The advances made in Alpine road tunnels and the Channel tunnel have given the public the perception that tunnelling is a straightforward engineering activity. Simply steer a tunnel-boring machine in the right direction and add concrete behind. 'If only', an underground engineer might say.

In June 2000, the metro project at Oporto, Portugal, was begun on a design, build, operate and transfer basis by the consortium Normetro. Participants Cinclus, Jacobs (Gibb) and Earth Tech (Kaiser Engineers) undertook construction management with responsibility for information, programme, safety, quality and cost control. Ensitrans carried out a project review, and following the accident and restructuring of the project, Geodata and Mott-MacDonald took up design and resident engineering responsibilities. Following a five year operating concession, the metro will be transferred to the owner, Metro Do Porto.

The project comprises 70km of light railway, with approximately seven kilometers in single bored tunnel. The bored tunnel sections comprise three separate lines – the Blue Line (C), the Yellow Line (S) and a southern continuation of the Yellow Line (S1) (see image, below, left). The tunnel accommodates two running tracks of standard gauge rail with anti-noise and vibration fixings. The new metro system also has 64 stations, of which 12 have been constructed underground using the new Austrian tunnelling method (NATM) (see box, over page) as well as the diaphragm wall and tangent pile techniques.

Physical challenges
The tunnels were excavated through the Porto granite that underlies the city. It is a hard, resilient two mica igneous rock characterised by a distinct heterogeneity caused by deep weathering. Facilitated by tectonic movements, deep weathering fronts have penetrated the granite in such a manner that completely decomposed granite can be encountered next to fresh material at any possible depth and location. As a result, the hydro-geological regime was also extremely complex and defined by sharp changes in permeability, pore spaces in soils and weathered granite to fractures in fresh rock.

Water levels were generally close to the ground surface and therefore represented the biggest challenge during tunnelling. Man-made ‘minas’ or water mines (see image, over page) and deep wells were also found, both intersecting and above the tunnel alignment.

Two Herrenknecht earth pressure tunnel boring machines (EPBMs), operating at up to three bar pressure, were used to construct the tunnels. They were lined with one-pass pre-cast concrete segments of either 7.8 or 8.0m internal diameter, comprising six segments and a key-stone. The first machine had nominal face openings of 20% to allow excavated material to flow through the machine face, although the opening was increased in the second machine to improve flow. A continuous conveyor belt was used to remove the spoil (excavated rock), with trucks employed to move other materials at grades of up to seven per cent.

The original budget for the whole scheme was 750 million euros, some 55 million euros being allocated to the tunnelling, excluding the lining. The construction programme lasted 60 months in total. Tunnelling started in June 2000, and was completed approximately 42 months later, following the introduction of the second EPBM.
In addition to the Commission’s report, a panel of experts was assembled to perform an executive review, providing constructive criticism and making recommendations on changes to be made to the EPBMs. The panel came up with two major proposals – 
■ The inclusion of an automatic bentonite injection system in order to maintain a minimum face pressure in any situation. A 4m³ pressurised tank was added for discharge at any time, regulated by valves adjusted to the minimum face support pressure. This was particularly useful while passing under high value structures. 
■ The addition of a double piston pump that is permanently attached to the screw conveyor in order to handle wet material that is not manageable with the screw conveyor.

The contractor added his own modifications in recognition of the closed mode operation that would be adopted, including – 
■ Ten independent foam generators. 
■ A new rotary fluid joint which permitted the passage of ground conditioning, high pressure water and hydraulic fluids. 
■ A new twin belt weighing system. 
■ Various improvements to reporting systems so that alerts and alarms could be given to the operator immediately in the event that any of the levels were reached.

The major development to be implemented on the project was the exclusive use of closed mode (pressurised) TBM operation, even through good quality granite proven by the probe holes drilled ahead. The consequence of this approach was the rapid wearing of the cutting discs (flat spotting) as well as the structure of the cutter head. This was despite the treatment with polymer ground conditioners added at the face, and the addition of ploughs in front of the discs to add protection and help avoid clogging. The maintenance of the discs in these conditions required hyperbaric working at between five-and-a-half and six hour intervals – every 7.2m to 7.4m advance – changing four to five cutters daily.

Tunnel collapse
The first tunnel boring machine was stopped after less than 25% of the first drive had been completed following the sudden collapse of two homes and the death of one of the occupants above the tunnel in January 2001 (see image, above, right). The incident, and the appearance of a 250m³ void, delayed the project by nine months and was subject to the Portuguese Government’s Commission of Inquiry.

