shield should amount to 55 mm in the event of worn disks. This free space is reduced to 25 mm when the disks are new, which still allows for sufficient shield movement.

Back-Up System

Trailing power supply, muck disposal systems, rapid temporary ground support installation, efficient safety devices, effective dust collection and ventilation, as well as continuous surveying are items required to support/back up the tunnel boring operations in an effective manner. The trailing equipment system is the TBM's ‘‘backup’’ and can be described as the critical logistic tail supplying all required support for the tunnel boring cycles. TBM back-up equipment design and employment are project-specific. The backup has a high number of logistical demands to fulfill. The conceptual backup presented here is based on a specific back-up system design.

The following aspects are evaluated and integrated when planning and designing the TBM back-up system: (1) operational and economic considerations for the design; and (2) both the temporary and the permanent tunnel supporting and lining concepts.

The following needs must be defined for the planning, design, and development of a TBM back-up system:

- Safety—What are the safety plan's basic parameters (e.g., personal protection, inspection of systems, redundant support systems, hazards, access)?
- Project requirements—specific project parameters impacting the tunnel excavation process and ground support actions
- Transport concepts for material supply and muck disposal—What type of transport (conveyor, rail, truck) will be used in conjunction with a mechanized TBM driving system?
- Ancillary requirements—ventilation, power, cooling, discharge water, lighting, survey, exploratory drilling requirements.

The specifications for developing a TBM back-up system include

- Technical and economic requirements that are of significance for devising the driving (excavating) process
- Analysis of construction progress—production per shift, per hour.
- Listing of ancillary work methods and materials for tunnel construction, including mechanical installations, equipment, and infrastructures, which are needed for carrying out the working operations (securing and lining measures)
- The handling of segments in the back-up area—When segments are used, a method for transporting the segments from the supply vehicle to the erector must be provided.
- Supply and disposal logistics—The project-specific transport concept is determined in accordance with the supply and disposal operations per cycle (e.g., excavation/boring, installing segments, and advancing the TBM). As a consequence, the critical path for each activity of the work cycle must be anticipated and engineered.
- Ventilation—requirements in conjunction with working hygiene, ahead of the TBM as well as at each workstation.
- Safety concept—Events and incidents must be analyzed with the protective features designed for normal and special operations. The fire protection concept has to be worked out and the residual risks must be assessed. Lighting, climbing, fall protection, and personnel access must be evaluated.
- Brief description of the backup—The functions of the most suitable backup must be described, and the train's overall length estimated.

The backup is designed as a compact cradle or as a tracked portal frame car. The backup is normally pulled by the TBM by means of draw bars. Separate travel gears are only made use of in the event of extremely heavy backups or in the case of inclined shafts. The back-up equipment with mobile portal frame constructions normally comprises multiple connected car units. In the case of a gripper TBM, this multifunctional structure would have the following tasks and functional work areas:

1. Separating material flows
    - Disposing of the excavated material (mucking) with conveyor installations for loading the trains or dumpers, or for feeding the gate and
    - Material supply—base invert segments, support arches, shotcrete, roof bolts, provision of rail/tracks, utility pipes, lighting, tools, spare parts, and power.
2. Separating working areas
    - Bottom invert construction,
    - Ground support work, and
    - Ceiling membrane installation.

These should be separated from the transportation flow and back-up infrastructure to enable concurrent work activities.

3. Carrier for the electric and hydraulic installations needed to drive the machine and operate supporting functions—These would include electric transformers, main electric motors, and grout injection pumps.
4. Intermediate storage for ground support elements and other supplies
5. Carrier for mechanical equipment used when installing ground supports, shotcrete, erectors for steel support arches, and hoisting devices (power winches)
6. Operator and control cab with regulating and steering units for controlling the cutter head and transport installations, the hydraulic and electric installations, and necessary pumps as well as monitoring and alarm equipment
7. Carrier for ancillary equipment such as fire extinguishing, first-aid, and rescue equipment; toilets; telephone; survey; spare parts; extension tubes; cables; and track storage with hoisting devices
8. Carrier for the dust control system with electric fans, and storage of ventilation duct material used to extend the ventilation duct
9. Loading device—The length of the backup is governed to a major degree by the manner in which the excavated material is removed from the tunnel. As a result, a distinction must be made between the following types of transportation: train or

