TUNNEL CONSTRUCTION
State of the Art and Research Needs
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The Transportation Research Board operates within the Commission on Sociotechnical Systems of the National Research Council. The Board's program is supported by state transportation and highway departments, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 150 committees and task forces composed of more than 1800 administrators, engineers, social scientists, and educators who serve without compensation. The program is supported by state transportation and highway departments, the U.S. Department of Transportation, and other organizations interested in the development of transportation.

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TUNNEL CONSTRUCTION

State of the Art and Research Needs

SPECIAL REPORT 171

TRANSPORTATION RESEARCH BOARD
COMMISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C., 1977
Notice
The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The views expressed in this report are those of the authors and do not necessarily reflect the view of the committee, the Transportation Research Board, the National Academy of Sciences, or the sponsors of the project.

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INTRODUCTION

In 1974 the Transportation Research Board established the Committee on Tunnel Construction to be concerned with all matters relating to the construction of tunnels for transportation. The committee set as its first task the investigation of the state of the art and research needs of underground construction and the preparation of a report of its findings. Committee members prepared a list of the subjects to be investigated and assigned each subject to one who had extensive knowledge and experience in that aspect of underground construction. Those to whom assignments were made were asked to prepare a brief report, no longer than 1500 words, discussing the state of the art and suggesting research that will make underground construction safer, faster, and less costly.

The reports prepared by the 16 authors are the chapters in this report. Although each chapter is the work of the individual author, all members of the Committee on Tunnel Construction reviewed and commented on all chapters. It is not intended that this report should serve as a textbook or handbook on the state of the art of tunneling. Rather it focuses on aspects considered most important by those who have expertise in the areas discussed.

Several authors made similar research suggestions, and these duplications have not been deleted. The committee felt that the repetition served to emphasize the need.

Much of the research suggested in this report is quite costly, involving perhaps millions of dollars. The committee did not answer the question of who would fund the research needed. Many would argue that in the U.S. industrial system the investment in research should come from those corporations or individuals who will profit from the investment.

Manufacturers of automotive and computer equipment spend large sums annually on research to make their products more competitive, and they are able to realize a return on that investment quickly from their high-volume sales. The experiences of these mass production industries, however, are usually not similar to those of the contracting or equipment manufacturing industry.

A company that fabricates tunnel mucking machines cannot afford to invest much in research because such an investment has little prospect of recovery in increased sales and lower production cost. When the annual sales potential is only 15 mucking machines that must be built to order, the cost is much higher than that of mass-produced machinery. The same situation prevails for other large machines such as tunnel boring machines. Smaller units such as drills, cutting tools, and pumps, however, wear rapidly and continually require replacement parts. Therefore, expenditure of research funds by these manufacturers can be justified.

A contractor can also not afford to invest much in research. Each contracting job is different from the previous one, and the job being performed may never be repeated. A chance for future profit based on current investment and experience seldom exists. Moreover an innovation used on a job is often copied by a competitor to underbid on the next one because patent laws are ineffective and the nature of contracting prevents the development of trade secrets as is effectively done in other businesses.

These considerations suggest that much of the needed research effort in underground construction must be funded with public money. That suggestion is given added weight by the fact that underground construction is usually a public effort (and an expensive one), and economies developed through research accrue to the public good.
STRUCTURAL SUPPORTS

Samuel Taradash, Underground Supports Division, Commercial Shearing, Inc.

STATE OF THE ART

Structural support in a tunnel maintains a stable, usable, and economical underground opening and prevents settlement in the surrounding media or adjacent structures. Design of supports has depended to a great extent on the ability of the designer to convert meager geologic data into practical information for use by contractor and supplier. Existing design procedures still depend greatly on empirical data and the judgment of a knowledgeable designer. To design the required structural supports, the designer must consider

1. Media through which tunnel is to be driven,
2. Method of excavation,
3. Function of support (primary or secondary support or both),
4. Time of support installation, and
5. Method of load imposition (expansion, grouting, blocking, or other means).

Only when the total system of construction is considered can the proper structural support be provided. Some structural supports in use are discussed below.

1. Timber sets are used primarily today in mines and in locations where timber is plentiful. Steel rib sets have replaced timber sets in practically all other instances.
2. Pans (cast or ductile iron) were developed for use with shield-driven tunnels. Welding and improved manufacturing techniques, together with the use of flexible liners, have limited their use.
3. Roof bolts were originally developed for mine roof supports. The wedge type was first used, the expandable was then used, and now the chemically or cement grouted is used. Often used in conjunction with shotcrete or gunite, roof bolts provide an economical support for proper rock conditions.
4. Steel ribs are probably the most popular tunnel support system in use today. This system is adaptable to changing ground conditions and conformable to practically any shape or size of member.
5. Pressed metal plates, commonly referred to as liner plates, are used generally in small tunnels, soft ground, and hand-mined operations. They have been used in conjunction with shields. More recently, gasketed liner plates have permitted temporary linings to be installed watertight.
6. Fabricated steel pans were first used on the land approaches for the Detroit River vehicular tunnel. Improvements in fabrication procedures and development of waterproofing methods have made this type of support acceptable. It is used today in conjunction with tunnel boring machines as a final lining in rapid transit tunnels.
7. Shotcrete provides an economical support where ground conditions permit. It can be used either alone or in conjunction with roof bolts or steel ribs.
8. Precast concrete segments are used in conjunction with the tunnel boring machine, frequently as a temporary lining. Waterproofing methods are now available to permit their use as a final lining.

Because they can advance rapidly, tunnel boring machines in use today have reduced tunnel costs and made tunneling a more accepted construction mode. Their progress is usually impeded, however, by the backup systems such as muck removal and installation of structural supports. The development of improved support techniques should not be the sole responsibility of suppliers and contractors. If so, only slight improvements will likely be made in existing methods when large advances are needed in the areas of new materials and better design procedures.

FUTURE RESEARCH

Geological Data

More accurate and complete data are needed to help eliminate underground surprises. Any support system must be adaptable to changing ground conditions. However, because of the time necessary to design, receive approval, fabricate, and install a support system, it cannot be changed from day to day. Research is needed to provide better or improved information for support design as well as to verify existing methods of design.

Demonstration of New Methods

Innovations in design methods and types of supports should be tried in a full-sized tunnel. A research program, part of a proposed tunnel system, could be the proving ground for support systems as well as the muck removal system. In addition to the testing of different support materials and concepts, the flexible or interaction design concept could also be verified to permit both primary and secondary supports to be designed more economically. Stimulus might thus be given to the increased use of tunneling as a construction mode.
Mechanical Loading of Explosives

One of the factors that increase labor costs in tunnel construction is the number of workers required to hand place and tamp the explosive charge. Machines to place the charges could result in significant savings in labor cost and loading time.

Hydraulic Drills

Manufacturers have recently introduced hydraulically powered drills and impact breakers that give great promise of success. Perhaps further experimentation with combinations of percussion drills and impactors of expansion breakers will lead to a new rock-breaking technique that will eliminate the need for explosives.

Smooother Excavation

One of the advantages of machine excavation is the elimination of overbreak. The removal of unnecessary material beyond the required excavation lines increases the cost for labor and ground supports and especially adds to the cost of concrete lining required to fill those unwanted spaces. Further research is needed in methods to permit better control of overbreak.

Faster Muck Removal

Little improvement has been made during the past 40 years in mucking machines. Faster production could undoubtedly be obtained by introduction of already known principles to tunnel excavation. Use of hydraulically powered and more compact shovels could result in faster and less costly handling of materials in underground excavation.

Labor Efficiency

A program of education and improved relations between employer and workers is needed to increase labor efficiency, improve safety, and reduce costs. An objective study should be made to determine the optimum number of workers required for various tunneling operations. Part of the high costs of underground excavation results from requirements of union management that more workers be employed than needed for efficient and safe operations with today’s equipment.

Measuring Surface Vibrations

Vibrations at the surface of the ground are caused by blasting for rock tunnels. The character of these vibrations cannot now be accurately predicted, and a measurement method is needed, particularly when blasting occurs under densely populated areas.
STATE OF THE ART

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MACHINE TUNNELING

J. D. Jacobs, Jacobs Associates

STATE OF THE ART

Machine tunneling, as used in this discussion, refers to underground excavation whereby the ground in its original state and position is disintegrated by milling, scarifying, or crushing with a power-driven tool. Several types of tunneling machines are in use today. These include the well-known "mole," which uses a rotating cutter head to bore a circular tunnel; the road-header machine, which has a smaller rotating milling head mounted on a randomly controlled boom; and the powerful backhoe excavator-scarifier, which is also mounted on a boom, the motion and position of which are controllable from an operator's station.

Excavation of rock by milling is not a new concept. In 1880 an Englishman by the name of Beaurnount designed a machine that successfully bored 3.2 km (2 miles) of a tunnel 2.1 m (7 ft) in diameter through chalk for investigation of the proposed Channel Tunnel. During the 1920s, the coal mining industry did a considerable amount of experimental work with continuous mining machines, most of which incorporated the principle of the chain saw.

In 1947, James Robbins, a mining engineer, designed a continuous mining machine based on the idea of using roller cutters to operate on the outstanding rings of coal left in the face between the grooves or kerfs formed by the drag bits.

In 1952, Robbins, working in conjunction with Mitty Construction Company, built a tunneling machine for boring the 7.8-m (25 2/3-ft) diameter diversion tunnels for Oahe Dam on the Missouri River in South Dakota. The material there was Pierre shale, a soft rock quite similar to the Bearpaw shale, which had been successfully cut with coal saws at Fort Peck Dam several years earlier. That machine made a good record, advancing as much as 49.1 m (161 ft) in a single day. It proved that soft rocks could be excavated with a continuous boring machine and was so successful in the shale at Oahe Dam site that, before that project was completed, subsequent contractors on later tunnel contracts there purchased three more boring machines of similar design.

Moles are today the most commonly used tunneling machine. Improvement in roller cutting wheels has constantly progressed until it has become possible to cut rock whose strength is 207 MPa (30 000 lb/in²) or more. As rock strength and hardness increase, however, the cost of tool replacement rises steeply and the rate of advance decreases.

The rotating head machine requires that a great thrusting pressure be applied to the rock face. This thrust is accomplished by use of hydraulic cylinders bearing on gripping devices against the tunnel perimeter or against structural tunnel supports that are erected as the bore progresses. When boring under favorable conditions, a mole is capable of average sustained advance rates of 1.5 to 3.0 m/h (5 to 10 ft/h). Record 24-h runs of 91.4 to 121.9 m (300 to 400 ft) have been reported.

There have probably been more than a hundred types of mole tunneling machines designed, fabricated, and put into service throughout the world since the first one at Oahe Dam in 1954. The art is developing rapidly.

Foreign manufacturers of these machines have reported success in recent years with fully shielded machines using precast concrete segments for tunnel lining in badlyfaulted and decomposed granite rocks where the conditions may change abruptly from fresh hard rock to running ground or to a mixed face of hard and soft rock.

