T&T INTERNATIONAL

Pretunnel advance system

Fast and constant advance rates in a variety of ground are offered by the Pretunnelling system, which is described here by Professor Ing. Pietro Lunardi of Rocksoil, Italy.

Numerous studies, observations and experiments carried out over the past 25 years to interpret the mechanics of stress-strain behaviour for tunnel advance have shown that the stability of a tunnel is inextricably linked to the core ahead of the face and its rigidity is a determining element for the statics of construction during tunnel advance.

Research carried out over the last decade has also shown that, by acting on the rigidity of the core, it is possible to regulate the deformation response of the face (extrusion, preconvergence) and of the tunnel (convergence), transforming the core into an instrument for the stabilisation of a tunnel.

In this respect, modern technology provides the means to control the rigidity of the advance core and in particular to provide protection around the profile of the advance core. This protection produces a preconfinement action designed to prevent the principal minor stress σ_3 in the ground around the tunnel from decaying to zero and also to protect the core from excessive stress states in terms of the major principal stress σ_1. The preventative formation of an 'arch effect' close to the walls of the excavation is thereby guaranteed even in the most difficult ground (such as in loose soils). This type of intervention can be used to complement ground improvement of the core ahead of the face. It provides best results in fairly homogeneous ground, providing regular advance rates and good speeds.

Recently, a new construction technology has been developed by Trevi with the assistance of Rocksoil of Milan (Italy). It is known as 'Pretunnel' advance and can be classified as belonging to the third of the types mentioned above (*T&T International, April '97, p32*). It combines the advantages of mechanised excavation with those offered by direct ground improvement of the core, minimising the inherent disadvantages of these two techniques and opening up possibilities for the construction of tunnels which, until now, were considered almost science fiction.

Pretunnelling involves laying the final load bearing structure before excavation. Excavation consists merely of removing the earth enclosed within a tunnel lining which is already functional. The idea developed out of mechanical pre-cutting technology and uses the same main concept. As distinct from mechanical pre-cutting, with Pretunnelling the actual final lining of the tunnel is produced in the form of longitudinally interconnected lining sections in the shape of 10-12 m long, 400-1100mm thick truncated cones.

Pretunnel technology is strictly dependent on equipment designed especially for it. This consists of a self-propelled tubular frame (Figs 1 and 2) fitted with an arm held by rotating telescopic locking arms powered by six hydraulic motors. The cutting tool ('cutter module') slides longitudinally inside the arm, which holds it and guides it through an arc of 270°. The machine moves along the tunnel on two Caterpillar tracks connected to the frame by telescopic supports. The latter are used to centre the machine on the longitudinal axis of the tunnel ready for cutting once the face is reached.

The cutter module consists of two chains, assembled on a single rigid arm with a box structure. The chains are fitted with discs and spikes and the geometry, cutting angle and number of cutters can all be varied according to the ground.

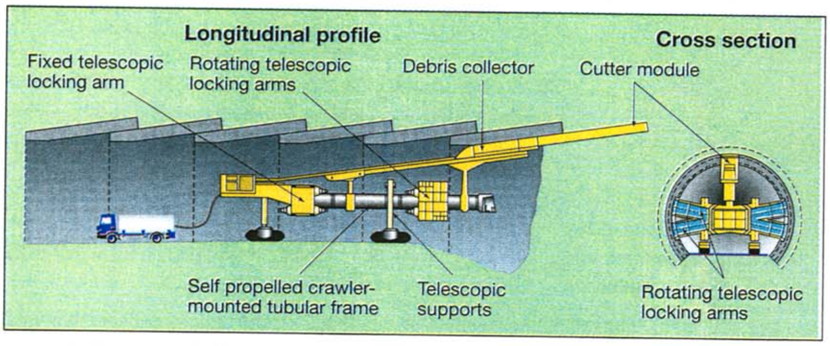


Fig 1. The Pretunnel advance system

The speed of rotation of each chain can be regulated: each rotates in opposite directions for point excavation (Point Pretunnelling) and in the same direction for continuous excavation (Continuous Pretunnelling). The machine can therefore be regulated for optimum cutting performance in all types of ground, including heterogeneous ground (stone blocks and/or random boulders, rocky interbeds, alternations of rock with degraded strata, etc.).

The cutter module is fitted with a series of sliding blocks which normally remain fixed into the side of the cutters (Fig 3). When the cutter module is in position and cutting actually begins, however, these blocks slide out and press against the soil or rock. Finally, a slipform for casting concrete is fitted behind the cutter module. It moves as a fixed piece together with the module, and concrete is pumped into it through special tremie pipes to fill the area that has been excavated (Fig 3).