The Commission report has essentially the force of law and is binding for all the involved parties, with the recommendations forming the skeleton of a specification under which the project could operate. A list of 16 recommendations was generated, which resulted in re-organising the roles of the contractor and construction manager, and the introduction of new design and resident engineer responsibilities. The findings suggested that the collapse could have been avoided by obtaining greater information during boring. First and foremost, drillers are to obtain information before boring by probing ahead of the boring machine. Other significant improvements to geological knowledge and reinforcing teams with trained geotechnical engineers also took place. Investigation of pre-existing ground structures was also conducted and new operating systems for the machines were implemented. All of these improvements were drawn up in a plan for advancing tunnel (PAT) document that circulated among management and engineers.

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Digging deep
The new Austrian tunnelling method (NATM) relies on the inherent strength of the surrounding rock mass being conserved as the main component of tunnel support. Primary support is directed to enable the rock to support itself. NATM requires installation of sophisticated measurement instrumentation embedded in linings, the ground and boreholes. The quick creation of a load-bearing ring is crucial.
Ground conditioning additives were tested, including polymer, foam and bentonite. Polymer was found to be the most reliable to help reduce wear in the face, reduce the density of the material in the chamber and aid material removal through the screw conveyor.

Point of reference
The PAT document, along with its supporting calculations, plans and tunnel sections, provided a summary of the tunnelling parameters for any given section of the drive. It permitted easy reference to any position along the tunnel alignment, showing buildings and condition surveys, expected settlement and other information considered invaluable to all parties during construction. Feedback from the rotary drill probing, compared to the actual conditions encountered, was used to validate and improve the PAT, with the document becoming indispensable for all of those involved in the daily management of the tunnelling works.

The role of modern data loggers and computer networks made possible the rapid and reliable exchange of data so that real-time observation of all important TBM parameters and instrumentation, such as settlement points, piezometers and inclinometers, were available on a continuous basis.

Daily meetings were held between the construction manager, designer and contractor so that information could be exchanged easily and prompt action taken if needed. Analyses of the tunnelling and TBM activities were also made on a daily basis so that any anomalies in the operation of the TBM could be reviewed. Although a formal ‘partnering’ process was not implemented, there was great value in these daily meetings in creating an atmosphere that was open to dialogue and mutual co-operation.

Further information
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Material of the Month

Lycra

What is it? Much popularised as the material of choice for aerobics attire in the 1970s and 1980s, lycra is largely known for creating the tight-fitting clothing that only the skinny can pull off. However, its composition and history are far more complicated than its public image lets on.

Older than it looks – Lycra is part of the elastane (or spandex) family of elastomeric fibres created in 1959 by DuPont chemist Joseph Shivers. Stronger and more durable than rubber, elastane has the ability to be stretched over 500% without breaking, and still recover its original length. The Lycra brand was commercialised in 1962, and is now a registered trademark of the Invista brand of textile products.

US Federal Trade Commission definition of spandex fibre – A manufactured fibre in which the fibre forming substance is a long-chain synthetic polymer comprised of at least 85% of a segmented polyurethane.

How is it made? Almost twenty years of research went into producing this material. Spun from a block copolymer, elastane fibres exploit the high crystallinity and hardness of polyurethane segments, yet remain ‘rubbery’ due to segments of polyethylene glycol.

How does it work? When the material is stretched, the ‘rubbery’ segments of polyethylene glycol move from their coiled state to a more linear structure. The hard segments of polyurethane act as ‘virtual cross-links’, preventing the polymer chains from slipping past each other and taking on a permanent structure. When the force is removed, the ‘rubbery’ segments move back to their preferred coiled state, returning the material to its original shape and length.

Hey good lookin’ – Lycra’s total adhesion to the wearer means that every roll, bump and crease on the body is displayed for the world to see. Outfits that are 100% lycra are therefore not the most popular fashion items. Instead, lycra is almost always combined or applied to other fibres, and has been used with almost every fabric available – cotton, wool, silk, leather, nylon and polyester. Lycra is heat settable, which means it facilitates the transforming of puckered fabrics into flat fabrics, or flat fabrics into permanent rounded shapes.

Advantages? The material’s resistance to body oils, perspiration, lotions and detergents continues to make it a favourite choice of exercise wear for athletes – its main uses are for athletic and swimsuit apparel.

Any uses outside of the gym? Lycra is often used in compression garments, bandages and supports to provide elongation and recovery. A new class of bicomponent polyesters from Invista, the world’s largest integrated fibre and resin company, are designed to provide extra-soft tension for compression garments.

Alexander Popov wearing lycra in the 2004 Olympics