The road-header machine has had greater acceptance in Europe than in America. It consists of a rotating milling head studded with hard-faced teeth or picks. The head is on the end of a hydraulically positioned boom capable of applying the cutter to any desired spot on the face or perimeter of the chamber. The machine, usually mounted on crawlers, is strongly powered and can exert great pressure between the revolving wheel and the rock. Fragments that are removed by the cutter fall to the floor and are removed by means of a mechanical gathering device feeding a conveyor. Road-header machines are capable of excavating soft and medium rocks with strengths to 138 MPa (20 000 lb/in²).

Random arm backhoes have been used successfully on several American tunnel projects. This type of excavator can only be used in ground that can be ripped. When working in suitable formations, the ripper-backhoe machine is often capable of rapid advance because its digging bucket becomes an effective tool for gathering and removing the loosened muck.

FUTURE RESEARCH

Bits and Rollers

Considerable private investigation has been and will continue to be done into effectiveness of cutting bits and rollers. Sufficient potential for profit probably exists to make such research worthwhile to a manufacturer. Additional publicly funded studies might contribute toward faster production and lower unit cost of cutters.
Working Face Access

Tunnel boring machines tend to perform well as long as they are penetrating uniform material free from geological abnormalities or excessive inflows of water. Characteristically, however, the interception of bad ground by machines that are designed for use in good, self-supporting rock causes a cessation of machine boring and initiation of conventional hand-mining methods. Most boring machines are concentrated masses of machinery that occupy the entire tunnel cross section and effectively block access to the face when new excavating methods must be adopted. Attention might be directed toward rearrangement of the machinery for easier access to the working face.

Ground Sensing Studies

Knowledge of ground conditions in the region ahead of the face is important. Drilling of advance exploratory holes is slow and costly. More studies should be carried out into sensing of ground conditions by electronic or other subtle physical means.

Machine Versatility

General purpose tunnel boring machines will likely be developed that can cope with practically any ground condition. The urgency of geological prediction will thereby be reduced. Researchers should strive to improve machine versatility.

Slurry Use

In Japan, England, and Germany, a considerable amount of development work has been done on tunnel boring machines that use slurry within a confined space surrounding the cutter head. The Japanese have had experience with many of these units and have reported performances as high as 276.5 m (907 ft) of a tunnel 5 m (16 ft 7 in) in diameter in 1 month. No machine of this type has been built or used in the United States.

Concrete Segment Liner

In the United States, no soft ground tunnel has been constructed in which precast concrete segments are used as a final liner. Other countries have all but standardized on this type of support. American engineers should be encouraged to examine this type of construction.

Flexible Tunnel Size

Many people have recommended that tunnels be standardized in size. Perhaps the better approach would be for design engineers to consider accepting flexibility in tunnel size rather than standardization. As an example, the designer may require a tunnel with a minimum diameter of 3.8 m (12½ ft), but would be willing to accept a larger diameter at the option of the contractor up to, say, 4.3 m (14 ft) in order to obtain a low bid from the contractor who has a tunnel boring machine capable of achieving a 4.2-m (13 3/4-ft) diameter hole.
MATERIALS HANDLING

P. E. Sperry, Consultant, Woodland Hills, California

STATE OF THE ART

Choice of a materials-handling method to be used on a particular tunnel project depends on type of access, size and slope of the tunnel, and material to be excavated. Access during the tunneling operation can be either horizontal through a portal or vertical through a shaft. Transportation tunnels are seldom smaller than 5.2 m (17 ft) in diameter, so large materials-handling units are usually used, although small units are commonly used in soft ground tunnels driven by use of shields. Grades vary from level to 5 percent. Transportation tunnels built under major cities are often in soil, but many tunnels in rural areas penetrate the rock cores of mountain ranges.

Tunnel construction does not exclude any materials-handling techniques commonly used in the construction industry. Prime considerations in the choice of a materials-handling system are economy, reliability, extensibility, and redundancy. Redundancy as used here refers to use of reserve or back-up units to prevent production delays due to breakdowns.

There are five general systems for removing excavated materials from tunnels: Rubber-tired trucks (both self-loading and separately loaded), rail mounted equipment, and conveyors are used for horizontal transport, and hoisting is used for vertical transport.

Self-loaded rubber-tired trucks, commonly known as load-haul-dump units, carry 3.1 to 7.6 m³ (4 to 10 yd³) of material at 6.4 to 16.1 km/h (4 to 10 mph). Separately loaded trucks carry 4.6 to 15.3 m³ (6 to 20 yd³) at 8.0 to 24.1 km/h (5 to 15 mph). Haul speed in both cases is governed by the smoothness of the roadbed. Neither type is limited by grades normally encountered in transportation tunnels. The separately loaded units are usually top loaded and have front-end loaders of 1.5 to 3.8 m³ (2 to 5 yd³) capacity that run on rubber tires or crawler tracks.

In order to pass, the larger units require a width of about 9 m (30 ft). Thus, widened areas must be excavated in single-lane tunnels. Rubber-tired units are seldom used in tunnels with circular inverts because of the extensive overexcavation required for passing. Economics usually limit the use of rubber-tired haulage to tunnels less than 1219 m (4000 ft) long.

Rail haulage is almost always used in long tunnels and in tunnels with circular inverts. Locomotives of 4.5 to 22.7 Mg (5 to 25 tons) haul 1.5 to 11.5 m³ (2 to 15 yd³) muck cars on 27.2 to 36.3-kg (60 to 80-lb) rails laid on 6096 to 10 668-mm (24 to 42-in) gauge at speeds of 8.0 to 24.1 km/h (5 to 15 mph). Haul speed is greatly dependent on the quality of the track. Grade is limited to less than 3 percent with short stretches of 4 percent. Rubber and rail haulage systems both require redundant loading and hauling units.

Reliability is usually lowered when a conveyor is a component of the loading unit. Conveyors are components of many muck-removal systems: overshot loaders, tunnel boring machines, and muck car-loading equipment behind the boring machines. Conveyors are seldom used as the only muck-removal method in tunnels. The high capital investment required and the difficulty of extending the system as the tunnel advances limit the applicability of conveyors.

Hoisting with wire rope is the method most often used for vertical transportation. With vertical hoisting, the material must either be transferred from its horizontal haulage units into skips; or the haulage units themselves can be hoisted. Surge capacity may be provided by dumping into a pocket that in turn dumps into the skip. With rail haulage, the muck car boxes sometimes are hoisted, either with or without the undercarriage and wheels. Shaft size limitations usually require that only one skip or car be hoisted at a time. Lifting capacity usually varies from 3.1 to 11.5 m³ (4 to 15 yd³). Most safety codes permit hoisting with a crane from depths of 21.3 to 30.5 m (70 to 100 ft), but require fixed guides for deeper shafts. Falling materials make shaft work hazardous.

In addition to the removal of excavated material, workers and many other materials must be transported in the tunnel. Large groups of workers are commonly transported in trucks or rail cars fitted with seats and a protective canopy. Small groups use pickup trucks or ride the locomotive. Materials that must be transported include tunnel supports, utility pipes, track supplies, tools, electrical cable, drilling and blasting materials, concrete, and formwork. These are commonly hauled on flatbed trucks or rail cars except fluid concrete, which is either hauled in special vehicles or conveyed through a system of pipes.

Conway mucker in tunnel (photo courtesy of Goodman Equipment Corporation).
FUTURE RESEARCH

Shaft Transportation

Access to transportation tunnels in urban areas is usually through shafts, which have been materials-handling bottlenecks for years. A continuous method of muck removal up shafts is especially needed. If the shaft occupies a small area, workers and materials can be transported by conventional means. Transfer from the horizontal haulage system and surge storage must be considered.

Rail Haulage

On tunnel jobs today, rail is the most economical means of transporting large volumes of material over an extensible system. Rail and haulage consumes one-eighth the energy and perhaps one-quarter the manpower that is used for rubber-tired haulage. Although properly designed and maintained rail-haulage systems can keep pace with present excavation rates, higher speeds and greater reliability will be needed in the future.

Mucking

Muck loading in conventionally drilled and blasted tunnels consumes an inordinate proportion of the excavation cycle. Equipment reliability and redundancy are often low.

Metallurgy

High wear rates on loading points, wheels, tracks, and bearings contribute to low reliability in all systems. Tunneling technology constantly pushes metals to the limits of shock and abrasion resistance.

Conveyors

Because conveyors provide zero redundancy in many materials-handling systems, their reliability is extremely critical. Conveyor downtime delays tunnel advance. Excavation would be greatly improved if conveyors were more reliable, were more readily extensible, and could carry muck up the shafts.

Pipelines

Pneumatic and slurry pipelines are excellent means to convey fine materials. Pipelines to handle tunnel muck deserve research, especially in the direction of ease in extensibility.
TUNNELING IN BAD GROUND

Norman A. Nadel, MacLean Grove and Company, Inc.

STATE OF THE ART

When tunnelers use the designation "bad ground," they are referring to ground that has adverse geological characteristics that make optimum construction progress impossible. In rock tunnels, these negative characteristics include

1. Rock that is badly fractured and jointed;
2. Rock that is disintegrated;
3. Rock that is subject to chemical or physical change or both in the presence of air and water;
4. Squeezing rock that tends to move under pressure into the excavated space;
5. Swelling rock that is a combination of rock of items 3 and 4 in that an actual increase in volume results from exposure to air or water;
6. Running ground or material that is so finely divided that, under action of water and ground pressure, it actually flows into the excavated space;
7. Physical conditions that permit large inflows of water to enter the tunnel; and
8. Explosive or poisonous gases.

If rock is badly fractured, jointed, or disintegrated, support must be installed immediately, and the length of round must be reduced. Measures must often be adopted to inhibit the caving of the face. Because of the need to continually excavate at the face, supporting the face presents a different and more difficult task than supporting the tunnel perimeter. A variety of techniques have been developed to temporarily support the face or a portion of it. This is usually accomplished in an earth tunnel by a shield at the front of which are mounted breast jacks. As the shield is shoved ahead, the jacks provide constant pressure on the face supporting it. In a rock tunnel, the tunnel boring machine provides the pressure on the face to support it. Unfortunately, in most cases in which the ground is bad enough to require face support, the tunnel boring machine is not an effective tool to excavate the tunnel.

Effective face support is difficult to provide in a rock tunnel that is being excavated by drilling and blasting. A breasting jumbo has been used in some instances, but the procedure commonly used entails the mining of the tunnel in several passes or drifts. The area of the exposed face is thus minimized, and the excavation of the tunnel is facilitated. Although this procedure provides the most safety, it is obviously time consuming and is therefore expensive.

Large inflows of water or the presence of explosive or poisonous gases can stop tunnel excavation altogether until the ground can be grouted to seal the fissures through which the water or gas is flowing.

