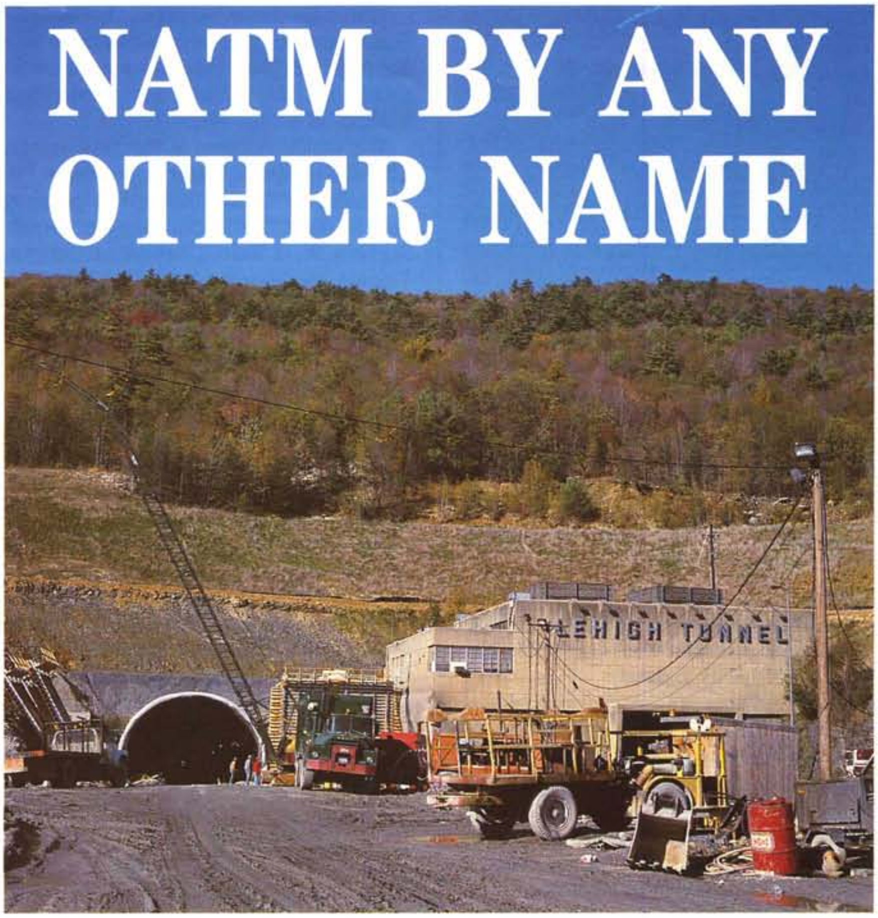
NATM BY ANY OTHER NAME



South Portal of existing tunnel and tunnel No. 2.

The use of the NATM system for building tunnels in North America has not exactly caught on since its introduction in 1983. The first NATM projects in America are the Washington Metro (WMATA) Red Line and the Port Authority railway tunnel at Mt Lebanon near Pittsburgh, Pennsylvania. Both of these tunnels were built by the Austrian contractor, Ilbau.

WMATA's estimate for building the Red Line's B-10 Section was placed at over $80 million. A pleasant surprise followed when Ilbau came in with an accepted bid of $52 million. This project was successful and established NATM as a tunnelling technique.

The most recent tunnel project to make use of the NATM system is the Lehigh Tunnel No. 2 at the Pennsylvania Turnpike Commission's northeastern turnpike extension, 32 km north of Allentown.

It is this project that will be reported on here, but first a comment will be made on the slow acceptance of the NATM system by some Americans.

NATM

The acronym NATM stands for the New Austrian Tunnelling Method. There is also an acronym in German, NÖT (Neue Österiechische Tunnelbauweise). There are tunnelling people who question the validity of designating the procedures used in the NATM as the New Austrian Tunnelling Method. Certainly there are some key methods incorporated in NATM that are not Austrian in origin. For example, the shotcrete application method has been credited to the Americans. The design and patent of equipment such as the cement gun is American. Other application techniques adapted by NATM were spawned in Prague, Zurich and Berlin, not in Austria.

