Drill and Blast Tunneling Practices

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Abstract: High-performance drill and blast methods for tunnel construction require that each of the individual working elements that constitute the construction process are optimized and considered as a system of sequential and parallel activities. The advantage of integrating the logistic backup systems facilitates an increase in performance. To achieve increased production, it is necessary to improve the drilling, explosive loading, temporary ground support installation—rock bolts, steel mesh, shotcrete, steel sets, lagging, mucking, and logistics. Better blast techniques, partial robotilization, and integration of all systems and processes is also necessary.

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Introduction

Tunneling, especially tunnel excavation by tunnel boring machines (TBMs) has increased in the last three decades. Twenty-five years ago, the question was, ‘‘Can the tunnel be excavated by TBM?’’ Today the question has become, ‘‘Can you afford not to excavate with a TBM?’’ Therefore, when a project is being analyzed the drill and blast-tunneling method is in intensive economic competition with TBM tunneling.

In principle the TBM method (Table 1) is a highly mechanized tunnel-manufacturing factory with well-organized logistics. The advancing TBM, however, has limited flexibility particularly when the tunnel cross section deviates in size or from the machine’s circular shape. Mobilization of the machine takes considerable time. The investment costs for a TBM and its required backup systems are very high. TBM technology has a high level of automation with mechanized processes that promote mining in a safe work environment. A TBM operation is characterized by very high performance, large daily footage advances, and low labor costs.

The drill and blast method (Table 1) is characterized by operations that occur in a repeated cyclic sequence. The level of automation and mechanization of these tasks is low and there is a high degree of hard manual labor involved. During temporary support installation and mucking, worker safety is a serious issue. This is because immediately after blasting there can be a high degree of risk from rock falls in the unsupported section of tunnel. The drill and blast excavation method is a very adaptable and flexible process in regard to the excavation of any tunnel cross section or intermediate section, and it allows for the installation of various kinds of temporary rock support. Further, the drill and blast method is characterized by a short mobilization time requirement due to the use of standard equipment. Compared with TBM technology, the performance (rate of advance) for drill and blast excavation is lower in most cases. The total labor cost for drill and blast tunneling is high, but the total investment cost is less as compared with use of a TBM.

This can be summarized as follows: Based on research at the Swiss Federal Institute of Technology, TBM technology shows an excellent cost efficiency in the case of tunnels longer than approximately three kilometers. The exact length is dependent on labor cost. However, even with TBM technology there are still efficiencies to be gained with regard to more utilization of automation for support system installation. Additionally, increased TBM mechanical availability would improve overall cost. This might be accomplished by using stronger and more durable cutting discs. The drill and blast technology has a medium cost efficiency in the case of tunnels having a length of more than three kilometers, and this cost efficiency decreases as tunnel length increases. Drilling and blasting has high unused efficiency potential in regard to simultaneous cyclic work and logistic improvements. This is especially true in the work zone to the rear of the heading.

Comparing Drill and Blast with Tunnel Boring Machine Excavation

In addition to the geology, project specific conditions such as tunnel length and cross section acutely influence the choice of the tunneling method. Currently, gripper TBMs or shield and telescopic shield TBMs are used for mechanized rock tunnel excavation. The ‘‘backup’’ plant serves to carry the logistics systems (ventilation, compressed air, water, discharge piping, electrical transformers, lighting, and motor control centers) and is the transfer point for material handling, temporary ground support, and muck. Depending on the size/cross section of the tunnel, a selection is made to utilize conveyor belt, rail, or rubber-tired vehicles for material supply and muck disposal.

The main difference between conventional mechanized drill and blast, and TBM tunneling is related to the process cycle and operational continuity. A TBM drive requires a predetermined (fixed) tunnel diameter. Such a circular profile can be excavated with a high degree of accuracy by the TBM. However, with drill and blast methods the tunnel cross section can be created to any required shape and, most importantly, the tunnel shape can be

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Table 1. Comparison of Tunnel Boring Machine and Drill and Blast Tunneling Technology

Tunnel boring machine	Drill and blast
(a) Principles	
Highly mechanized—tunnel factory	Labor-intensive cycle work
Limited size and shape flexibility—restricted to constant tunnel cross section	Very adaptable to tunnel shape—flexible process
High level of automation and mechanized processes	Low level of automation and mechanized processes
Good worker environment	Poor worker environment
Safe work area	Dangerous work area
Long time duration for mobilization—procurement lead time and initial installation	Short time duration for mobilization—standard equipment
High performance	Medium performance
Low total labor cost	High total labor costs
High investment cost	Low investment cost
(b) Summary	
Cost effective for tunnels having length of 3 km and greater	Medium cost efficiency for tunnels having length of 3 km and greater
Areas of potential improvement: automation; increased mechanical availability—improve amount of boring time	Areas of potential improvement: simultaneous and improved cycle work; rear area logistics

changed along the length of the drive. The diameter of a circular cross section can be increased or decreased as required, or a circular section can be changed to a horseshoe form when necessary. However, in the most unfavorable drill and blast case, there can be blasting overbreak amounting to 10–25% of the design cross-sectional area. This material must be removed and the space may possibility have to be refilled. With drill and blast, considerably more temporary ground support work must be undertaken at the face and in the excavation area than is usually the case for a TBM excavation. There are situations when a shield TBM is the only suitable tunneling method. In situations where TBM and drill and blast methods are both feasible, the risks must be assessed by carefully considering the positive and negative factors, particularly with respect to the risks and costs should unexpected or unforeseen geological circumstances arise. Tunneling is a high-risk activity, and the frequency of accidents as well as their extent is roughly the same for both methods (Tarkoy 1995).