In soft ground tunnels, groundwater most often creates bad ground. In the presence of any appreciable head, water will usually flow into the tunnel and will carry soil with it unless measures are taken to prevent the flow. If water is permitted to flow into the tunnel carrying soil with it, subsidence of the ground surrounding the tunnel will result and, in most cases, substantial damage will be incurred.

The flow must be prevented and can be accomplished in several ways. The first and most common way is to predrain the ground or dewater. A variety of techniques can be employed depending on the geological conditions. If the soil is relatively impervious, predrainage may not be feasible. Fortunately, except for soil materials of low shearing strength, the impervious nature of the soil will itself usually ensure that there is no major flow problem. Predrainage can be relatively difficult, if not impossible, if within the cross section of the tunnel there are pervious soil materials overlying impervious soil materials or rock.

Another way to deal with groundwater is to use the compressed air or plenum process. This involves the introduction of compressed air into the tunnel at a pressure sufficient to balance the head of the groundwater. Because of labor union, legal, and medical restrictions with respect to working hours and decompression times for workers, this method can be costly. Another disadvantage of using compressed air is the potential health hazard to the compressed air workers. In recent years progress has been made with respect to the reduction of this hazard mainly by increasing decompression times.

The presence of undesirable gases such as methane or hydrogen sulfide is common in soft-ground tunnels, particularly in tunnels driven through ground of organic origin. Because of the danger of explosion, poisoning, and asphyxiation, measures must be taken to normalize the tunnel atmosphere. The usual procedure to accomplish this is to provide large quantities of ventilating air to keep the concentration of gases low.

All cases of bad ground whether in rock or in earth are more effectively dealt with if the existence of negative characteristics is known before work starts. Equipment and methods can be selected and devised to deal with the conditions or combination of conditions that will be encountered. If encountering bad ground is a surprise, then the work may have to be stopped and the methods and equipment, and perhaps the contract under which the work is being performed, may have to be modified.

FUTURE RESEARCH

Geological Exploration

The ability to predict the presence of bad ground is important so that the element of surprise is eliminated and proper plans can be made to deal with the bad ground. Improvement in present techniques and development of new techniques for exploration and interpretation are needed.

Equipment for Use in Bad Ground

Tunnel boring machines are most effective and productive in reasonably uniform ground conditions. Often in bad ground, the boring machine cannot excavate properly and gets in the way of conventional equipment that can work more effectively in bad ground. If boring machines can be
developed that can operate efficiently in both good and bad ground, considerable savings will be realized.

Ground Stabilization

Bad ground can often be stabilized by means of chemical consolidation or ground freezing, but these procedures are expensive and time consuming. Research directed toward reducing the costs and improving the technique can be rewarding.

Face Stabilization

If a method or technique can be developed by which the face can be quickly treated from within the tunnel to make it sufficiently stable to stand unsupported for the relatively short time necessary between blasts, material savings in time and cost can result.
SHIELD-DRIVEN TUNNELS WITH OR WITHOUT COMPRESSED AIR

Robert S. Mayo, Mayo and Associates

STATE OF THE ART

Operating under compressed air is an essential method for construction of subaqueous tunnels and those passing through silt. Tunnels penetrating water-bearing sand or gravel may also require compressed air, unless the water table can be lowered by drainage. In the Chicago and Detroit areas, compressed air is used to support the ground in impervious clay and, sometimes, to prevent the entrance of explosive gases.

The following discussion of major shield-driven tunnels describes the state of the art, the problems, and the imposed restraints. No one method is considered to be best, for the method used will depend on specific project conditions, which vary widely.

The initial Chicago subway system was built in the period from 1938 to 1943 and was 12.4 km (7.7 miles) in length. The single track horseshoe tunnels, about 7 by 7 m (23 by 23 ft) in cross section, passed through a soft impervious blue clay. All were hand mined, except for that section under State Street where a shield was employed. Compressed air was specified, and most contractors carried 82.7 to 103.4 kPa (12 to 15 lb/in²). Little water was encountered in this ground and little, if any, explosive gases.

The Chicago tunnels were 13.1 m (43 ft) below the surface, which gave about 6 m (20 ft) of cover. Since this ground weighed 1782 kg/m³ (110 lb/ft³), the weight on the roof was about 106 kPa (2200 lb/ft²). Thus, an air pressure of 103.4 kPa (15 lb/in²) was equivalent to the weight of the ground. Liner plates and steel ribs were specified. Most contractors concentrated every other day so that the ribs and plates only supported the ground for 24 h. Since the pressure was less than 103.4 kPa (15 lb/in²), medical locks were not specified or installed and, as far as can be ascertained today, there was not a single case of the bends.

There are nine vehicular tunnels under the Hudson and East Rivers in New York, all shield-driven with compressed air. The primary lining consisted of cast iron segments 9.4 m (31 ft) OD, with a shove of 7620 or 8128 mm (30 or 32 in). These tunnels had a secondary lining of concrete with tile finish.

There are about 30 additional railroad and rapid transit tunnels under the same rivers. The outside diameter varies from 5.1 m (16 ft 7 in) to 7 m (23 ft). The rapid transit tunnels are 5.5 m (18 ft) OD. These all have a primary lining of cast iron of the "heavy" type with a web thickness of 35 mm (1 3/8 in) and no secondary lining. The shove in all cases was 7620 mm (30 in). Air pressure averaged about 158.6 kPa (23 lb/in²) with a maximum of 275.8 kPa (40 lb/in²).

The Bay Area Rapid Transit (BART) system in San Francisco is 120.7 km (75 miles) long with 30.6 km (19 miles) in subway. This includes 5.8 km (3.6 miles) of the Trans-Bay section, which was built by sunken tube methods. Fabricated steel plates furnished by the owner were used in the 12.9 km (8 miles) that were shield-driven. These segments were 5.3 m (17 2/3 ft) OD with 1524-mm (6-in) ribs and designed for a 7620-mm (30-in) shove. These plates were sprayed in the shop with a coal tar epoxy. Later a cathodic protection system was installed to prevent erosion of the plates by stray electrical currents.

On the Oakland section of BART, specifications required that the contractor install a complete compressed air system before beginning work. This included steel bulkheads, man and muck locks, and the compressor plant. All these tunnels, however, were eventually built in free air. In San Francisco, the specifications also required the installation of compressed air equipment. The section under the lower end of Market Street to the Ferry Building was driven under an average pressure of 103.4 kPa (15 lb/in²), except that, when the connection was made to the Trans-Bay Tube, the air pressure was raised to hydrostatic pressure of 241.3 kPa (35 lb/in²). One other shield-driven tunnel on the San Francisco side required compressed air for a short distance.

The rapid transit system for the Washington, D.C., metropolitan area will be 157.7 km (98 miles) long, of which 75.6 km (47 miles) will be in tunnel. Work began in 1980, and trains started running on a portion of the system in 1978. All the soft-ground tunnels are being shield-driven. Most of the contractors are using rib-and-wood lagging with an outer diameter of 6.1 m (20 ft). These have 1524-mm (6-in) wide flange beams at 1.2-m (4-ft) centers and 1524-mm (6-in) wood lagging. The lagging is being expanded as soon as it leaves the tail of the shield to eliminate or reduce settlement due to the tail void. There will be a secondary lining of concrete to give a 5-m (16 1/2-ft) inside diameter as required for trains to pass.

Other contractors are using a fabricated steel segmented lining identical to those used in BART. One contractor is installing segments of ductile cast iron to give a 12 192-mm (46-in) shove. These primary linings of fabricated steel and cast iron do not require a secondary lining.
FUTURE RESEARCH

Safety Regulations

The regulations of the Occupational Safety and Health Administration for tunnel construction by means of compressed air are strict. As a result, many tunnels that should be driven under compressed air are bullheaded through by crude and dangerous methods. This should be given further study and then discussed with OSHA with the possibility of modifying the regulations for work performed in "mild" air [less than 101.4 kPa (14.7 lb/in²)].

Tail Void

The tail void is now first filled with pea gravel and then by low pressure grout. Methods are needed for filling the tail void more quickly and more effectively. Perhaps a foam or expandable slurry might be discovered.

Tail Seals

Many shields have been equipped with rubber tail seals to prevent grout, pea gravel, or water from running back into the shield. This has not been too successful because the seal becomes "frozen" into the grout, is torn off, and is nearly impossible to replace. An improved seal is needed.

Precast Concrete Segments

Precast concrete segments have been widely used in Europe, Japan, and Mexico, but have not been so widely used in this country. A precast concrete primary lining should be developed that would be reasonably watertight and would require no secondary lining.

Extruded Concrete Lining

In a tunnel project constructed several years ago in Buenos Aires, a shield was jacked against the still-liquid concrete that effectively filled the tail void. This scheme worked successfully and should be studied. No secondary lining was required.

Backhoes

Many shields, designed for hand mining, are equipped with a backhoe to break down the face and pull the muck back onto the loading conveyor. A more efficient backhoe is needed to improve the rate of progress in shield-mined tunnels.

Smaller Subway Cars

Rail rapid transit systems in San Francisco and Washington, D.C., use a subway car that is 3.2 m (10½ ft) wide and requires a tunnel with an inner diameter of 5 m (16½ ft). Cars in Chicago are 2.8 m (9½ ft) wide, and cars in Montreal are 2.6 m (8½ ft). Small U.S. cities cannot anticipate crowds as large as those in big cities and should, therefore, consider using narrower cars. Since the cost of the shield-driven tunnel varies with the square of the diameter, a smaller car could mean substantial savings. Car builders should be encouraged to prepare designs for such a car.
LONG-HOLE DRILLING IN ADVANCE OF TUNNEL PENETRATION

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STATE OF THE ART

Increasing attention is being given to the drilling of horizontal exploratory holes ahead of tunnel excavation so that geological conditions ahead of the advancing face can be known and proper methods and procedures can be set up to handle the excavation, support, and safety of the tunnel. When initial tunnel investigations are inadequate, the need for long-hole drilling is greater for dependable predictions of ground conditions to be encountered during excavation. Even with the best geologic exploration, pinpointing unusual hazardous conditions is difficult. Some conditions that may not show up in initial exploration are fault zones, squeezing or swelling ground, running ground, water, and gas. In addition, proper ground support procedures and methods may not be possible to establish.

At present long-hole drilling is done through the tunnel face or from a cut-out in the side or back of the tunnel. In a tunnel being driven by drilling and blasting, long-hole drilling can be performed from the jumbo during the drill cycle, or it can be done on weekends or on days that the tunnel is not being worked. Both of these methods contain undesirable aspects. Drilling from the jumbo cannot be done far enough ahead of the tunnel face to allow time to properly analyze the conditions to be encountered. Drilling on weekends is expensive, requiring extra backup crews and overtime payments, and cannot be done far enough to stay ahead of tunnel excavation during the ensuing week.

In mechanical driven tunnels, long-hole drilling is done when the mole is not advancing or is done on weekends. The footage drilled during mole shutdown or on weekends is not so effective because of the rapid advance in a mechanically bored tunnel.