The Austrians appear to have incorporated various construction materials and applications methods into a well-orchestrated system that improves the safety and cost-effectiveness for tunnel construction in ground conditions where immediate tunnel reinforcement and/or support is necessary during advancement. This is no small feat. The ultimate objective of any tunnel project is to build a quality tunnel by the safest and least-expensive method available. The NATM system can often meet those objectives.

Why then has the acceptance of this method been so slow in America? There is no single answer. In part, the conventional tunnelling methods have been very successful and there is the old adage, 'if it works don't fix it'. Another reason for not accepting NATM is that it's concept is not fully understood by the public sector nor many American tunnel design engineers, the people who could make it happen. Also, some Americans take offence at it being referred to as the 'Austrian' method. It has a ring to it that doesn't sit well with some people. Perhaps those who are promoting NATM would be advised to play down the acronym and call it something else. They just might lose the battle but win the war.

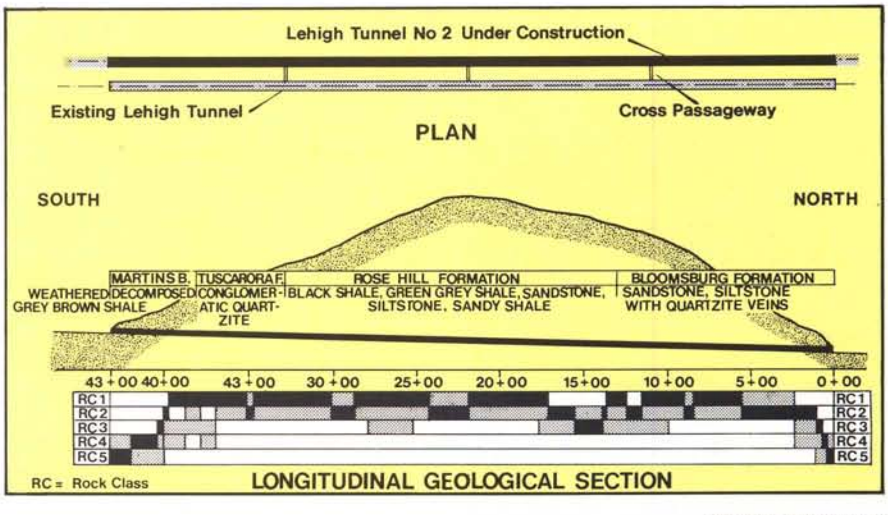
Dr-Ing Gerhard Sauer, of Herndon, Virginia described one hindering factor caused by "a sophisticated and dangerous" legal system that exists here in America. Although the NATM system has a failure probability no greater than any other tunnelling method, the insurance costs are three to five times greater than in Europe. Labour is also a problem because of union demands on classifying and restricting job descriptions. This necessitates more workers to get the same tasks done, according to Sauer.

LEHIGH TUNNEL

Contrary to the slow acceptance of the NATM system in America some innovators defy all the excuses and forge ahead, convinced that it is the best choice for their tunnel project. This is the case with the Lehigh Tunnel. The owner, The Pennsylvania Turnpike Commission, is one of the more progressive highway agencies in the United States. Unlike many of the State Department of Transportation agencies, the Turnpike Commission welcomes new ideas that will improve the 756 km of four-lane motorway under its authority.

The Turnpike Commission is 50 years old

Longitudinal geological section.



Tunnel with shotcrete.

this year and was the forerunner of the national motorway system in the United States. From the start the Commission has been the leading innovator of motorway design by building the first four-lane motorway, which runs east-west through Pennsylvania, border to border, for a total of 579 km. There are nine motorway tunnels, with the Lehigh Tunnel No. 2 being the tenth when completed. The Lehigh Tunnel is on the north-east extension, which was constructed after the original east-west motorway.