In the case of long tunnels through geology having suitable rock properties where high rates of excavation advance can be anticipated by the TBM method, drill and blast will not be competitive. However, as soon as the geology becomes somewhat complex and there are zones of disturbance, drill and blast performance can become significantly better as compared with a TBM.

Synchronized and Mechanically Assisted Drill and Blast Processes

Drill and blast techniques are extremely adaptable tunnel excavation methods. This is particularly true in relation to cross-sectional geometry of the tunnel and encountered geology. The heading sequence, length of advance, and the required temporary ground support at face and heading govern the cycle time of the tunnel excavation. The extent of excavation support required and its placement locations are the decisive factors in allocating excavation and ground support classes. Temporary ground support measures have to be undertaken in accordance with the specific requirements to protect the works at the face and in the loading area, and to stabilize the tunnel section. Ground support is both a safety and a structural issue.

During tunnel excavation, the operational obstruction caused by the ground support system increases as the geology worsens. In the case of good rock, the resulting obstruction is insignificant to tunneling operations. However, when unstable rock structures are encountered, temporary ground supporting measures govern the excavation progress. Support is achieved by rock bolts and/or steel mesh, shotcrete, or in the case of extremely bad conditions the installation of heavy steel ribs and nailing or bolting the face.

The working stages, which govern the coordination of the excavation and ground support operations, are balanced with respect to both their efficiency and their economic viability. A certain degree of harmonization must be achieved. The reason for this is that the tasks are still largely manual or only partially mechanized sequential discrete activities (Bock 1990; Girmscheid 1997).

Mechanization of Drill and Blast Tunneling

How can the competitiveness of drill and blast tunneling be improved against the TBM method? First, it is necessary to maintain flexibility in regard to changes of the excavated cross-section form and size and to the installation of various kinds of temporary rock support. But two areas of potential improvement that merit special attention are (Fig. 1)

1. The heading area, with the repetitive cyclic production operation of heading drill, blast, excavation, muck loading, and installation of primary temporary support; and
2. The rear area, with both its heading excavation operational support services and final ground support work, including
   - Simultaneous movement of support infrastructure that must follow the excavation/heading process, and
   - Separation of material flows and support infrastructure from the equipment parking, material storage, and handling zones as well as from the tunnel invert construction area.

Introducing mechanized processes into drill and blast tunneling can increase performance and decrease cost. This would include using highly automated, robotic, and specialized equipment in the excavation/heading area and further mechanization of the simultaneous movement of all support infrastructure services in the rear area. Today, the mode of operation with the drill and blast

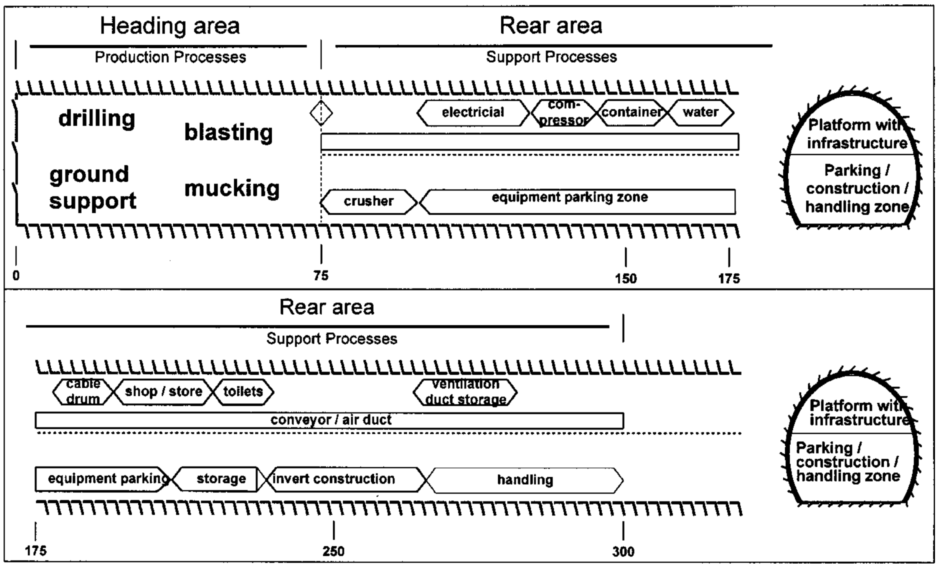

Fig. 1. Drill and blast functional areas with backup system

tunneling cycle is to move each support service individually forward, following the heading. What is needed is a production cycle organized such that transport and work processes can be carried on simultaneously. This can be achieved by systematically separating storage and working areas in the rear of the heading and carefully coordinating transport flows. Furthermore, it is necessary to improve the working conditions by reducing the heavy manual work and improving the air quality.

What processes can be enhanced in the drill and blast tunnel construction cycle? Fig. 1 identifies the areas and functional zones within each area where the different processes take place. The production processes in the heading area are mechanized for each phase of the work cycle by different types of equipment. The rear/service area operations can be improved by using a steel platform suspended from the roof of the tunnel. When a suspended platform is used, the ground support operations as well as the work process for installation of the final tunnel lining can be separated into

1. The *top area*, where the infrastructure, initial phase of the muck flow away from the header, air supply ducts, and utilities are located; and
2. The *bottom area*, where equipment parking and storage, invert construction, and material handling for supply (ground support, explosives) are located, and where at the end furthest from the header the muck is loaded into the tunnel transport system.