Drilling from a niche cut in the side or back of the tunnel can continue independent of the tunnel advance. In a mole-bored tunnel, it is extremely difficult with the present state of the art to keep ahead of tunnel advance and maintain accuracy of hole alignment.

Present methods for drilling long holes in tunnels include

1. Percussion machines, which use jointed steel and take sludge samples;
2. Rotary-percussion machines, which use a diamond drill type of flush jointed rods and take sludge samples; and
3. Diamond drills, which use flush jointed rods and take either sludge sample or core or both.

FUTURE RESEARCH

Faster Drilling

Increased ground penetration with reasonable accuracy by either core drill or plug drilling is important so that tunnel progress is not delayed and yet information is available in enough time to make proper decisions.

Smaller Drills

A smaller drill is needed that could be set up close to the tunnel rib and would not require excessive extra excavation.

Geophysical Methods

Tunnel engineers are failing to take full advantage of geophysical methods. They can be used in drilling long holes from the tunnel face, side wall advance drilling, or drilling holes from the surface. The correlation of geophysical methods from surface and underground holes can be of great help in determining ground conditions ahead of tunnel advance.

Long-Hole Drilling From Moles

Manufacturers of moles should design their machines to allow a center hole so that drilling can go ahead as a separate operation from mole advance. The advantage of the center hole is that the long hole can be drilled a great distance ahead of tunnel advance and the drilling will not interfere with tunnel advance. The long hole could be used for grouting a bad ground area ahead of mole penetration.
CONTRACTUAL RELATIONS IN TUNNEL CONSTRUCTION

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STATE OF THE ART

Most tunnels are constructed by contractors according to plans, specifications, and contract documents prepared by professional engineers. Because ground conditions can be quite variable, the engineer usually designs several cross sections for the tunnel supporting system or the shape of the tunnel or both. Usually an effort is made to estimate the amount and the type of temporary and permanent support required. Alternate methods of support are frequently designed and allowed for in the bid schedule.

The actual amount of support may differ widely from that contemplated before the start of construction and has been found to vary by more than 100 percent from the estimated quantities. Sometimes the engineer will include in the bid schedule larger quantities of support items than may be required to ensure that the work will be completed within the estimated time. On the other hand, the engineer may underestimate the amount of support required because of inadequate knowledge of the ground conditions. In either case, substantial variations in quantities often lead to claims by the contractor. If the amount of support is underestimated, the result can be higher prices and costs to the owner.

Contract documents usually include or make reference to geological reports and drill logs so that the contractor will have all the information available to the engineer. Occasionally, all data are not made available to the contractor before bids are taken, and such cases frequently result in claims that have disastrous results to the owner. Most contract documents provide for adjustment to the contract price if changes are made in the contract or if changed conditions are encountered as the work progresses.

Because of safety requirements, the final decision as to whether to use temporary support and how much is usually left up to the contractor. If the contractor has a profitable price on support items, the temptation is to use more support rather than less, sometimes considerably more than necessary.

A certain amount of overbreak is bound to occur in tunnels driven by drilling and blasting. Additional overbreak results from the configuration of joints in the rock and the manner in which the work is performed, including the time of placing temporary supports. Attempts by the engineer to control overbreak include the specifying of a maximum pay line, a minimum line within which there may be no rock protrusions, and the payment for concrete at bid prices to the nearest line only, sometimes with allowance only for the materials cost of cement or aggregates or both for filling the overbreak.

Contracts may be of the following types.

1. The unit price is the base for most tunnel contracts, i.e., a price per cubic meter for excavation and concrete, a price per kilogram for steel tunnel support, a price per cubic meter for grout, and so on. If the type of ground to be penetrated and the amount and type of support can be forecast with reasonable accuracy, this type of contract can be used to good advantage.

2. The lump sum contract can only be used if thorough exploration is made before bidding or the geology is well known so that the quality of the rock to be penetrated is understood before work is started. This type of contract may be in the form of a price per meter of tunnel, including temporary support and permanent lining. This latter type of contract puts the entire burden of cost of overbreak and support on the contractor. It eliminates the concern of the engineer about the use of too much support but can result in excess cost to the owner if actual support used is less than the parties to the contract assumed to be required and can still result in claims for overruns.

3. The cost plus fixed fee type of contract eliminates the problem of changes and changed conditions but provides no profit incentive to the contractor to reduce costs to the minimum.

4. The target estimate type of contract requires the contractor and the engineer to agree on a target estimate of cost and a base fee. The base fee is increased or decreased by the contractor sharing in a percentage of the cost savings or overruns; maximum and minimum limits are placed on the amount of fee to be paid. This type of contract is useful if contracts are to be negotiated rather than awarded on the basis of competitive bids or if plans are not fully developed. Since the estimate can be modified from time to time as the plans are completed, the contractor has almost the same incentive as on unit price or lump sum work to keep the costs as low as possible, and the owner is assured of reasonable costs if a competent contractor is selected. It largely avoids the unpleasantness of claims.

Further information on tunnel construction contracts is contained in a report, Better Contracting for Underground Tunnels, prepared by the U.S. National Committee on Tunneling Technology and published in 1974 by the National Academy of Sciences.

FUTURE RESEARCH

Payment for Overbreak

Payment or nonpayment for overbreak has been handled by different owners in many different ways in an effort to reduce its impact on costs. Research into the results of the various methods could help in developing the best approach to this problem.

Amount and Type of Temporary Support

No satisfactory solution has been found for controlling the amount or type of temporary support in tunnels and at the same time satisfying all concerned that safe conditions exist with limited support. Research is needed to develop contract terms that would protect the contractor and at the same time make it profitable to use the most inexpensive type of support that would produce safe working conditions.
Bidding Arrangements for Temporary Supports

Bid quantities for temporary support items, because of alternate types, are difficult to accurately determine before construction starts. Research is needed to develop better arrangements for bidding and controlling the use of these items. For example, an incentive might be given to the contractor for underruns in the amount of support used.

Comparison of Original and Final Costs

A research study of the various types of contracts that have been performed would help in determining the best type to use on a specific project. How much does the actual total cost of tunnels, including settlement of claims and final cost of supports, differ from the original contract price?

Handling Water

Research is needed to determine the best way to contract for handling of water. Should it be cost per cubic meter of water pumped? increased cost of excavation for different amounts of water? other means?

Consolidation Grouting

What is the best way to handle consolidation grouting performed during excavation?

Insurance

Should insurance be owner or contractor furnished?

Payments for Mobilization

Are there advantages or disadvantages in making payments for mobilization?

Value Engineering

A study is needed of the advantage of including a value engineering clause in the contract.

Delays in Review of Plans

A study is needed of the effect of delays in replies by the owner or engineer to plans or shop drawings submitted by the contractor.

Delayed Payments

A study is needed of the effect of delayed payments to the contractor for changed conditions when both parties to the contract have agreed that such a change has taken place. Frequently payment is delayed until completion of the contract, requiring the contractor to carry the great burden of financing a major part of project cost.
TUNNEL SAFETY

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STATE OF THE ART

Construction, the nature of which involves assembling people, equipment, and materials to accomplish a purpose within a specified period of time, imposes many types of risks and hazards. Concern about employment risks and hazards has led to concentrated efforts by government and industry to minimize those damages and thus to reduce accidents and injuries to workers.

Within the construction industry, attitudes regarding safety have varied widely in the past. Safety practices were derived mostly from ideas of employers and employees as to what constitutes a safe job. Thus, uniform practices throughout the construction industry are not prevalent. Present trends, however, are to eliminate much of this variation.

Tunneling has its own peculiar risks as well as some that are common to other types of construction. In some instances, the safety aspects of tunneling are not recognized as being unique but are thought to be similar to those of mining. Most states, through their bureau of mines, have long-established safety regulations and assume that safety regulations pertinent to mining can be readily applied to tunneling. To do so, however, is not always appropriate. Tunneling must be recognized as a specialized underground construction effort. But federal and state mine bureau personnel, because they are familiar with underground construction, do represent a highly qualified group available to monitor tunnel safety.

The general public becomes aware of safety problems in tunneling through the news media, frequently from dramatic reports that do not contain facts or findings by qualified personnel. The public may not differentiate among specialized types of underground work and will conclude that any underground work is dangerous.

The tunneling industry must ensure that the public is well informed by the orderly, centralized dissemination of factual information concerning a tunnel project. To fully augment this concept, it should see that the safety aspects of the work are diligently monitored, documented, and reported by qualified project safety personnel. This factual information should be available to news media reporters during the course of the work and, subsequently, compiled into usable national safety statistics that provide a basis for monitoring tunnel work. At the present time, there are no established safety norms for tunnel work.

The U.S. Occupational Safety and Health Administration is responsible for improving the safety record of all industry. But in the safety field along with OSHA are local, state, and other federal agencies, all charged with the promotion of safety. The multiplicity of safety agencies and regulations tends to cloud the issues and create confusion in industries such as tunneling. Some of the problems are

1. Cross jurisdiction or unknown jurisdiction among federal, state, and local agencies, all claiming responsibility for inspection and enforcement of project safety;

2. Safety inspection personnel who lack training and experience necessary to evaluate and interpret safety situations; and

3. Complex and repetitive reporting requirements by multiple agencies.

Under present types of contracts, the practice of safety during construction is usually assigned to the contractor. Frequently, a contractor discovers that the design creates serious safety problems and must be modified to facilitate the work or enhance the safety of the work. The engineering attitude toward such design modification is often inflexible and unfavorable and becomes the source of dispute and delay.

Safety during construction, therefore, must be a prime consideration of the designer. Preliminary designs should be thoroughly reviewed by qualified safety and construction personnel before the final design is prepared. Designers and contractors should exhibit flexibility to meet and solve unanticipated safety problems that may arise during construction. Designers and owners can further contribute to the safety aspect of tunnel construction by establishing realistic time periods for project advertisement and construction. Realistic construction time would facilitate safety by minimizing the number of construction activities now commonly scheduled simultaneously for a given work area. Realistic construction time would reduce congestion commonly found within the close confines of a tunnel.

Because tunnel safety is so multifaceted, it cannot be the sole responsibility of the owner or contractor. Safety must be equally pursued by owner, contractor, and labor. Labor can contribute by providing competent workers trained to accomplish the work in a safe manner. Employees and supervisors that have poor safety records should be mandatorily retrained. Contractors and owners can materially contribute by providing additional project supervision on all work shifts, particularly swing and graveyard shifts.

FUTURE RESEARCH

Uniform Safety Rules and Regulations

The establishment of a single set of rules and regulations would substantially contribute to tunnel safety. Owners, labor, contractors, equipment manufacturers, and all local, state, and federal agencies should work under a common set of rules.

Jurisdiction

Jurisdictions should be established that clearly delineate safety inspection and enforcement responsibilities of local, state, and federal agencies. Cross jurisdiction often leads to squabbling and bickering among agencies.
Safety Records and Reporting

Requirements for safety records and reporting should be reviewed in an effort to reduce the number of reporting documents and to eliminate needless repetition. Coordination and standardization of reporting procedure could be more readily achieved if uniform safety rules and regulations were adopted.