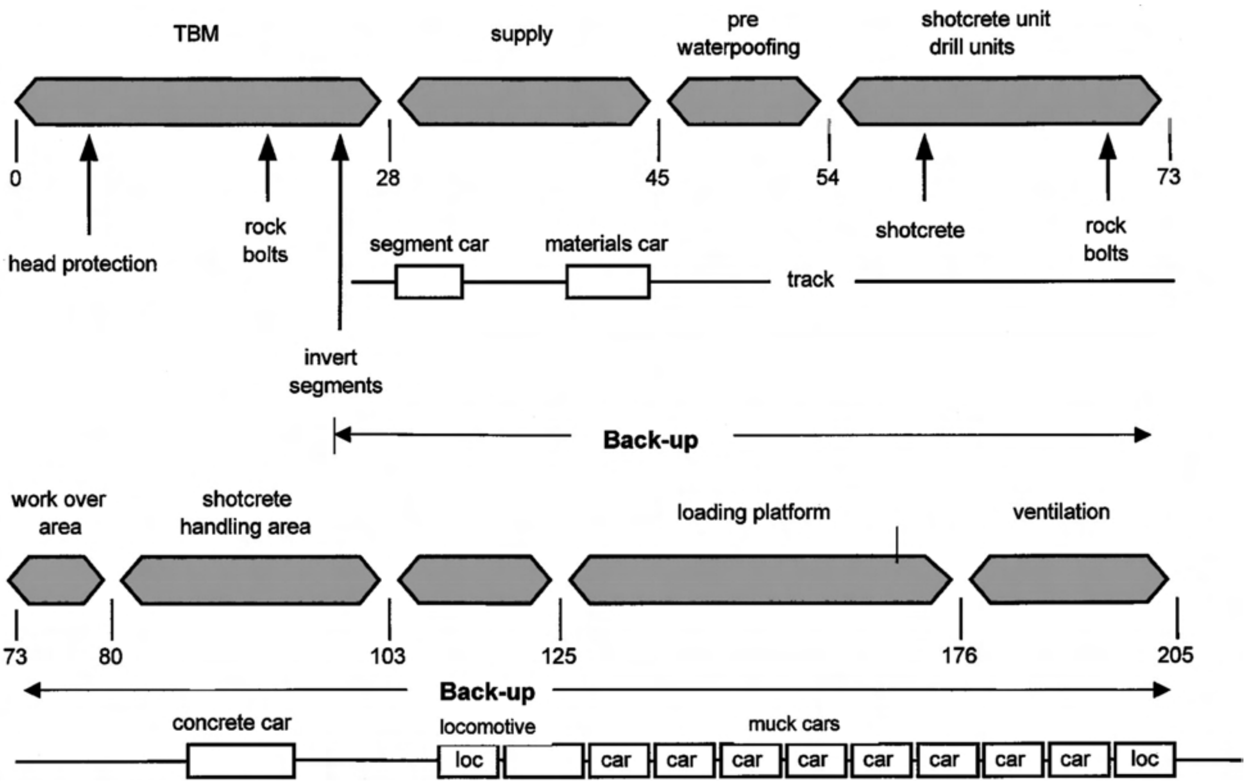

Fig. 9. Back-up functional areas for typical gripper TBM (distances in meters)

conveyor transport. Nowadays, usually train and/or conveyor transportation is utilized. The backup's length is governed by the length of the mucking train (locomotive and muck cars) when train transportation is used. The mucking cars' capacity is engineered in such a manner that the excavated volume (loose material) from a single driving cycle (one stroke) can be carried by one train. If possible, trains are changed during the gripper TBM advancing phase or when the segments are being installed in the case of the shielded TBM. The backup will be considerably shorter in overall length when continuous conveyor muck transportation is used.

The dimensioning of the backup (Fig. 9), particularly in the case of the open gripper TBM, is carried out in accordance with the following functional work areas:

- Excavating, and supporting area—hoisting, storage and thrusting devices for steel support arches and roof bolts (for primary ground support behind the cutter head) as well as base invert segments (if used); operator control cab and electric and hydraulic drive units with the necessary circulation tanks,
- Water control area—platforms for installing drains, dewatering pipes, and flexible membranes to control the underground water as well as to seal the surface by means of a dry-mix spraying unit,
- Material storage area,
- Loading area for excavated material and supplies—train or main conveyor, and
- Ventilation, electrical power, and utilities area.

The backups for gripper TBMs must be designed in such a way that they provide flexibility and adapt to ground support installation demands. Demands vary in conjunction with the geological conditions that are encountered. This is the reason why gripper TBM back-up systems are considerably longer than those of shielded TBMs, as the flexible supporting measures must be carried out manually with mechanical equipment using ancillary devices on the backup.

The length of the excavating, and supporting areas depends on the size of the stationary drive, on the hoisting and transport equipment, and on the storage requirement for initial tunnel ground supports (arches, rock bolts, steel mesh) that may have to be installed directly behind the TBM. Its length is obtained from the planned rate of advance and the extent of the measures to be undertaken as well as the capacity of the roof bolt drilling equipment and the shotcrete equipment. The length of the water controlarea is dimensioned according to the anticipated extent of the advance sealing operations related to the cycle time required for a boring stroke advance. The back-up storage requirement is obtained from the maximum amount of excavation material generated, the maximum possible consumption rate of the ground support material, and the supply train's transport cycle.