Heading Operation

The mechanization opportunities at the drill and blast heading focus on the improvement of the cyclic heading process by mechanization and robotization of individual tasks:

1. Computer-supported high-performance drilling;
2. Mechanized computer-controlled loading/charging of emulsion explosives;
3. Mechanized muck loading with high-performance tunnel excavators or side dumping loaders; and
4. Mechanized installation of temporary ground support with
   - Computer-controlled rock bolting equipment,
   - Mechanized erection of steel arch supports, and
   - Robotized application of shotcrete.

Drilling Technology

For achieving the required tunnel section and for optimal fragmentation of the rock, accurate drilling is an important prerequisite. Drilling critically impacts blast performance. The drilling cycle includes the positioning of the jumbo, checking that the proper drilling pattern is employed to match the position along the tunnel length (station location), positioning the drilling arms (booms), and drilling the holes.

The latest generation of jumbo drills (Fig. 2) with two or three booms can attain high production in semi- or fully automatic robotic operation. The positioning of the drill jumbo is accomplished manually by means of a tunnel laser, but the drilling pattern for the appropriate location is produced via computer-aided design to the jumbo's process control computer. On the basis of the jumbo positioning data, the on-board computer calculates the positions for the drilling booms and the specific drill pattern (horizontal, angle, depth, spacing). This can all be done in either a semi or fully automatic mode (Girmscheid 2000).

Blast Technology

Three factors influence developments in tunnel blasting technology: (1) safe handling of explosives (reduction of accidental detonation risk); (2) reduction in toxicity (postblast gases, nitrous oxides, and carbon monoxide); and (3) rapid and straightforward loading/charging of the bore holes (Girmscheid 2000).

Explosives

There is a wide range of commercial explosives available for use in tunnel blasting. Contractors favor pumpable site-sensitized emulsions because of their higher safety, lower toxicity, and charging speed. The tamping rod is introduced manually. The site sensitized emulsion explosives are loaded with a computer-controlled pumping vehicle (Fig. 3). The two emulsion components are mixed in the borehole by automatic means. The amount

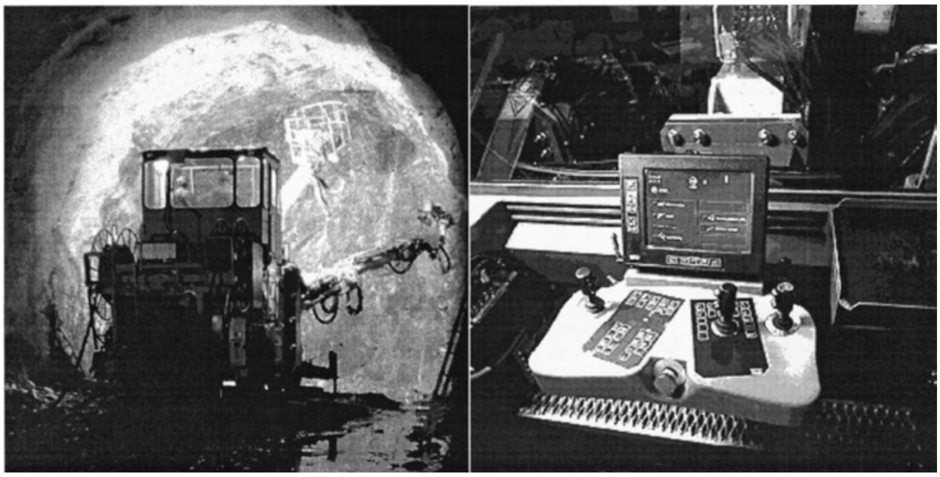

Fig. 2. Fully automated hydraulic borehole-drilling equipment

of explosive is volumetrically controlled based on the degree of fill necessary to achieve the desired fragmentation.

Detonators

The two primary detonating systems are electric ignition and pyrotechnic tube ignition. The advantage of the electric ignition system, with regard to blast controllability, is the ability to test the circuit and ensure that all explosives are connected. The pyrotechnic tube ignition system has the advantage of simple installation and robustness, and it can be used in combination with *electronic detonators*. Electronic detonators guarantee safety and at the same time provide an accurate firing sequence of the individual holes. This facilitates low vibration and precise blasting. Owing to their high individual costs, electronic detonators are used in combination with the tube ignition system. Using electronic detonators in the perimeter zone helps achieve high cross-sectional accuracy and a clean break along the contour. The combination of *pyrotechnic tube* and *electronic detonators* with pumpable emulsion explosives enhances the economy of drill and blast tunneling.

Mucking Technology

Mucking denotes the gathering together of material from where it has been deposited after the blast. The size of the individual rock fragments and the volume excavated per length of advance are essential criteria for selecting a mucking process.

Muck haulage can be undertaken via mucking trains, belt conveyors, or dumpers. Under normal circumstances, a crusher is used at the transfer point for feeding the conveyor belt or the train. If rubber-tired trucks are used, sufficient width and height must be available so that the wheel loader can dump its bucket. Side dump buckets are also feasible, for they can be used in small tunnel widths. Loaders can be utilized for short distances or in extremely constricted conditions as a combined loading and transport unit. Universal machines are combined units that possess both a loading device and transfer bridge. The trend is towards a high-performance mucking concept, e.g., using front shovel crawler excavators (Fig. 4). With this piece of equipment, productions up to 500 t/h have been achieved even in restricted width tunnels (Girmscheid and Moser 2001).