The Lehigh Tunnel No. 1 is a two-lane, two-way tunnel that has served the northeastern extension (177 km), since 1957. In recent years, the tunnel has proved inadequate during peak traffic flow demands, with vehicles lined up at both portals of the tunnel. A ½-1 hour wait before proceeding through the tunnel was not unusual. All other tunnels along the Commission's motorway are double, two-lane. Each such tunnel serves traffic flow in one direction only.

The Turnpike Commission realized back in the late 1960s that a second tunnel at the northeastern extension would have to be built. The conventional method, drill and blast, was decided upon by the Commission and the project was let out to bid in 1972. The lowest bid was about $25 million, which was so far over budget that the Turnpike Commission had to shelve the project.

PVC waterproof membrane in place.

With more funds available, the Turnpike Commission decided to go ahead again with the project in 1988. This time the contractor could bid the project for conventional methods or for the NATM system.

The design engineer is the joint venture GSGSB/McCormick, Taylor & Associates, Inc. The company is responsible for specifying both methods. The engineering and consulting firm, Dr. G. Sauer Corporation, Herndon, Virginia, was brought in for the design and specifications needed to carry out the NATM bid. Sauer is an Austrian-based company specializing in NATM tunnel projects primarily in Europe and North America.

The Lehigh Tunnel No. 2 is to be 1,335 m long. It will feature a two-lane motorway that is 7·62 m wide by 5 m overhead clearance. The tunnel grade is to slope from south to north by 2·5%.

The lowest bid, using the NATM system, was $37 million. The lowest bid using the conventional method was over $43 million. To put this into perspective and in relationship to the 1972 low bid, the NATM bid for the tunnel excavation, excluding construction of the approaches, was $24 million.

The 1972 conventional method bid price of $25 million also did not include the cost of building the approaches, which were a separate bid.

Essentially, there was no increase in bid price despite the rate of inflation experienced during that time in America.

GEOTECHNICAL CONSIDERATIONS

The Lehigh tunnels are directed north/south through the Blue Mountains. The dipping strata is uniform and overturned, making the older formations higher than the more recent formations. There are shales, siltstone, sandstones, quartzite and conglomerates to be found in thick interbedded layers. These rocks are classed as sedimentary and are detrital in composition. The rock types encountered on this project range from soft to hard to very hard, with most of the rock being medium hard to hard.

The dip of the geologic structure predominantly ranges between 30 and 40° inclination from the horizontal in a south direction. The extreme dip range, infrequently found, is 20 to 55°.

An NATM rock classification has been made for matching ground mining conditions with the selection of materials needed to reinforce and/or support the tunnel immediately after a predetermined measurement advancement.

The rock classification simplifies the

Table I

NATM ROCK CLASSIFICATION	TUNNEL SUPPORT SYSTEM
CLASS-1: Sound rock, moderately jointed, rock mass stable during construction.	Local Support as needed, rock bolts and/or sealing shotcrete (eventual sealing throughout the tunnel). Top heading advance/round-3·65 m. Bench advancement/round-7·3 m AS.
CLASS 2: Moderately to closely jointed; roof conditions moderate, some wet areas, immediate support to prevent fall-outs.	Shotcrete 5 cm thick throughout area; top heading advancement, 2-2·75 m/round; bench, 4·25-5·5 m/round; some rock bolts, 3-4·5 m long.
CLASS 3: Closely spaced joints; shear zones; roof conditions brittle, some extensive wet areas; stand-up time, <2 hours; immediate support.	Shotcrete 15·25 cm min. thickness, reinforced w/l lattice girder & 1 welded wire fabric/round; top heading advancement, 1·8-2·1 m/round; bench 3·6-4·2 m/round; 7-8 rock bolts/round, 3-4·5 m long.
CLASS 4: Weathered rock, intensely sheared fault zones, brittle roof conditions, extensive wet areas; stand-up time <2 hours; immediate support.	Excavation-top heading, bench and more for invert arch installation; top heading advancement, 1·2-1·5 m; bench, 2·4-3 m; shotcrete, 20·3 cm thick, reinforced w/l lattice girder welded wire fabric; local rebar spiling installation; 9-10 rock bolts (3-6 m long)/round.
CLASS 5: Decomposed rock, very poor roof conditions, squeezing rock conditions. These conditions found primarily in the portal sections. Pre-support is needed.	Shotcrete, 25 cm thick with 5 cm immediate application, 1 lattice girder and 2 layers welded wire fabric/round; top heading advancement, 1·22 m/round; bench, 2·4 m/round; excavation in invert not to exceed 4·9 m/round; 14 rock bolts, 3-6 m long/round; invert arch after bench excavation; additional reinforcement at the portals.