Work platforms are allocated to each working task in order to undertake the special securing, supporting, and lining operations concurrently. This facilitates continuous operations during the boring stroke. For this reason, the roof bolt drilling equipment must be readily shiftable in both the longitudinal and the radial directions. The loading area for shotcrete as well as the ventilation and energy connection area are geared to the size of the shotcrete transport car, the ventilation duct storage, and the electric cable storage drum. The loading area is designed for the required train loading capacity, as dictated by the amount of material excavated during a boring stroke. In addition, the length of the back-up system of both gripper and shielded TBMs is determined by the base invert support.

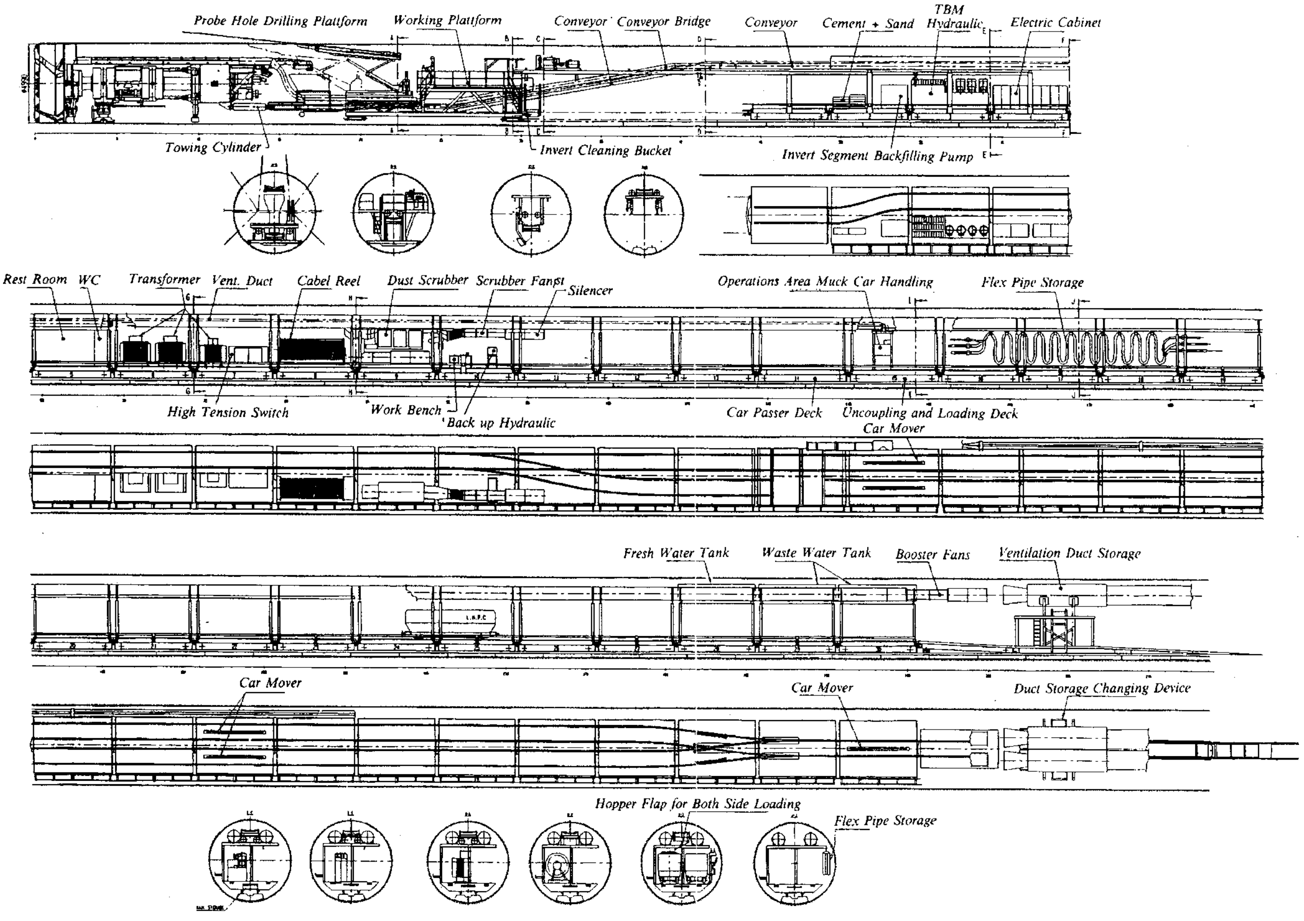

Fig. 10. Back-up areas for typical gripper TBM

A level transport road is needed in the tunnel to ensure that the muck is removed efficiently and materials are delivered for ground support purposes. As a consequence, the base in the case of tunnels without base segments but with ventilation and utility ducts is normally installed between the front securing back-up section and the rear loading backup. The back-up section, which is required for installing the base invert, is located between these sections, which are connected by a bridge. The front securing back-up car usually supports itself radially on the overall cross section, whereas the loading back-up section rests on the substructure, installed under the back-up system bridge, in the central part of the tunnel. The base invert segments can only be installed directly behind the TBM. These then serve as a temporary road in the case of tunnel cross sections that do not require ventilation ducts below the carriageway. The combination of the multiple work tasks, material handling, supplying the TBM, as well as continuously providing ground support in the tunnel requires a relatively long back-up structure.