How it operates

The first stage consists of positioning the machine at the face using the telescopic supports on which the frame is mounted. The axis of rotation of the equipment must coincide with the centreline of the truncated cone to be excavated. The arm holding the cutter module is then positioned, setting the length and radius so that the outer edge of the new cut coincides with the inner edge of the previous cut.

The cutter first penetrates lengthways into the ground ahead of the face and then changes direction after insertion of the formwork to cut around the profile of the future tunnel. As cutting proceeds, the empty space left behind the cutter is continuously filled with concrete. Maximum effective cutting depth is currently 12m and the thickness can be varied.

The machine can be used for tunnels with a minimum i.d. of 9m to a maximum of 15m. However, the same principles could be applied to design smaller or larger machines which would exceed these limits.

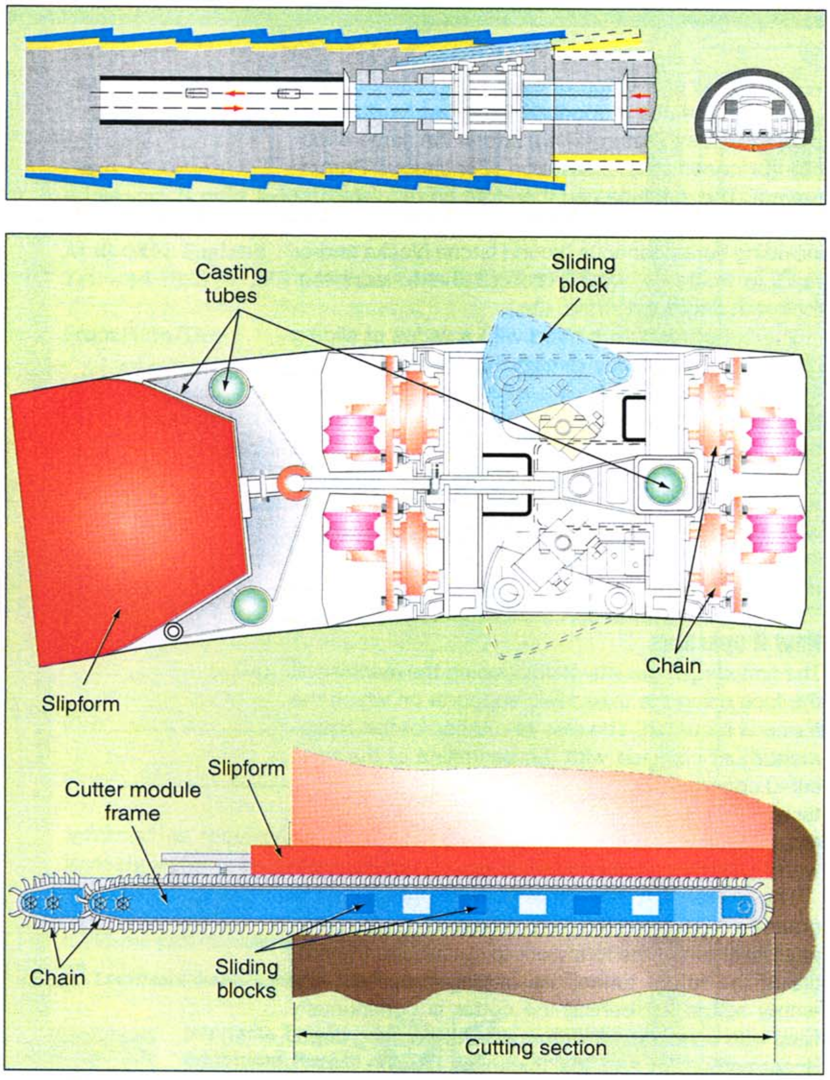
The concrete may be fibre reinforced and is pumped under pressure behind the cutter. It fills the empty space left by the cutter uniformly and provides the thrust needed to guarantee the correct 'contact pressure' of the cutter against the soil or rock.

The surface of the fresh concrete that is left at the face as the cut and cast operation gradually proceeds is initially protected by a slipform attached to the cutter module, which advances with the module. When this has passed, a shotcrete plug with fast setting silicate admixtures prevents the concrete from flowing out when the slipform is withdrawn.