ground conditions description so that practical decisions concerning excavation and reinforcement methods can be quickly made as the mining advances.

Table 1 provides a condensed description of each rock classification and tunnel support materials to be installed.

Table 2 shows the ground conditions encountered during advancement, starting at the southern portal through to the northern portal. In practice, however, the mining was advanced simultaneously in both directions starting at the two portals.

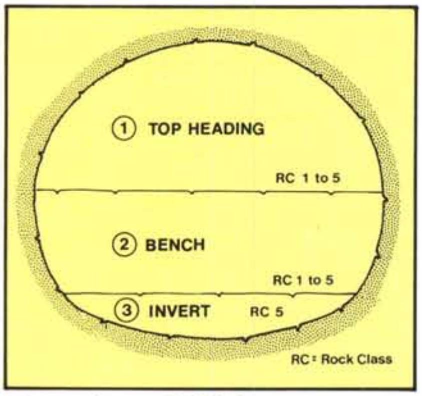
Table II

Tunnel Section	Rock Class	Geotechnical Conditions	Mining Conditions
0-91m	RC-4, -5	Weathered, decomposed, grey brown shale	Very poor roof conditions.
91-213m	RC-1, -2, -3, -4, -5	Fractured, decomposed in some areas; also green shale with quartzite sandstone	Mostly sound roof conditions with some wet areas.
213-358m	RC-1, -2	Black shale, green/grey shale with quartzite and sandstone	Variable roof conditions.
358-510m	RC-1, -2, -3	Sandstone with black shale; beds of siltstone	Variable roof conditions with areas of excessive water.
510-578m	RC-1, -2	Siltstone and sandstone; sandy shale	Variable roof conditions with wet areas.
578-816m	RC-1, -2	Quartzite with dark grey shale, slicks throughout	Some water zones; wet to excessive wet areas also; variable roof conditions.
816-1,069m	RC-2, -3	Sandstone, siltstone with quartzite veins and calzite	Water zones, wet to excessive wet areas; variable roof conditions.
1,069-1,176m	RC-2, -3	Shale with some greenish-grey zones	Water zones, wet to excessive wet areas; variable roof conditions.
1,176-1,222m	RC-3, -4, -5	Weathered rock, limey zone, calzite and quartzite	Very poor roof conditions.

SEQUENTIAL EXCAVATION

The excavation sequence method ordinarily applied within the NATM system is first to excavate the top heading followed with excavating the bench. This procedure includes excavation in all five rock classes. In addition, the invert must be excavated in rock class five (RC-5).

This excavation method appears simple enough, but the advancement must be carefully co-ordinated with the shotcreting and installation of reinforcement materials such as rock bolts, lattice girders, welded wire fabric and pipe spiling.



Excavation and initial support.

The importance in co-ordinating these tasks is not only for the sake of production efficiency but it is also necessary for installation of timely tunnel reinforcement after completing a specified advancement round. An important feature of the NATM system is to develop maximum self-supporting capacity in the ground (rock and/or soil) surrounding the excavation.

The contractor, Newberg, Walker, Rogers, a joint venture, experienced a very slow start, which prohibited it from fully recovering in time to get the project back on schedule. The completion date was to be the beginning of June 1991 but was subsequently rescheduled for the end of November 1991.