Tunnel Ground Support Technology

Tunnel rock supports are installed in one, two, or three stages depending on the type of tunnel cross section: (1) in the face area; (2) in the excavation area; and (3) in the rear area. Bolting operations (i.e., drilling, placing, and prestressing of the rock bolts) are

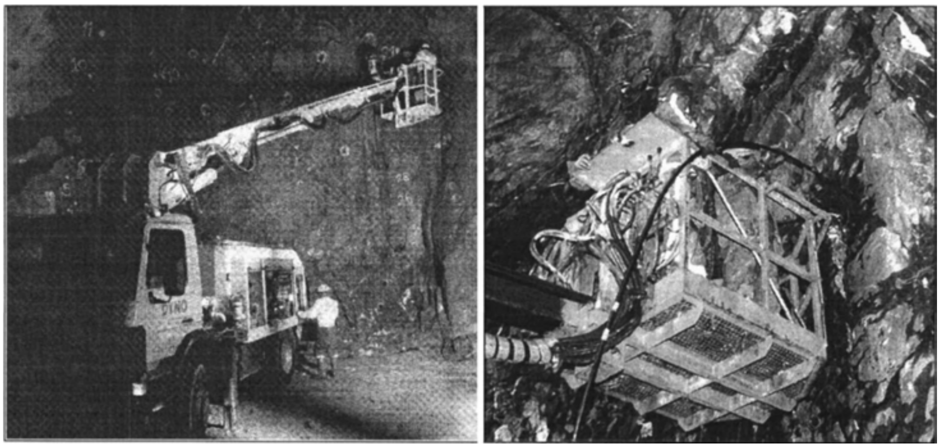

Fig. 3. Working from manbasket to load/charge emulsion explosives into drilled face

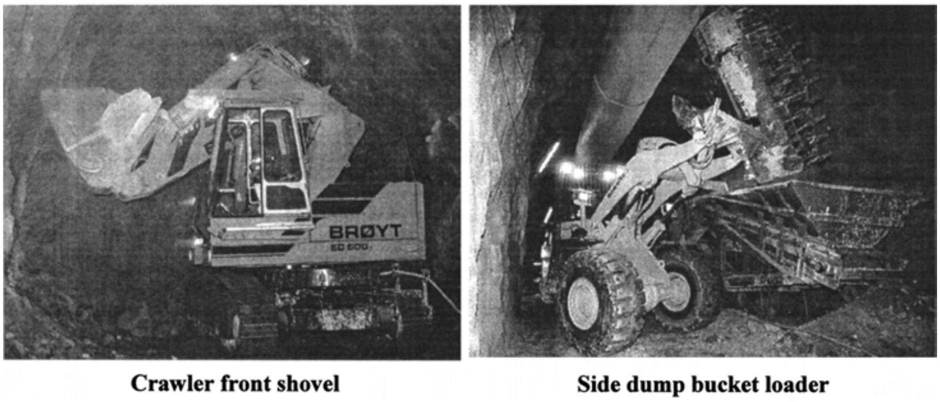

Fig. 4. Excavating and loading muck with hydraulic excavators: crawler front shovel and side dump bucket loader

in most cases completely automated. Two types of rock bolting are utilized:

- System bolting pattern: This means rock bolts are installed according to a systematical predetermined pattern (spacing) that depends on the rock support class; and
- Local bolting of single fracture blocks: This refers to the means used for holding back and preventing the falling of fractured rock.

The tunnel design engineer has designed a support system and bolting patterns based on anticipated geology. But the site engineer/geologist and the operator are responsible for specifying the exact location of bolt application so that the bolt's bearing capacity can be fully exploited. The bolt position and direction must be fitted to the surrounding ground conditions and the direction of fissures and joints.

Steel arches/ribs are still placed manually or with excavator equipment having ancillary attachments. The current state of the art regarding the installation of steel arches is by hydraulic manipulators (Fig. 5). A mechanized installation process can be accomplished with an erection manipulator. These machines offer great potential for reducing the time required to install the temporary steel arch support system, and they make the process much safer.

If steel mesh is required, its installation is an extremely time-consuming operation. Mechanized equipment for laying out steel mesh with combined bolting devices is being developed and shows promise. When that equipment becomes available, this work will be much easier and safer. When the cross section has been blasted accurately this equipment should significantly improve production.

Placing shotcrete is undertaken either manually or by manipulators using either the dry or wet spraying method, depending on the geometry of the excavated cross section and the volume to be applied in a given time. At the Swiss Federal Institute of Technology in Zurich, a shotcrete robot has been developed in collaboration with Master Builder Technologies (Fig. 6) (Girmscheid and Moser 2001).

Some companies claim their manipulators are robots, but most of these machines still require hand-guidance by a human. The equipment presented here is a computer-controlled shotcrete robot (Fig. 6). The computer controls the mechanical action as well as the application process. This shotcrete robot is equipped with a laser device that scans the surface of the tunnel on which the shotcrete should be applied. The computer then calculates a virtual surface based on the measured spherical tunnel surface. The virtual plane is located at a distance "*d*" from the tunnel surface on which the nozzle of the shotcrete robot will be guided and held perpendicular to the rock surface. This makes the optimized application of shotcrete possible, with low rebound and high surface smoothness.