National Statistical Tunneling Norms

National statistical tunneling norms should be developed from job safety statistics by using data processing techniques. This information would be readily available and would serve as a means of evaluating project safety. Such data would be useful for reporting to the public the safety achievements on tunneling projects.

Safety Input Into Design

Safety should be incorporated during the design stages of a tunnel project. Safety reviews of preliminary designs could be obtained from safety and construction personnel before the design is completed.

Safety Training

Qualified tunnel safety personnel must be provided by owners, contractors, and enforcement agencies, and stringent requirements should be established to ensure that this is done. Mandatory training programs should be set up and used to further the safety education of all those concerned with tunneling (designers, engineers, supervision, and trade personnel). Training education must be associated with incentives that ensure results. Safety personnel must have the necessary support of labor and management to adequately execute their duties.

Methods for Changing Attitudes Toward Safety

Owners, employers, and employees who are not receptive to programs for tunnel safety should be impressed with the need for changing their safety attitudes. Means of changing these attitudes, whether through education, fines, or other methods, should be derived.

Safety Considerations in Tunnel Contracts

Tunnel contracts should be written to emphasize safety and promote the sharing of responsibilities and costs for safety programs. Assignment of safety responsibilities and costs to only one participant in the tunnel project does little to contribute to the overall goals aimed at achieving work safety.
EXOTIC METHODS

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STATE OF THE ART

Research is progressing on more than 30 new methods of disintegrating rock. In these methods, rock is removed by four basic mechanisms:

1. Mechanically induced stresses,
2. Thermal spalling,
3. Fusion, and
4. Chemical reactions.

Drills that break the rock by mechanically induced stresses include abrasion, explosion, erosion, implosion, spark, and ultrasonic and high-energy projectiles. Continuous high pressure water jets operating at pressures of 68.9 to 413.7 MPa (10 000 to 60 000 lb/in$^2$) have demonstrated that they can effectively cut slots or holes in all types of rocks. Water cannons that fire water jets at rocks at high velocities and create stagnation pressures in excess of 6894.8 MPa (1 million lb/in$^2$) can blow large craters in even the hardest rocks. A 90-mm cannon that fires 3.9-kg (8.5-lb) concrete projectiles at velocities as high as 1524 m/s (5000 ft/sec) has been used to drive a 3.96-m (13-ft) diameter tunnel a distance of 16.8 m (55 ft) into hard granodiorite [172.4-MPa (25 000-lb/in$^2$) compressive yield strength]. These projectiles remove an average of 1134 kg (2500 lb) of rock per shot.

Devices that thermally spall rocks by heating them to 400 to 600 °C include jet piercing, forced flame, electric disintegration, high frequency electric, induction, and microwave drills. These devices have little potential for tunneling because most rocks will not thermally spall.

Devices used to fuse rock at 1000 to 2000 °C include electric arcs, plasmas, electron beams, lasers, and a system called Subterrene. These fusion devices could be used to fuse the entire tunnel face because of the high energy requirements for fusing rock. For example, a 6.1-m (20-ft) diameter tunnel machine advancing at 3 m/s (10 ft/h) would require a power output of 123.8 MW (166 000 hp) to fuse the entire tunnel face. Fusion devices could be used to cut slots in the tunnel face, thereby unsupporting the rock to be removed by the mechanical cutters. Experiments have shown that cutting these slots could increase the advancement rate by a factor of 2 or 3 while reducing the thrust requirement on the cutter head. If fusion devices were used to cut a 63.5-mm (0.25-in) kerf around the tunnel face, only 0.42 percent of the rock would have to be fused and the fusion power requirement would decrease to about 5.2 MW (700 hp). Focused heat sources such as lasers or electron beams could possibly cut narrower slots and thereby further reduce power requirements.

Chemical devices that use highly reactive agents such as fluorine have been used to drill sandstone, limestone, and granite. The high cost of the chemicals precludes their use as a primary rock-removal device. Research is progressing on chemicals that weaken rock and reduce the amount of energy required to mechanically break the rock. These chemicals could possibly be used in conjunction with conventional tunnel borers or with other exotic techniques that mechanically break the rock.

FUTURE RESEARCH

Methods for Joint Use of New and Conventional Devices

Research should be aimed at combining the use of new rock-disintegration devices with conventional disk and roller cutters. These conventional cutters remove rock efficiently, but they are limited in hard rock because of structural strength problems and because of their inability to transmit energy effectively to hard rock. By using new devices to slot the rock and conventional cutters to remove the unsupported rock, the advancement rate of tunnel borers could possibly be increased by a factor of 2 or 3.

Tests of New Devices

Proposed new techniques for cutting slots in the rock are high-pressure water jets (impulse and continuous), lasers, electron beams, and the Subterrene fusion device. These devices should be tested on small-diameter tunneling machines [1.2 to 1.8 m (4 to 6 ft)] to determine their true potential for tunneling.

Tests of High-Energy Impact Devices

Further testing should be done with the high-energy impact devices, both as the primary rock-removal devices and in conjunction with conventional cutters. Novel explosive tunneling techniques should also be tested since they have high power outputs and therefore have high potential advancement rates.

Tests of Fusion Devices

If breakthroughs are made on the power outputs of focused heat sources such as lasers or electron beams, they should be tested on conventional tunnel borers to assist the mechanical cutters. These fusion devices should have power outputs of at least 100 kW in order to be useful on large tunneling machines.
SUNKEN TUBES

R. B. Stevenson, Parsons, Brinckerhoff, Quade and Douglas

STATE OF THE ART

Although land tunnels have been constructed for centuries, subaqueous tunnels are generally considered to be a relatively new concept. The first successful underwater tunnel of record was constructed in the nineteenth century beneath the Thames River in London under the guidance of Marc Brunel. The tunnel was started in 1821 and took nearly 30 years to construct. Beseiged with problems—both construction and financial—its ultimate success hinged on Brunel’s invention of a tunnel shield and the use of compressed air to prevent inflow of water.

Even in that era engineers were searching for other means of underwater tunneling. Before Brunel’s efforts, Wyatt is credited with the conception of a tunnel in about 1812 that was composed of several circular brick tubes that would later be placed in a predredged trench beneath the river bottom and backfilled with a minimum earth cover of 1.5 m (5 ft). Records exist indicating that three of Wyatt’s brick tube elements were built and sunk in a dredged trench with modest success. The scheme was not pursued further at that time. Engineers continued, however, to be impressed with the trench type of tunnel method of construction, and the concept gradually began to assume a prominent position in the design and construction schemes for subaqueous tunnels to such an extent that railroad and rapid transit systems began to employ this novel tunnel method early in the twentieth century. The development of the “horseless carriage” stimulated the need for highway tunnels. Although the shield type of construction dominated in the beginning, the trench type of tunnel construction gradually began to assume a competitive position. At the present time, trench tunnels can sometimes be built for half the cost of compressed air shield tunnels. Where practicable, they are usually more economical than cut-and-cover methods.

Trench tunnels are usually constructed where soil conditions under waterways are conducive to the dredging of an open trench with stable side slopes. Tube elements of convenient lengths, usually in the 90 to 110-m (300 to 350-ft) range, are constructed either in dry dock facilities, existing shipways, or in special man-made outfitting basins. The tube elements may be constructed totally of concrete or of a combination of steel shells lined with concrete. Most trench tunnels in the eastern United States have been constructed as composite, concrete-lined steel shell elements. In either instance, the tubes are closed on the ends with temporary watertight bulkheads. Individual completed tube elements are then launched and floated into position over the dredged trench. Tubes may be buoyant, requiring ballast for sinking, or may be heavy enough for final placement without ballast. The latter case would require pontoons, after the outfitting basins are flooded, for support through launch and delivery stages, and the former method would permit placement of structural concrete lining after tube launch and while the tube is afloat. This construction stage is usually accomplished at the construction site. This method of tunnel construction is quite flexible and permits the use of small shipyards that are more readily available than drydocks. Since this type of tunnel is quite often constructed in built-up areas, space for man-made basins is more often than not unavailable.

Upon delivery to the tunnel site, the tube elements are then lowered into position in a predredged trench onto a prepared gravel foundation course or onto pile bents. A means is provided to effect a watertight connection between adjacent tubes and to allow the joint connection to be dewatered. After the dewatering occurs, the bulkheads are then removed and the interior joint lining is installed. The backfilling around the tubes and joints is then completed. Subsequent contracts complete the tile finish, ceiling, and electrical-mechanical equipment.

FUTURE RESEARCH

Bottom Soundings

Present-day electronic sounding equipment does not appear to be capable of obtaining sufficiently accurate results in deep water. Hand line soundings on a close grid are usually relied on.

Testing of Welds

In addition to the requirements that 10 percent of all welds be X-rayed, it is usual to specify that all modular butt welds be soap and air tested. This method of testing welds is archaic and far from reliable when one considers the number of welds that could ultimately result in potential leaks.

Grout Voids

Full contact of concrete to the underside of the steel shells in tunnel roof is desirable. The present method for discovering voids requiring grout consists of rapping shell with rods or hammers and could be improved.

Watertight Joints

Research in ways to improve the type of watertight joints between sections of the tunnel and the methods for installing the joints should be pursued.
TUNNEL GUIDANCE

George Colson, Engineering Fields Associates

STATE OF THE ART

The control of alignment and grade during underground construction operations is a highly specialized application of the surveyor's art. Investigation of the ruins of ancient tunnels reveals that 2000 years ago the Romans skillfully guided their subterranean excavations by use of primitive surveying techniques, some of which can now only be guessed at. Today, as tunnels are being bored all over the world for various purposes, we have much more sophisticated equipment to aid us.

Even the finest of equipment, however, is useless without the knowledge and skill of the surveyor. Those who believe that the laser, electronic distance measuring, and instruments such as the gyrocompass are about to eliminate the human factor are misguided.

The use of the laser as a construction alignment aid came into common use in the 1960s. Many models and systems have been devised and tested, and laser guidance techniques today are greatly improved over earlier efforts. The low-powered laser beam, which can be used safely with reasonable caution, is basically an unbreakable string line. It is peculiarly suited to tunnel work. The low light level, plus the presence of humidity and dust particles in the air, makes the line itself quite visible. In most cases it is located out of the way of the heaviest action; but, should it become obstructed or disturbed, that fact is immediately evident.

One of the positive advantages in the use of the laser beam lies in its visibility. In machine-driven tunnels the spot on the targets is positioned so that the mining equipment operator can readily see and be guided by it, and the tunnel engineer or foreman can also become immediately aware of any variation. Another advantage is that the operator does not become involved in computations and can concentrate on the positioning of the machine.

Guidance of straight tunnels by means of laser beams is comparatively simple. When a tunnel alignment includes complex curves both horizontally and vertically, a characteristic of transportation structures, the task of steering the boring machine or shield becomes more difficult. The Tunnelaser method, a proprietary system developed during construction of BART, has successfully solved the problems of guiding tunnel driving equipment around curves as well as on the straightaway.