The poorest advances were the initial excavation rounds made from the southern portal. The first 91 m from the portal of the tunnel is weathered, decomposed, grey-brown shale (see table 2). The top heading advance in this first section averaged 1·2 m/2-shift day. This is in sharp contrast with advances made shortly before the breakthrough of the excavation when production was as high as 7·3 m/day and 39·6 m/week.

There are reasons for the poor production performance early in the project.

A key manager with broad technical knowledge and tunnelling experience unexpectedly took ill and died. Training for replacement took some time, but, once the contractor's people gained sufficient tunnelling experience, and some new equipment was brought on to the project, a dramatic increase in production followed.

SHOTCRETE

The use of shotcrete is important for carrying out a basic premise of NATM, namely to stabilize the tunnel immediately during excavation. The speed with which the shotcrete can be applied is the reason the newly created tunnel arch can be quickly stabilized and become load-bearing. It helps in supporting and maintaining the strength characteristics of the ground formation that surrounds the tunnel. The shotcrete is often applied in conjunction with rockbolts, rebar spiling or wire mesh depending on the ground conditions. All three reinforcement methods were used on this tunnel project as outlined in Table 1.

The contractor met with difficulties early on with the first applied dry shotcrete because it barely met the minimum strength specification, which is 3,000 lb/in^2 (20·7 MPa). The contractor brought in the concrete specialists, Master Builders Inc., of Cleveland, Ohio, to help in improving the mix designs for both the shotcrete and the final concrete tunnel lining. Master Builders' technical sales manager, George Yoggy, designed a shotcrete programme that included the batch plant dispenser equipment, training the batch plant technician and shotcrete crews, and providing the mix designs.

In place of the powdered accelerator, W. C. O'Brien, director of the Master Builders Shotcrete Division, recommended adding the Master Builders MB-QSL 100 liquid shotcrete accelerator to the shotcrete at the delivery nozzle. This liquid admixture not only produced higher early strengths but also reduced rebound and waste. The mix design can be found in Table 3.

An acceptable rebound is 10% for the walls (vertical surfaces) and 25% for the roofs. The rebound experienced with the new design mix has been 10% and 20% respectively. Panel-test compressive strength results made on 10-hour-old shotcrete specimens ranged from 2,300 to 2,400 lb/in^2 (15·8 to 16·5 MPa). Compressive strength core-test

Table III

DRY SHOTCRETE	
MATERIAL	QUANTITY
Cement	850 lb (385 kg)
Stone ⅜″ or less	900 lb (408 kg)
Sand	2,022 lb (917 kg)
MB QSL 100*	3-4% of the cement weight
Total water	323 lb ±7 lb (146·5 kg)
WET SHOTCRETE	
MATERIAL	QUANTITY
Cement	850 lb (385 kg)
Stone ⅜″ or less	900 lb (408 kg)
Sand	1,985 lb (900 kg)
MB QSL 100*	3-4% of the cement weight
MB-Super-Plasticizer**	10-25 oz/cwt cement (6·6-16·4 ml/kg)
Total water	340 lb (154 kg)
FINAL LINING CONCRETE	
MATERIAL	QUANTITY
Cement	588 lb (267 kg)
Stone #57	1,620 lb (735 kg)
Sand	1,408 lb (639 kg)
Pozzolith 122N***	8 oz/cwt cement (5·3 ml/kg)
MB-VR****	3·5 oz/yd^3 (136 ml/m^3)
Total water	280 lb water/cement .48 (127 kg)

* Liquid shotcrete accelerator.

** High range, water-reducing admixture for wet shotcrete.

*** Normal set, water reducing admixture.

**** Admixture for entraining air in concrete.

results of 28-day-old specimens averaged 6,500 lb/in^2 (44·8 MPa).

The same admixture, MB QSL 100, was added to all of the wet shotcrete. The mix design can be found in Table 3. Whilst the strength achieved at 10 hours was similar to the dry shotcrete it fell short of the 28-day-old dry shotcrete, averaging 6,000 lb/in^2 (41·1 MPa).