The shotcrete robot has different operational modes: manual, semi-automated, and fully automated. It is possible to apply the

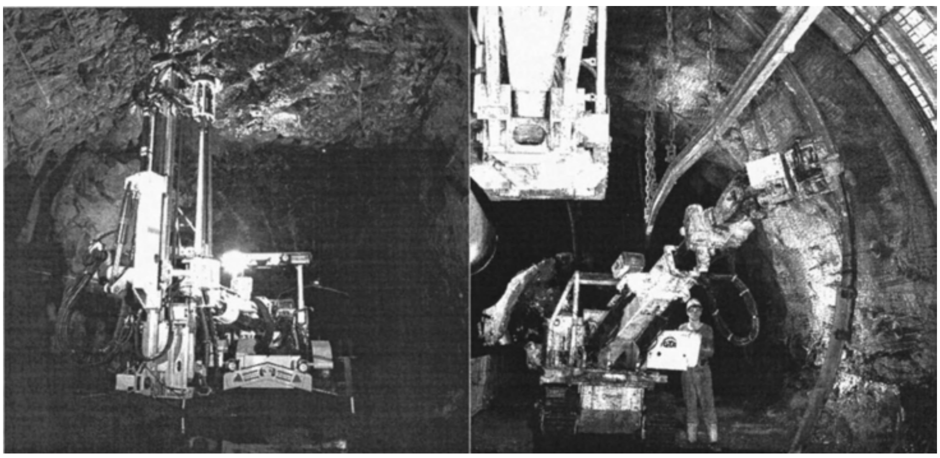

Fig. 5. Fully automated rock bolting and erection manipulator for placing steel arches

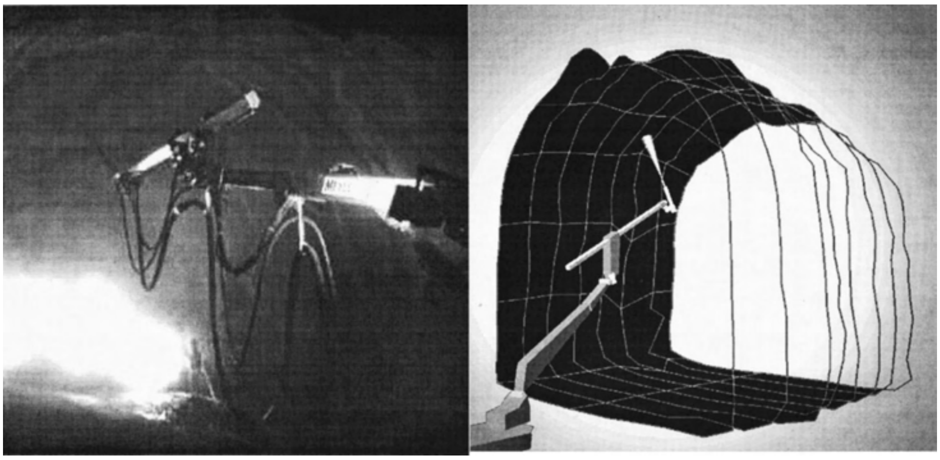

Fig. 6. Shotcrete rock support applied by robot and parameterized work space

shotcrete over an area at a constant thickness ranging from 4 to 30 cm. It is also possible to equalize the blasted surface to a final plane area. The application process is done on meandering paths. The single paths are superimposed to build up the required thickness.

This development in fully automated shotcrete application facilitates high performance with increased safety for the workers. The quality control in regard to layer thickness, compaction, rebound, and homogeneity is inherent in the application process (Aldrian et al. 2000; Girmscheid and Moser 2001).

The input programming for the shotcrete robot requires a selected smoothness and layer thickness. The process control calculates automatically the path line distance and all other operational parameters as well as the expected rebound for the chosen operational data. The system consists of the carrier vehicle, manipulator arm, concrete pump, and additive tanks with a dosing unit, which are fed directly from the mobile mixer or via pump delivery lines. Performance depends on the consistency of the fresh concrete. Quality shotcrete can be assured with delivery amounts of up to 12 m^3/h. The early strength that is called for in many cases can be attained by means of additives.

Solutions for Rear Operations

The mechanization objectives for the rear area operations are:

- Separation of the linear transport movements—heading advance, support, mucking;
- Separation of working areas from transport processes; and
- Separation of support infrastructures from transport movements and working areas.

Furthermore, the excavation services structure handling has to be simplified from a single pick-up procedure to simultaneous handling. The focus has to be on *parallel work* and the *parallel transport flows* in the same area of the tunnel.

One solution for improving drill and blast services operations is a suspended platform. The suspended platform acts as

1. Carrier for drill and blast tunnel infrastructure:
   - Muck conveyor belt,
   - Ventilation air duct and air duct storage for continuous extension,
   - Location of safety, sanitary, utility, work team, and office containers, and
   - Electrical cable and utility pipe storage for the extension of the utility lines during the carrier movement;
2. Bridge over the parking area for the cycle heading execution equipment;
3. Bridge over the invert construction area;
4. Bridge over the handling area for transfer of muck from the carrier conveyer to the tunnel transportation; and
5. Bridge over material supply for heading and invert construction.

The length of the suspended platform depends on

1. Number and type of infrastructure;
2. Length of parking zone for excavation cycle heading equipment not in use;
3. Length of invert construction zone; and
4. Length for the material handling zone to load the muck onto the tunnel conveyor, or into trucks or trains for transport out of the tunnel.