The backups are usually individual car units, from 5 to 15 m in length, that are coupled together. The back-up car units normally run on rails/tracks. After a tunnel section has been excavated, track is carried to the front via the backup's traveling cab and installed to advance the rail. By means of a hoisting unit, the rails are laid in position in front of the backup. In this way, the back-up system can continuously follow the TBM. A back-up system for a gripper TBM with train muck transportation is shown in Fig. 10.

Mucking

Mucking represents an integral component of TBM operation, as well as that of the back-up system. The TBM accomplishes mucking by a muck transfer conveyor. The tail of this transfer conveyor is located in the cutter head (Figs. 2 and 6). Within the cutter head, muck is loaded onto the conveyor by means of bucket scoops and a feed chute. From this first conveyor the muck is transferred onto the back-up conveyor at the junction between the TBM and the backup. Transference to rail transportation or to dumper transportation can be carried out directly via a conveyor loading unit or via an intermediate bunker. The bunker makes possible continuous tunnel driving with discontinuous loading during the driving phases, such as occurs in the case of dumper transportation.

There are the following two different possibilities in the case of rail transportation:

- The train is slowly shunted below the conveyor's material discharge.
- The train stands still and is filled using a shiftable loading belt (drag conveyor), which is located under the back-up conveyor and fed by it.

Use of a drag conveyor possesses the advantage that the operator of the train can manage the loading. With the train at a standstill, the train operator controls the belt while monitoring the volume placed in each car. If the train must be shunted into position, an operator and an assistant are required to operate the belt and check the fill volume of the cars. The shiftable drag conveyor is a bit longer than half the train. The back-up belt ends roughly at the middle of the train and transfers the excavated material via a feed hopper onto the passing drag conveyor. This method first fills the last car of the train, with the discharge of the back-up belt above the rear section of the drag conveyor. The drag conveyor is pulled forward in the longitudinal direction of the tunnel by means of an electrically driven chain haulage according to the extent to which the cars are filled—something that is possible until the middle car is reached. Then the belt's running direction is reversed, and the loading process is effected from the front car until the middle one is filled up. Neoprene aprons cover the gaps between the various mucking cars. In this way, material is prevented from falling onto the track between the coupled rail cars during the loading process.

Final Remarks

In 1999 the Swiss railways began a major tunneling effort in support of their rail system modernization. The two main tunnels in this program are the Lötschberg Base Tunnel and the Gotthard Tunnel. Much of what has been described here is based on work supporting tunneling method decisions or on actual experiences for the construction of these rail tunnels. Intermediate attacks for the Gotthard Base Tunnel are planned in the Amsteg, Sedrun, and Faido sections. Overall construction time is expected to be approximately 10 years. But there have been some design delays as a result of the tragic fires in Alpine tunnels—particularly the tragic fire on October 24, 2001 in the existing Gotthard Tunnel. These events have caused the designers to reevaluate tunnel safety features. The Gotthard intermediate attack at Sedrun has been under construction since the spring of 1996. A 1 km access adit and a ventilation adit have been completed. The early construction in Sedrun will ensure that the difficult Tavetsch zone can be holed through northward and southward on schedule. Two 8.83 m diameter TBMs have been ordered for the Bodio and Faido sections of the Gotthard. These are the Gotthard's southern connections. Their construction is scheduled for a spring 2002 start. About two-thirds of the 57 km total Gotthard Base Tunnel lengthwill be excavated using large TBMs, and about one-third will be excavated by mechanized drill and blast methods.

The construction of the Lötschberg Tunnel began in July of 1999. The base tunnel runs 34.6 km from Frutigen to Raron. There are five access locations to the tunnel—portals at Frutigen and Raron, and lateral adits at Mitholz, Ferden, and Steg. The tunnel boring machines 9.6 m in diameter are boring (cutting) their way through the Alpine rock. On average, they are advancing at a rate of 18 m per day (two boring and one maintenance shift per day).

In areas with highly variable geology or rock that is difficult to tunnel through, the TBM method is less suitable. Such conditions would include

- Raveling ground,
- Extremely squeezing ground,
- Soft rock,
- Unstable or crumbling rock,
- Mud, and
- Water bearing rock.

In such sections, the traditional method of drill and blast tunneling is being used.