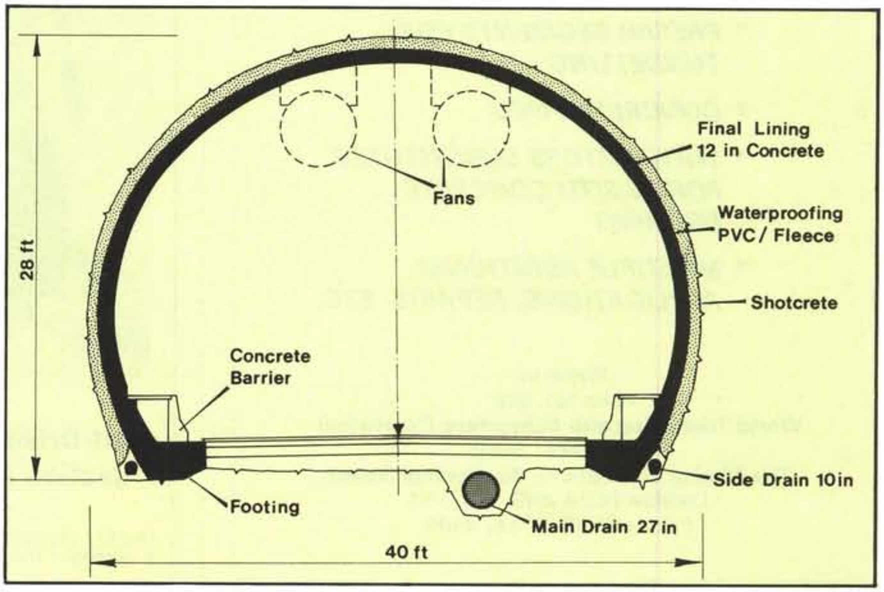
Dry shotcrete was initially applied to the tunnel roof and all wet areas, followed later with an application of wet shotcrete. Wet shotcrete was the choice for the tunnel walls, thereby increasing the production rate.

WATERPROOFING

Water intrusion is one of the great enemies in tunnels. Building a tunnel that is free of water drips or seepage is the goal of all tunnel designers but a goal rarely reached. The waterproofing system installed at the Lehigh Tunnel goes a long way in realizing that goal. A PVC plastic membrane has been installed between the primary lining (shotcrete) and the final lining.

A permeable geotextile is first installed to line the roof and the sides. The geotextile is a non-woven polypropylene 4 mm thick with a permeability rate of 1·11 mm/s. This geotextile liner directs all intruding water behind the walls of the tunnel to two 254 mm dia. collector side drains that are installed longitudinally on either side of the motorway. Lateral pipelines in turn direct the water flow to the 68·6 mm dia. main drain pipe that also runs longitudinally but directly under the motorway.

Regular cross section of Lehigh Tunnel.



The form for the purpose of installing the membrane.

The PVC film comes in rolls of various widths. The film is bonded at the seams after installation to make the liner a complete water-tight membrane. The thickness of the film is 1·5 mm. The tensile strength is 107·4 kg/m^2 and ultimate elongation is 200%.

The Master Builders people also assisted with the final lining concrete design mix. There were many different mixes made up and tested to find the best for this situation, taking into consideration economics and materials specifications. Table 3 shows in detail the design mix that was chosen.

The Lehigh Tunnel is a well-designed and well-built tunnel and is a good example of the results that can be expected from applying the NATM system. The owner has saved considerably on the cost to build the tunnel compared to using the conventional drill and blast method. NATM is a relatively safe method for the workers whilst construction is under way. Perhaps this tunnel is best summed up by comments made recently by

Final lining and the slip form.

the tunnel owner's James B. Wilson, of the Pennsylvannia Turnpike Commission: "While it is too early to come to any final conclusions, we are satisfied with the results of the tunnel to date. We invited bids specifying building the Lehigh Tunnel using either the conventional or the NATM method and NATM won out. If we were to build another tunnel we would probably design and specify the NATM system only."

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