Suspended Platform System

The suspended system has been used by contractors in long tunnels with excavated cross-section dimensions for single-track rail lines like the Vereina South or Mitholz in Switzerland (Teuscher 2000). At Mitholz there was a 9.4 m diameter drill and blast tunnel section 2 km long. The Vereina South drill and blast section was 7,474 m in length. Two kilometers of the drive length had twin track tunnels with an excavated cross section of 70–86 m^2; the further 5.4 km long section was a single track tunnel (40 m^2). Good success was recorded on this heading by the use of a 230 m long suspended platform with integrated conveyor belt. Use of the suspended system made it possible to increase the production of the drill and blast excavation.

Through the application of such a system (Fig. 7), it was possible to run working processes parallel to one another and to uncouple the material flows affecting supply and muck disposal. The shiftable infrastructure carriers are suspended platforms (Fig. 8) riding on rails that hang from rock bolts in the roof of the tunnel. On each side of the platform, pushing jacks with locking grips are installed to move the platform forward on the suspended rails. The locking grippers of the platform jacks are engaged to the suspended rail, and by extending their hydraulic arms the platform is pushed along the rail. It is mandatory that the pushing jacks move simultaneously.

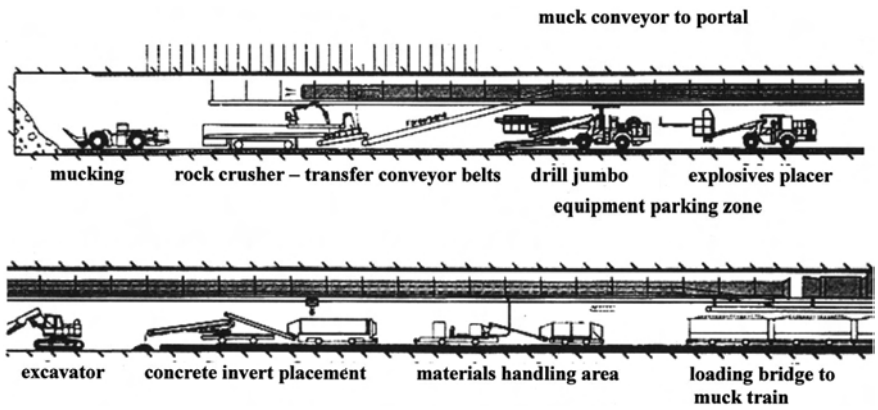

Fig. 7. Backup system, Vereina South Tunnel (Switzerland)

The front area of the suspended platform is protected against flying rock debris during blasting by a chain curtain (Fig. 8). A crawler mounted traveling rock crusher (Fig. 8) is installed in front of the inclined feeder conveyor and advanced for mucking purposes up to roughly 30 m behind the face.

The entire support infrastructure for the drilling and blasting is transported on the suspended backup platform. This includes electrical transformers, compressors, emergency power, shotcrete aggregates, explosive storage containers, crew and foreman lounges, workshop, toilets, utilities, and vent duct storage.

Two different material flows must be coordinated at the end of the platform furthest from the face (Fig. 9). The material for the temporary ground support construction and other work supplies must be transported over the invert construction zone (Fig. 10) and through the equipment-parking zone; this all takes place under the platform and is accomplished with the overhead rail crane (Fig. 9). At the same time the muck must be transported away from the face. A belt conveyor located on top of the suspended platform accomplishes this task; therefore, the muck movement is separated vertically from the parking, storage, and invert construction. At the loading bridge the muck is transferred to the tunnel transport system, which is typically either a muck train with locomotive (Fig. 11) or a muck conveyor system. Either method can be used to complete the movement of the muck to the tunnel portal.

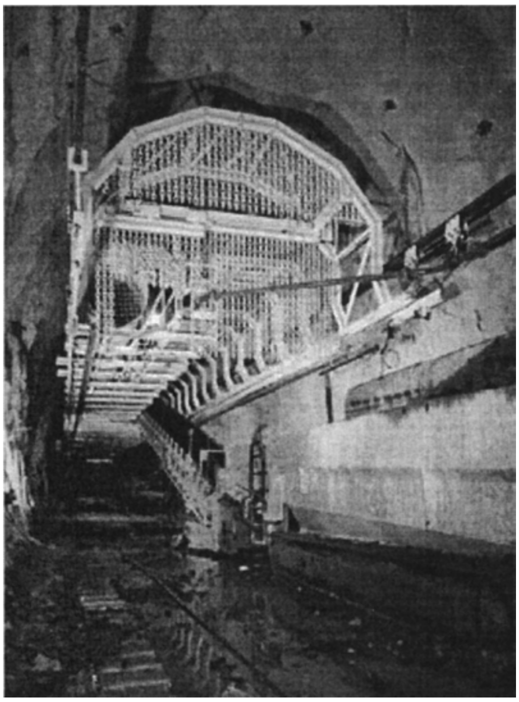

Fig. 8. View of equipment from face of tunnel—rock crusher, inclined conveyer belt hanging chain for fly rock protection

Innovation

Innovations in drill and blast tunneling are subjected to a process involving field trials and development. The following process developments should be pursued in conjunction with the mechanization of drill and blast operations:

- Use of robotic devices for loading explosives;
- Use of robotic devices for placing shotcrete;