In this system two targets are mounted, one forward and one aft, on the mole or shield, carefully located horizontally and vertically in reference to the axis of the machine. They are usually spaced so that the operator is between them. The rear target is transparent. Since it is rarely possible to place these targets on the centerline axis, they are normally located on an offset in one of the upper quadrants of the machine, which keeps them away from conveyors and workers. Many machines have personalities of their own, causing them to dive or drift. The operator can make minor adjustments of position of the spot on a target to counteract this problem. Since no sophisticated thinking or computation is required, the operator can concentrate on mechanical controls.

Primary underground survey control between the entrance and the laser stations still depends largely on the use of optical surveying instruments such as transits, theodolites, and precise levels. In place of the old and laborious hand-chaining method for measuring distance along the tunnel line, many tunnel surveyors are making use of modern devices using reflected beams of plain or laser light. The North Seeking Gyro, a spin-off from space age technology, is becoming more and more important to the mine surveyor and underground mapper, particularly in deep and multilevel mining operations. By furnishing a direction, or azimuth, while completely underground, with relatively close precision, it eliminates many of the laborious methods heretofore used.

Precise surface control to ensure accurate meeting of tunnel headings and to locate the tunnel with reference to appurtenant structures has been improved and speeded by wide use of modern theodolites, precise levels, and sophisticated distance-measuring instruments using electronic and light-beam techniques in place of old-fashioned triangulation and hand chaining.

FUTURE RESEARCH

New Guidance Concepts

It is not impossible to visualize that one day a master controller will be developed by using the components available now. Some combination of gyro, computer, laser, and guidance equipment in use today in the space program or some completely new concept will be adapted in the relatively near future to guide the innumerable tunnels yet to be bored.

Automatic Steering of Equipment

There seems to be need for improvement of feedback mechanisms with which a tunneling machine can be steered automatically without having to feed signals through the eyes, brain, and hands of the operator. Some work has been done in this direction. Most of the required technicians are already known to the computer, electronic, and aerospace industries. Probably the principal need is for a knowledgeable organization to apply such methods to tunnel construction equipment, which is daily becoming capable of faster and faster rates of advance.

Transmission and Display of Alignment Information

There also seems to be a need for electrical or electronic devices capable of transmitting and displaying instantaneous tunnel alignment information to stations remote from the face. For instance, a superintendent in an office on the surface would be able, at any moment, to observe, perhaps on a digital display panel, the progress and course of heading equipment and thus be relieved of much worry.
PREDRAINAGE METHODS FOR TUNNEL DEWATERING

Robert G. Lenz, Moretrench American Corporation

STATE OF THE ART

Tunnel dewatering, as it is practiced in the United States today, is partly art and partly science. Although removal of free water from a heading or from unlined stretches of a tunnel has always been a necessary chore in tunneling work, improved dewatering equipment and techniques today have made partial or complete predrainage of soils a relatively common occurrence in tunneling operations. The purpose of a tunnel dewatering program may be any one of the following:

1. To lower the water level so that the static compressed air pressure required to conduct mining operations is within acceptable contractual or physical limits;
2. To lower the water level to within reasonable distances of impervious layers so that the quantity of water and the pressure under which it flows into the heading do not have an adverse effect on the soils and the mining operation; and
3. To lower the water level below the invert of the tunnel to eliminate interior pumping and maximize the stability of soils in the heading.

Predrainage methods that achieve these objectives may be performed either from within the tunnel or from the surface, depending on soil characteristics, surface conditions, and tunnel size and design.

Water has been a problem in tunneling work since the beginning of tunneling activity. Probably the ancients, with more patience than the modern tunnel contractor, made better use of the principle that the tunnel itself may be the best predrainage device and that mining techniques and time can do much for depressing the water table during the course of the tunneling work.

One of the first recorded engineering efforts in which the movement of water in soils was understood and methods of accomplishing predrainage were analyzed was with the Kilsby Railroad Tunnel in England, which was constructed in the 1830s. In that project a pocket of "quicksand" 365.8 m (1200 ft) long was encountered, and this treacherous material was stabilized by pumping from a series of shafts and bore holes, most of which were in the tunnel.

Until the mid-1920s, tunnel dewatering involved crude pumping equipment, and fantastic results were frequently obtained by use of gravel, salt hay, french drains, spiling, sandbags, and other breasting methods and techniques. In 1925 the well point became a commercial tool and, although limited in tunnel applications because of suction lift restrictions, provided a basis for applying predrainage concepts to tunneling work.

In the late 1930s, 1940s, and 1950s, the new science of soil mechanics was applied to tunnel dewatering. For the first time, a scientific basis for predicting dewatering results was available. This new science, along with the advent of the ejector well point, the tremendous improvement in deep well construction techniques, and the practical development of the submersible electric pumps, tremendously improved our ability to predrain soils for tunnel construction.

In most tunnel dewatering applications, the choice of dewatering systems comes down to the ejector well point or the deep well installed from the surface to effect partial or complete removal of water. The choice of the dewatering tool revolves around the quantities of water to be pumped and the necessity for closely spaced pickup points.

Wells have an application in which large quantities of water can be removed from relatively few locations with a reasonably predictable and dependable result between wells. Ejectors are used where communication in the soils from one dewatering device to another (or to the tunnel) is limited or constrained, or where aquifers are rather thin or where horizontal flows would occur over the top of impervious layers at the level of the heading.

Tunnel dewatering systems should incorporate instrumentation to permit the verification of results sufficiently in advance of the tunneling operation so that any modifications to the dewatering program may be made in a timely manner without impeding progress in the tunnel. It may also be necessary to develop installation tools for dewatering equipment that will permit rapid augmentation of a dewatering system should conditions in the heading require it.

Every effort in tunnel construction has the one basic purpose of allowing the heading to be advanced in the shortest possible time cycle consistent with safety and quality. Development of various tunneling machines, breasting techniques, spoil handling methods, and so on all have the common purpose of permitting more rapid and safe progress. Tunnel dewatering has the same purpose. One difficulty in planning for dewatering is that the repetitive nature of the work is not completely consistent because there is a new variable in every shove, and that is the drainage characteristics of the soil. Therefore, the first step in tunnel dewatering is to understand the soils and their drainage characteristics and to provide the type of predrainage systems that can cope with the variation that may occur in soil drainage characteristics.

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FUTURE RESEARCH

Understanding of Soils

Basic understanding of the pertinent soils and their drainage characteristics is necessary. All too frequently it occurs that techniques are lacking for recognizing changes and variations in soils. Accurate and complete soil profiles are essential to success, particularly where the soil stratification is complex and where a major aquifer does not exist at and below the heading elevation. An understanding of the soils is essential for the making of decisions on dewatering design, construction, and evaluation.

Improvement of Installation Equipment

Future improvement of the equipment and techniques that are used to install dewatering devices, generally at significant depth and frequently under congested surface conditions, can be the means of dramatically reducing the cost of tunnel dewatering. Rotary and percussion drills and jetting equipment have all been considerably improved in recent years; however, there is room for further research in this direction.

Improvement of Dewatering Equipment

Dewatering equipment, too, has been improved in recent years. The submersible pump is a practical reality. Piping, screens, and pumps are commonly made of materials that are chosen to provide long life and good wearing characteristics under sometimes severe conditions. Techniques of hydraulic transfer of power are just entering the pumping field, and further research is warranted. Designs and equipment should be continually upgraded to improve the cost and effectiveness of tunnel dewatering.
 PRESSURE GROUTING OF TUNNELS

Edward D. Graf, Pressure Grout Company

STATE OF THE ART

Pressure grouting is used in many ways and for various purposes in tunnel construction. As a construction tool, pressure grouting is used frequently for one or more of the following purposes:

1. To shut off high inflow of water;
2. To reduce high hydrostatic pressures on the tunnel;
3. To solidify running sand;
4. To consolidate loosened material at or above the working face;
5. To strengthen a poor rock face, especially after the face has failed; and
6. To fill chimneys.

As a design method, pressure grouting is used frequently for one or more of the following purposes:

1. In soft ground tunnels driven with shields or tunnel machines to fill the annular space outside of the lining left by the tailpiece of the shield;
2. As contact grouting to backfill grouting behind lined tunnels to ensure that all voids between the lining and the soil or rock are filled;
3. As high pressure grouting in water tunnels to seal all possible leaks through the tunnel rock;
4. To shut off water infiltration into a finished tunnel; and
5. To strengthen weak sections of old tunnels.

To accomplish these purposes, a wide range of materials is used. Most commonly used is portland cement mixed with water only; sand; soil; fly ash; bentonite or local clay; sawdust, bran, or other filter builders; water-reducing agents; retarders; accelerators; expansion agents; and reagents to closely control set time (seconds or minutes). Other particulate grout (particles in suspension) materials used are bentonite, silicate-bentonite, local clay, fly ash, lime-clay, lime-fly ash, and emulsified asphalt.

Chemical grout (pure solutions, no particles in suspension) can penetrate fine sands, silts, and fine rock fissures that particulate grout is unable to penetrate. To varying degrees, the following material systems are commonly used: Joosten process (silicate-chloride), silicate-formamide, silicate-acid salt, acrylic resin, urea-formaldehyde, phenolics, and polyurethane.

The state of the art in the United States is less advanced than that in Europe, although an awareness of use of the available technology has recently increased in the United States. The equipment, materials, and skills are available in this country, but they are mostly used on small private projects or by tunnel contractors who turn to grouting as a last resort.

Modern grouting is a highly specialized field that requires continual analysis and field modification for optimum cost effectiveness. The few knowledgeable grouting engineers in this country are mostly employed by specialty contractors. As long as pressure grouting is considered "contract" work, rather than a professional engineering service, U.S. design work will follow standard specifications and be limited to portland cement, with a few standard modifications, and to one or two chemical grout systems.

FUTURE RESEARCH

Stress-Strain Design Criteria

Stress-strain design criteria for different chemical grouts under different soil conditions are necessary for adequate and economic solidification of soft ground to facilitate tunnel driving and to make rational analytical predictions of surface movements.

Grouting Tailpiece Annular Space

Techniques for grout filling tailpiece annular space and materials to allow filling of that space as the cavity is formed are especially important for urban area soft-ground tunneling where surface settlement is critical.

Grouting by Tunnel Machine

Grout injection systems should be incorporated into tunnel machines to provide continuous grouting as the tunnel advances. Most work today requires stopping the tunnel driving for grout injection or else grouting ahead from the surface. Under most conditions, grouting from the surface is economically more wasteful than grouting from the face.
INSTRUMENTATION IN TUNNELS

E. J. Cording, University of Illinois at Urbana-Champaign

STATE OF THE ART

Instrumentation in tunnels is significantly related to design and construction problems. An instrumentation program is most valuable for monitoring the project, designing future tunnels, and advancing the state of the art. Instrumentation should be considered a tool for extending the capabilities of the observer. In some cases, instrumentation may consist only of simple settlement surveys and other information normally available on the project. In other cases, specialized instruments may be required to obtain useful results. The following are areas of concern in instrumenting a tunnel; they are similar to those for designing and constructing a tunnel.