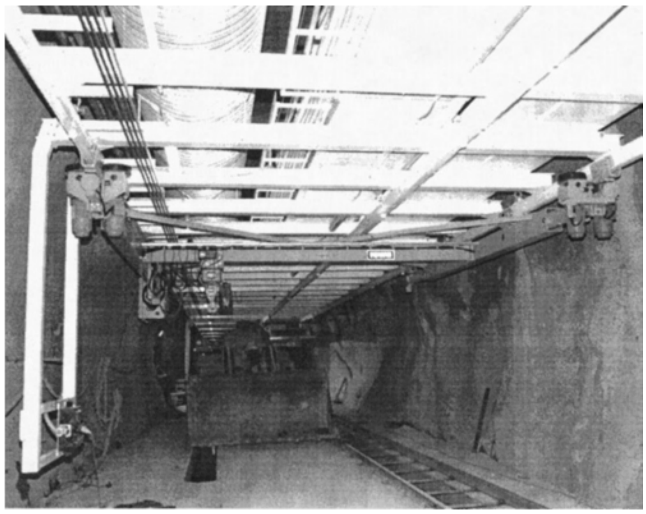

Fig. 9. Handling area under suspended excavation services platform with supply overhead crane mounted ($\sim$5 t) on underside of platform—fixed utility (electrical) supply drop on the left side, drainage slot left center under left edge of loader bucket, and track for supply train lower right.

Fig. 10. Invert excavation, using hydraulic hammer mounted on small excavator boom, taking place underneath suspended excavation services platform

- Use of spray-applied membrane waterproofing systems. The idea of using spray-applied membranes has been advanced and seems to offer particular advantages. The benefit of spray-applied membranes over conventional sheet membrane systems is that high bond strength exists between the concrete layers and the spray-applied membrane. This bond strength allows the structure to practically act as a composite, thereby allowing a reduction in the total lining thickness, while providing protection against groundwater pressure. Unlike conventional waterproofing systems, steel fiber-reinforced shotcrete can be used in all cases in conjunction with the spray-applied membrane system; and
- Use of steel fiber shotcrete for temporary ground support. This could result in an enormous simplification of the working cycle in comparison with shotcrete reinforced with steel mesh, and there would be a significant construction cycle time saving. Steel fiber shotcrete with spray-applied membranes represents a suitable structural system for the single-shell tunnel construction system. These could be applied by robotic placing machines.

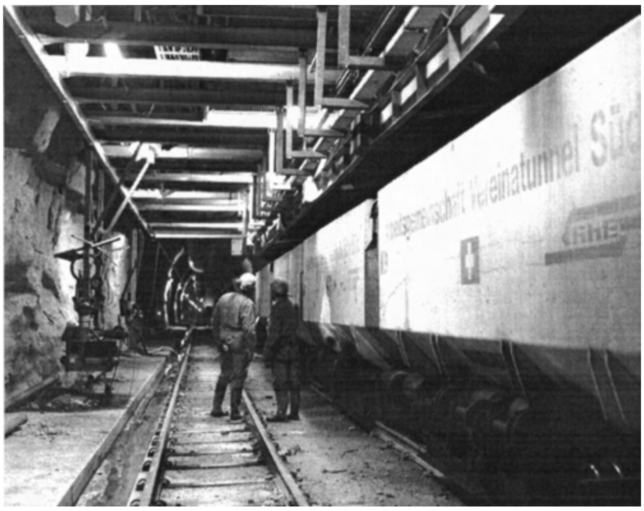

Fig. 11. Loading bridge area with muck transfer from suspended excavation services platform conveyor to muck train

High-Performance Drill and Blast Excavation Concept

On the basis of the successful site experience obtained at the Vereina South and Mitholz projects in Switzerland, backup systems, including platforms, for conventional drill and blast tunnel excavation are being further developed for use in other New Alpine Transit route (NEAT) tunnel projects. This includes two tunnels: (1) Gotthard ~45 km; and (2) Lötschberg ~35 km. With the existing concept, the potential of acceleration of the heading operation is limited. The target of the next development step is to concentrate on mechanizing operations in the heading area. The objective is to attempt as far as possible to execute the different steps of work simultaneously and to optimize the interaction between heading and rear area operations. This ongoing development work is based on the suspended platform concept, the use of mechanized and computer controlled equipment, and the separation of working processes in the heading area.

The starting point for speeding up a blasting cycle requires consideration of all heading operations and how to optimize the total operation. The latest high-performance drill and blast excavation concept developed at the Swiss Federal Institute of Technology in Zurich and presented here is based on the utilization of two backup platforms: (1) a lightweight, high-speed working platform immediately behind the face; and (2) an infrastructure suspended platform further back. Presently available semi-automatic production machines (jumbos, explosive loaders, shotcrete robots) are integrated in the new backup systems concept so that the system efficiency can be increased. So far, such backup systems have proved themselves in tunnel cross sections of up to 70 m^2. These systems seem to be contributing to a considerable increase in performance. In the case of tunnels with excavated widths of less than 7–9 m, the operations of drilling/charging, mucking, and the setting of roof bolts and placing of arches must be carried out sequentially. The invert can be created, as a parallel operation, in the rear area underneath the suspended platform (that is, parallel in terms of both header work and invert work occurring at the same time). What must be done now is to exploit the potential for increasing performance in tunnels with larger cross sections. In the case of tunnels with excavated widths in excess of 9–10 m, the phases in the header and the immediate adjacent area can be executed parallel to each other. Drilling can be carried out in one half of the excavation area while roof bolting is accomplished in the other half. Subsequently the phases are switched and the boreholes charged and made ready for firing. The invert, which serves as transport road in the rear, can be created while mucking material passes overhead on the steel suspended platform.

Apart from distinguishing between large and small cross sections, a division into excavation and support classes must also be undertaken in terms of ensuring that the time related operations are optimized. The subcategories that follow have a decisive influence on the working processes in the face area.

Excavation Category 1

In excavation category 1 [stable-crumbling rock (*Schweizerischer* 1993)], minor to substantial supporting measures have to be undertaken at the face and in the cross section immediately behind the face. For this excavation category the suspended infrastructure platform remains approximately 70 m behind the face. This distance is maintained for blast protection reasons. The high-speed platform in front of the infrastructure platform is provided with multifunctional, high-performance machines for drilling and setting bolts, arches, and suspension rails, and is equipped with a storage area for steel mesh and steel support arches. The high-speed platform is moved back for blasting and forward to the face for installing support systems. During mucking the platform must remain beyond where the excavator is working to remove the muck at the face. An excavator with a front shovel can muck the face in an optimal fashion; possibly it can cope with the muck (excavated cross section $>70\ m^2$). Roof bolts with and without steel mesh are installed in the face area. After mucking, the crusher is drawn back; if needed shotcrete is applied using a robotic vehicle, then the drilling cycle is again commenced. During the drilling operations, secondary bolting and the application of shotcrete and if necessary, spray-applied waterproofing takes place between the two suspended platforms.

Excavation Category 2

In excavation category 2 [low stability (*Schweizerischer* 1993)], massive supporting measures have to be undertaken at the face and in the cross section directly behind the face. The excavation is executed in short lengths or by mechanical means using a hydraulic hammer, cutter head, or excavator shovel.

The infrastructure suspended platform is drawn forward some 50 m behind the face, as there is only limited blast debris and most excavation is by mechanical means. The high-speed platform (approximately 30 m in length) is then moved to within 10 m of the face. Should an advance support using nails or bolts be required, these can be driven or drilled into the face and cross section from the high-speed platform. During mucking, the support arches are preassembled and the steel mesh prepared on the high-speed platform. Should the cross section be sufficiently large, heavy steel can be installed in the other half of the excavation parallel to the extraction side. The high-speed platform is provided with a bolting unit and a small shotcrete manipulator.

The forthcoming penetration of the NEAT, Tavetsch Intermediate Massif North from the Sedrun intermediate point of attack (Switzerland) calls for a smooth transition between drill and blast and mechanized excavation due to the extremely complex geology. The high-performance drill and blast excavation concept with two suspended platforms ensures that the greatest possible rate of advance is achieved. The high-speed platform is devised to cope with both excavation categories. Through compliance with this requirement, the flexibility of this excavation method can be retained through the mechanization of the drill and blast excavation.

Summary and Outlook

The following advantages have already been achieved in comparison with the traditional manual tunneling operations:

- The performance has been increased by 30% due to the cyclical high performance equipment and the suspended platform use;
- Working man-hours in the heading area have been reduced by about 30%;
- Cost has been reduced;
- By separating the transport processes from the working and equipment operation zones, safety has been improved; and
- Progress has been made in reducing heavy manual labor.

The following efforts still have to be made:

- The use of robots and computer-directed machines for what was previously manual labor must be proven to and accepted by management and
- Handling the highly sophisticated machines used in cyclic operations requires a highly trained work force. The qualifications of the work force and the site managers must be raised.

The right steps for industrialization of drill and blast tunneling have been initiated by innovative, specialized, and computer-controlled equipment. Additionally, the application of the suspended services platform has resulted in the separation of simultaneous processes, but the potential for mechanization stills presents many opportunities. It is necessary to increase the mucking performance. Today mucking averages about 300 m^3/h but 500 m^3/h should be achievable. The erection and installation of rock support systems, particularly in arch construction, needs to be accelerated. It is essential to increase the simultaneous operations in the heading and services areas.

In future tunnel work, greater flexibility should be offered at the bidding stage so that responsible contractors can coordinate the required temporary ground support requirements with the design of the services/backup systems. Open team collaboration between planning engineers and the responsible contractors facilitates optimal technical and economic tunnel excavation.

References

Aldrian, W., Melbye, T., and Dimmock, R. (2000). ''Wet sprayed concrete—achievements and further work.'' *Felsbau,* 18(6), 16–23.

Bock, T. (1990). ''Möglichkeiten und Beispiele für Robotereinsätze im Bauwesen.'' *VDI-Berichte Nr. 800*, 137–158.

Girmscheid, G. (1997). ''Rationalisierung und Kosteneffizienz beim Sprengvortrieb durch Teil-Roboterisierung und Innovationen.'' *Sonderdruck anlässlich des 40 jährigen Firmenjubiläums*, MEYCO Equipment, Winterthur, Switzerland.

Girmscheid, G. (2000). *Baubetrieb und Bauverfahren im Tunnelbau*, Ernst & Sohn, Berlin.

Girmscheid, G., and Moser, S. (2001). ''Fully automated shotcrete robot for rock support.'' *Comput.-Aided Civ. Infrastruct. Eng. Mag.*, 16(3), 200–215.

Schweizerischer Ingenieur und Architekten-Verein. (1993). Untertagebau SIA 198, Zürich.

Tarkoy, P. J. (1995). ''Comparing TBMs with drill+blast excavation.'' *Tunnels & Tunneling*, October, 41–44.

Teuscher, P. (2000). ''Hochleistungssprengvortrieb.'' *Tunnel,* 8, 55–56.