1. It must be possible to advance the tunnel safely and to maintain the integrity of the opening. Displacement measurements, using borehole extensometers, are the most useful methods for monitoring the stability of an opening. Such instrumentation is particularly applicable for large underground openings, where it is possible (a) to monitor the effects of the various excavation sequences in time to permit adjustments in the excavation and support of the later sequences or (b) to modify the support in the portions of the opening already excavated. An engineer or shift foreman, even though capable of visually evaluating the support requirements in a single heading, is not able to assess the overall stability of a complex system of multiple openings. Instrumentation integrated into the design and construction process can provide the needed information.

2. Construction of the tunnel must not excessively damage adjacent or overlying buildings, streets, or utilities. This requirement is of primary concern for tunnels in soil. In a rock tunnel, stability of the opening is usually most critical: If the stability can be maintained, then the rock displacement will not be great enough to damage adjacent or overlying structures. However, in a soil tunnel soil displacements can result in damage to nearby structures even though the stability of the tunnel is maintained. Instrumentation to monitor soil displacements is used to assist the designers in evaluating the need for underpinning and in helping the contractor determine which construction procedure is causing ground to be lost.

There are two major aspects in the measurements of soil displacements: The first is to evaluate the movements immediately adjacent to the tunnel so that they can be correlated with construction procedures and so that the source of the lost ground can be determined. If the cause of the ground movements is known, corrections to the tunnel procedure can often be made to minimize lost ground. The second is to determine the distribution and magnitude of lateral and vertical displacement away from the tunnel that could damage structures. Once this distribution is known, the extent of underpinning required or the damage limits can be evaluated for various amounts of ground lost into the tunnel. Displacement measurements for evaluating damage to adjacent structures consist primarily of settlement surveys at the ground surface near the tunnel. The settlement surveys involve deep settlement points to determine lateral displacements both at the surface and at depth.

3. The tunnel should be capable of withstanding all the influences to which it may be subjected during its lifetime. Initially, the lining must be able to support the tunnel as it is excavated. Instrumentation can be used to measure the loads and distortions imposed on the initial lining as it is eroded and as the heading advances away from that portion of the tunnel. Such instrumentation is often difficult to install and protect in the congested heading. The instruments must often be installed and read in a short period of time as the heading advances away from the instrumented section. Instruments that can be installed prior to construction or that require a minimum amount of assembly in the tunnel are to be preferred.

Instruments on steel ribs may consist of strain gauges to evaluate thrust and moment. Thrust can also be measured by placing load cells beneath steel ribs. Distortion measurements can be made by using tape extensometers and tunnel surveys. Strain gauges embedded in shotcrete can be used to correlate strains with cracking of the shotcrete.

The observations described above do not provide much information on the adequacy of the permanent lining for the life of the tunnel. In many tunnels a permanent lining is installed after the initial lining has stabilized the tunnel. Initially, stresses and strains developed in the permanent lining are related primarily to shrinkage and temperature effects during curing of the concrete and are secondarily related to soil or rock loads. If the soil or rock is creeping and distortion of the initial lining is still taking place as the final lining is installed, soil or rock loads will develop with time on the permanent support. Such loads can be measured, if the instrumentation has long-term stability.

Described below are some of the measurement systems that can be used in tunnel instrumentation.

1. Borehole extensometers and settlement probes are installed in boreholes and measure displacements parallel to the borehole. An extensometer may consist of nothing more than an anchor in a borehole and a rod extending from the anchor to the collar of the hole. The position of the rod with respect to a reference surface anchored at the collar can be measured manually by using a depth micrometer or dial gauge. Extensometers may be installed in boreholes from within the tunnel. The reference surface is at the collar of the hole in the tunnel, and anchors are located at various distances from the collar of the hole. So that a complete history of displacements can be obtained, extensometers can be installed in advance of excavation from a nearby excavation or from the ground surface.

Because the extensometer measures a relative reading from the collar of the hole to the anchor, it is desirable to install one of the anchors for the reference surface at a point that is outside the zone of expected significant movement around the tunnel. If all anchors and reference surfaces are located within the zone of movements, then a survey point
should be tied into the top of the extensometer. Extensometers can be read to 25.4 µm (0.0001 in) by using a depth micrometer or dial gauge; thus, the instrument is sensitive for use in rock tunnels, where displacements as small as 2.54 mm (0.01 in) may indicate potentially unstable conditions.

Around soil tunnels, settlement probes rather than extensometers are usually adequate. The settlement probe consists of a rod anchored at the bottom of a borehole. The movement of the anchor is measured by surveying the top of the rod. The settlement probe thus has the accuracy of a normal settlement survey.

2. Over soft-ground tunnels, a survey of the settlement profile at the ground surface can be combined with the survey of settlement probes anchored immediately above the tunnel. In this way both the source of the lost ground and the distribution of settlement can be evaluated. It is particularly important to tie the settlement survey to a stable bench where regional settlements occur in compressible soils because of groundwater lowering. Such settlements extend many diameters away from the tunnel.

3. The inclinometer measures displacements perpendicular to the axis of a borehole. The inclinometer, in combination with settlement points and extensometers, can be used to obtain the three-dimensional pattern of movement about a tunnel. The inclinometer consists of a slope-measuring torpedo that rides in a grooved casing. The inclinometer torpedo measures the inclination at specific intervals in the casing. These inclinations are summed to determine the lateral displacement of the casing with respect to some fixed reference point in the casing. Inclinometer torpedoes available in the last 5 years have improved accuracy and repeatability over units previously available. A servo-accelerometer type of torpedo unit has repeatability of approximately 2.54 mm (0.01 in) over 3 m (10 ft) of casing length.

4. Strain gauges can be installed in or on the support to estimate thrust and movement in the section. Strain gauges can be either mechanical gauges (such as the Whitemore gauge), vibrating wire gauges, or electrical resistance gauges.

5. Distortions of the tunnel lining can be measured by using portable tape extensometers attached to hooks on the lining. Displacements can be measured by using tensioned tape extensometers to a precision of approximately 2.54 mm (0.01 in). Settlement surveys can also be used in the tunnel to evaluate settlement and vertical distortion of the lining crown and invert that is greater than 2.54 mm (0.01 in).

**FUTURE RESEARCH**

**Interpretation of Displacements Around Soft-Ground or Mixed-Face Tunnels**

One of the primary concerns in soft-ground and mixed-face tunneling is limiting displacements that can damage nearby structures. Data are needed to correlate sources of lost ground with ground movements that can affect nearby structures. Accurate records of construction conditions should be correlated with measured ground movements. Surface surveys should be supplemented by deep settlement points, and readings should be made with time as the tunnel is advanced by the measurement cross section.

**Instrumentation for Large, Shallow Openings in Rock, Soil, and Mixed-Face Conditions**

Multiple drift techniques, ground stabilization, and support techniques will be required in large, shallow openings such as those constructed for highways or subway stations in urban areas. In such projects, instrumentation can evaluate these techniques and provide information on stability, the ground displacements affecting nearby structures, and the conservatism in initial and permanent support capacity.

**Improvements in Instrument Reliability, Ease of Installation, and Ability to Read Instruments**

Instruments providing the needed accuracy for measurement are available. There is a need for improving their reliability and developing a system of rugged instrumentation that can be used by field crews to provide a comprehensive picture of tunnel performance.

**Integration of Measurement Program With Field Observations and Construction and Design Requirements**

The most valuable information and greatest benefits will result from instrument programs closely related to design and construction objectives. Programs have failed in the past because this coordination did not exist.

**Manual of Instrumentation for Underground Construction**

Instrumentation of underground construction is a comparatively new technique. There is need for more literature on the subject for guidance of design engineers, geologists, and contractors. A manual or handbook on tunnel instrumentation, compiled by a knowledgeable individual or agency, should prove useful.
CUT-AND-COVER TUNNELING

Henry R. Tiedemann, Jacobs Associates

STATE OF THE ART

Methods and techniques currently used in cut-and-cover tunnel construction have evolved under the influence of environmental factors at the work site. Though this type of construction may be carried out in a suburban area, it is more likely to be associated with an urban surrounding where constraints are more prevalent than in open areas. The complexity of the area (narrow confined streets, large buildings, and heavy traffic, both vehicular and pedestrian) contributes to the decision to place facilities below ground. Construction economy dictates that the structure be placed as close to the surface as possible because the cost of cut-and-cover construction increases rapidly with depth.

The following operations are usually performed sequentially on a cut-and-cover construction project: relocate utilities, underpin adjacent structures, dewater where required, install ground-support system, excavate street surface, place temporary street decking, continue excavation below street, construct structure, restore utilities, remove temporary street decks, and repave street.

1. Relocate utilities. Most urban streets contain sewers, water lines, gas lines, and electrical and telephone ducts that must be continually maintained during construction. Major streets often carry the main lines of these utilities. Smaller lines are usually maintained in place during construction, supported below street decking. Heavy sewers and utility manholes may be temporarily replaced by lighter facilities, to be restored after construction. Gas lines and large water mains must sometimes be temporarily or permanently relocated for reasons of safety.

2. Underpin adjacent structures. Requirement for underpinning depends on the value and proximity of an adjacent structure, condition and design of existing foundation, type of ground-support system used, and nature of the soil. Properly designed and installed, ground-support systems prevent excessive ground movement and reduce underpinning requirements. Underpinning may involve hand-excavated pits or caissons, pile clusters jacked below spread footings, or small-diameter friction piles drilled down through the footing. On smaller buildings, temporary support measures such as pile pickup or jacking piers for support walls may be employed to prevent uneven settlement.

3. Dewater where required. If groundwater flow is small, trenching and sumping ahead of excavation may suffice. Dewatering equipment, where required, should be installed and activated prior to excavation. For shallow excavation, a system of well point is usually the most economical. For deeper excavations, eductors may be used for relatively light flows and deep wells for heavier flows.

4. Place temporary street decking. Street decking usually consists of structural steel beams across the width of cut, resting on the ground-support walls. For wide structures, intermediate support piles may be required. Removable timber mats placed on the beams form the temporary deck. Traffic must be restricted during placing and removal of the deck. Wide decking is usually placed sequentially on one side of the street while limited traffic is permitted on the other side. Traffic is then diverted to the completed deck while decking of the second side takes place. The procedure is reversed during decking removal. Some decking operations may have to be done on weekends to minimize disturbance. Access to adjacent buildings for pedestrian and emergency vehicles must be maintained. When cut-and-cover structures are located in less congested areas, there often is sufficient room for detouring traffic and thereby eliminating the requirement for temporary decking.

5. Install ground-support system. Though many ground-support systems have been developed, soldier piles and lagging are probably still the most widely used. Good workmanship and careful procedure must be followed to prevent ground movement and subsequent settlement of adjacent structures, utilities, and pavements. Because of the environmental disturbance of pile-driver noise and vibration, vertical soldier beams are now usually placed in predrilled holes. Lagging is placed between the piles as the excavation and bracing proceeds.

Sheet piling has traditionally been used in wet running ground, but the noise of pile driving now restricts its use in urban areas. Cast-in-slurry concrete diaphragm walls, though more expensive than sheeting, have been used in a number of projects including several subway stations in San Francisco and Washington, D.C. These walls not only reduce the need for underpinning but are structurally capable of being incorporated in the completed structure.

6. Excavate below street level. Bracing of the ground-support wall is usually by horizontal steel wales and struts.
placed concurrent with excavation. Struts are usually on the same spacing and in vertical plane with deck beams for ease of lowering materials and raising excavated soil. Earth-anchored tiebacks are gaining in popularity for foundation walls, but have not been used much for cut-and-cover work.

Excavation and backfilling operations are governed by environmental considerations. Urban restrictions preclude the use of large scraper equipment so effective on highway projects. Small dozers, backhoes, front-end loaders, and crane-mounted clamshells are inherently expensive. The first excavation pass, to expose utilities and place decking, is usually loaded by front-end loader or backhoe into dump trucks.

Below the deck, digging is done by dozer or front-end loader, which transports the soil to central areas where it is usually lifted to the surface by a large clamshell and loaded into dump trucks. Where the soil does not contain much clay, conveyors are an attractive alternate for lifting.

Costs can frequently be saved by using the permanent steel frame of a structure as temporary bracing.

FUTURE RESEARCH

Environmental, Social, and Economic Impacts

Most future improvement for cut-and-cover work will involve ways to minimize environmental, social, and economic impacts. There has been a growing awareness that construction cost alone is not the only factor to be considered. Though not easily assessed, delays to commuters, interruption of normal business activities, and loss of local business income and tenants are all affected by the construction methods employed. Noise and dust ordinances have already had an impact on construction methods and costs.

The time of exposure is the single most important factor of social and economic losses. To reduce the exposure at street level, major alternate construction sequences are being investigated. Placing a permanent street deck in lieu of temporary decking eliminates the need for the disruptive period of decking removal. It also reduces the problems of maintaining traffic on a less than ideal deck surface cluttered with construction equipment. Subsequent excavation, bracing, concrete, and backfill below the street must be performed from side ramps or shafts without the benefit of removable decking. New techniques need to be developed to keep these operations from becoming overly expensive.

Ground Support

A new type of ground support has been developed in Europe and is being studied by the U.S. Department of Transportation. Precast panels are placed in a slurry trench to form a continuous ground-support wall that can be used also as part of the permanent structure. It has the following advantages: Concrete quality control is better; panels can be delivered with waterproofing on the outside; the inside has an architectural finish; and bearing plates, keys, dowels, and recesses can be included in the casting. This system would combine well with a permanent street deck.

Street Decking

Development of precast panel street decking will also be required for a permanent deck installation, for the placing and curing of cast-in-place concrete slabs would negate the purpose of minimal disruption.

Utilities

Utilities, as always, remain a problem. There are two possible methods of handling maintenance of utilities. The first is to provide before main excavation twin utility tunnels (utilidors), one on either side of the street. All utilities (with the exception of gas lines) serving local buildings would share these tunnels. This would leave the center of the street clear and would permit the precast structural roof to serve as a street deck, placed with minimum encumbrances. The second method is to support utilities below a permanent street deck and to place a second structural slab below the utilities, providing in effect a utilidor above the roof. Such methods have been used in other countries, but have not gained wide acceptance in the United States.

Other Areas

Other areas for future research include ground consolidation methods to reduce dewatering and ground support requirements. Transportation of excavated soil by hydraulic or pneumatic pipelines could be investigated as an alternate to lifting by clamshell or conveyors.
USE OF UNDERGROUND SPACE

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STATE OF THE ART

The worldwide increase in population and urbanization and the accompanying problems of congestion, environmental disruption, and pollution increase the need for and the importance of using underground space. Present use is extensive and growing. Increased costs of land and surface facilities, both economically and environmentally, and improved underground excavation methods make use of underground space more attractive. Mining for various minerals can often be carried out with planned later use of the mined-out space. In some locations the value of the excavated rock as concrete aggregate or special fill may pay the cost of creating the underground space. Savings in energy needed to heat and cool underground space, compared to surface facilities, can be as great as 60 percent or more. In all instances, the geology of the area will determine how and to what extent underground space can be used.

Tunnels are vital arteries for water supply, communications, and transportation of people and goods. For instance, New York City has more than 210 km (130 miles) of large-diameter tunnels for its water supply system. Water utilization projects in the West involve several hundred kilometers of tunnels. Future needs will entail moving water over long distances, requiring many more tunnels than in the past. Transportation of sewage to treatment plants and disposal involves many tunnels. Chicago, for example, is well along with a program including more than 160 km (100 miles) of large-diameter tunnels as part of a wastewater transport and storage system to handle peak storm and sanitary sewage flows for later treatment. The increasing emphasis on positive control of water pollution means more tunnels.

The United States now has more than 725 km (450 miles) of rail rapid transit tunnels and expects to double that amount during the next decade. More than 100 highway tunnels, mostly through topographic barriers but some under high-density urban areas, have a portal-to-portal length of about 145 km (90 miles). Twenty additional tunnels, primarily on the Interstate Highway System, are under design and construction.

Utility tunnels have long been used in institutional building complexes such as college campuses. Originally constructed to distribute lines from a central heating plant, they now generally include most other utilities. Multitunnel tunnels have not reached important acceptance in the United States, although the potential appears great. As density increases, more need develops for underground utility space. A large subdivision in Stockholm, Sweden, is being planned with all transportation access and utilities, including hot water for heating, in tunnels.

Construction of water and sewage treatment plants underground offers advantages of controlled conditions and absence of environmental disturbances. An outstanding sample of effective sewage treatment is the Kappala plant in Stockholm. Built to serve a population of 540,000, its 60.3 km (37.5 miles) of tunnels comprising the underground works can be expanded to serve twice as much population without adverse effect on the choice surface residential areas.

Underground storage for fossil fuels is growing. In 1974 there were 365 underground storage areas that were used for 184.1 Gm$^3$ (6.5 trillion ft$^3$) of natural gas, about one-third of the yearly production. Under favorable geological conditions, unlined underground caverns lend themselves well to storage of water, oil, and other liquid products.

Where temperature and humidity control is important, underground offers many advantages to warehousing and manufacturing and provides especially favorable storage space for frozen foods. The Kansas City area, with its mined-out limestone space, leads the nation in using underground facilities. A manufacturer of precision instruments has found the controlled humidity, temperature, and vibration-less floors with heavy loads especially favorable. Weather hazards are reduced, maintenance costs are less, and energy savings are 65 percent and more. Development of a large-scale underground industrial park is under way, and planning is being done to use all the available underground space.

Underground facilities are placed in tunnels and caverns that honeycomb the great Rock of Gibraltar. Peking, China, is reported to have underground facilities in which the entire 7 million population can be accommodated. Poland has a 500-bed hospital 213.4 m (700 ft) underground in an old salt mine, which appears to have medical value to those suffering from bronchial asthma and other respiratory problems. A similar installation is at Solotvino in Soviet Carpathia.

Parking garages underground are increasing in number, and their cost compares favorably with surface construction. Shopping plazas and malls, such as the Place Ville Marie underground complex in Montreal, Rockefeller Center in New York, and the underground plaza connected with the new subway system in the center of Paris, demonstrate the remarkable possibilities with an easily controlled environment. A new similar development under Tokyo already has 350 enterprises. Similar developments are under way in Osaka and Nagoya.

About a fourth or more of the hydroelectric plants being designed and constructed in the world today are being located underground. One of the world's largest is the Churchill Falls Project in Canada where 1.76 Mm$^3$ (2.3 million yd$^3$) of rock were excavated to provide the large underground chambers. Completely underground pumped storage facilities are being actively considered at several locations. For instance, a two-state, Francis pump-turbine installation in a 1097.3-m (3600-ft) vertical shaft would support a 1600-MW, 10-h peak capacity with underground storage of about 5.4 Mm$^3$ (7 million yd$^3$). Costs are becoming increasingly favorable. The example just cited would require a capital cost of about $200/kW. Such installations offer a great many advantages such as freedom from topographical controls and environmental constraints. They can be located close to load centers, reducing transmission costs and environmental problems, and can provide a source of concrete aggregate and rock near market centers. Underground nuclear plants, such as the 266-MW pressurized water plant in
Ardennes, France, and a 500-MW plant being planned in Stockholm, Sweden, offer potentials that are receiving intensive study. Underground transmission of electricity in built-up areas is increasing, and extensive research is developing ways to improve technology and reduce costs for this major problem.

The needs for the use of underground space are great, and the potentials for better meeting the goals of a quality life for people are growing. With an aggressive, positive research and development program covering the full range of physical, economic, social, and environmental considerations, the use of underground space is expected to accelerate.

FUTURE RESEARCH

Methods of Analysis, Design, and Construction

Research needs include the full range of physical and geological methods of analysis and design of underground openings. Shape of openings, types and degree of supports needed, actual performance records, and methods of strengthening various geological formations are representative of the problems needing additional research. More geological information is a big requirement. Methods for which underground excavation can be improved from the standpoint of economics and accomplishment need further advancement. Safety provisions for underground construction and labor relations need improvement. Better methods of contracting for underground work need to be developed and used. The best way to provide ventilation, fire protection, and regular and emergency access requires specialized study directed to the specific needs of underground space use.

Effects of Underground Environment on People

With the potential that underground space use appears to have, especially as economic advantages of surface space disappear, a better understanding of the effects of underground environment on people is a must. The usual adverse reaction to working underground needs careful examination. General reactions from those actually working underground, for instance in Kansas City and in Sweden, appear favorable. However, specific facts and data need to be established. From a medical standpoint, underground workers appear to be less susceptible to common colds; and accident rates for underground workers seem to be lower (those engaged in office, warehousing, and manufacturing activities, not construction). Attitudes of underground workers suggest a feeling of security and composure, and this may reflect favorably in underground plazas and shopping malls. Healthful and healing influences are indicated in some underground environments. These probabilities need to be well researched and documented by psychological and medical professionals. The influences of decoration and lighting adapted to underground operations should be established from existing information and from additional experimenting and research.

Best Use of Underground Space

How the underground space can contribute to the entire goals of society, not just from the technical and physical standpoint but from full consideration of a quality life for people, needs continuing objective analysis with multidiscipline considerations. More study needs to be made of what should be placed in underground space for the greatest overall benefit. With this determined, then ways to adapt institutional arrangements, which have been established generally without consideration of the use of underground space, need careful research and analysis to determine how best to adapt them to optimize underground space use. Factors to be considered include tax treatments, ownership, insurance rates, zoning, and the whole array of related problems.