The line of the cut is maintained and local variations in the quality of the ground are overcome by opening or closing the sliding blocks individually and by regulating the concrete pressure as it is pumped along the length of the formwork through tremie pipes (Fig 3).

When tunnels are located at considerable depth or in swelling ground where convergence must be controlled to reduce stress on the lining, the formwork can be shaped so that the outer band of the cut is filled with compressible material as concrete is cast in the inner ring. This material will absorb deformations of the rock mass to the extent allowed for in the design specifications. Once the cut has been made, the cutter is withdrawn together with the slipform, followed immediately by point casting to fill the empty space created with concrete.

Fig 2. Details of the Pretunnel equipment and operation



The operating procedure just described is termed Continuous Pretunnelling to distinguish it from Point Pretunnelling, which involves longitudinal cutting only and filling with concrete immediately after withdrawal of the cutter. The latter method is used to create a lining consisting of a series of interconnected panels. All the 'odd' panels are completed first and then the 'even' panels so that perfect joints can be made between them by partially overlapping the even panels with the odd panels, which have already set.

Once each section of lining is complete, the equipment is backed out and the section of lining is 'emptied' of the soil it contains. Soil excavation stops before the full 10m length of the installed lining section is reached. The reason is to leave a safety margin with regard to stability of the face, which is indispensable to the Pretunnelling technique.

Once the soil has been removed, the machine is returned for the installation of another section of tunnel lining. When the tunnel is complete, an extra lining can be cast as a finish to smooth out the otherwise stepped appearance, or else panels can be fitted.

Statics advantages

The use of Pretunnelling technology as opposed to traditional technologies provides many advantages from a statics point of view:

- During excavation. The 'cut and cast' technique of casting a lining at the same time as the rock is cut produces continuous confinement of the walls of the excavation, reducing negative effects such as ground breaking off free surfaces or swelling of some materials. The enormous shear strength of the lining sections just cast significantly increases safety as far as potholes in the ceiling are concerned, especially with reduced overburdens.
- Projection of the lining section from 1m (minimum) to 10m ahead of the face retards the appearance and diminishes the effects (longitudinal stability of the tunnel) of extrusion phenomena by shifting the zone in which the effects are triggered further into the rock face. Ideal preconfinement action is achieved by laying the final lining before actual excavation of the tunnel. This prevents even transitory removal of the minor principal stress σ_3 in the ground surrounding the tunnel.

Consequently, formation of a band of ground with plastic behaviour around the tunnel is reduced or in certain circumstances actually prevented and the rock mass is able to support itself and to develop an 'arch effect' ahead of the face which is capable of ensuring the stability of the tunnel in the long and short term (transverse stability of the tunnel).

- The truncated cone shape of the lining sections increases their rigidity and consequently reduces squeezing on the core, especially if the sections are closed to form a complete ring. This reduces extrusion, increases the bearing capacity of the sections and consequently their stability. Friction forces develop along the inner surface of the lining sections which act to oppose extrusion at the face. The above considerations mean that subsidence phenomena typical of tunnels with shallow overburdens and wide spans in urban areas are eliminated.
- After excavation: the lining sections are already in place and ready for load bearing when the support provided by the material in the core is removed. The lining that has been constructed is the final one and is fully capable of retaining the loads that develop in the long term after excavation. The lining can be 'closed' rapidly without having to postpone unduly the instal-

lation of a tunnel invert.

For a better understanding of how Pretunnelling works with regard to tunnel excavation, it is worth looking at how it interacts with the surrounding ground during advance.

The graph calculation method, known as the characteristic line method, is particularly appropriate for this purpose. A characteristic line is a curve that relates the confinement pressure exerted radially on the walls of a tunnel to the radial convergence of the tunnel. Three principal characteristic lines can be constructed for a tunnel:

- the line of the core: this can be used to forecast the behaviour of the tunnel at the face (extrusion, preconvergence) and to predict the influence of the rigidity of the core on deformation of the cavity;
- the characteristic line that acts at the face: by taking into account the effect of the three dimensional stresses in the vicinity of the face, this can be used to deduce the amount of convergence the tunnel has already been subjected to from considerations about the stress-strain behaviour of the core;
- the characteristic line of the cavity acting on any section of the tunnel that is sufficiently far from the face for the stress-strain state to be considered lying in one plane.

Fig 4 shows the typical characteristic lines for a tunnel to be excavated in ground with poor geomechanical properties in relation to the original natural stress state. It can be seen from the characteristic line for the cavity (A), calculated in the absence of preconfinement of the excavation, that the tunnel would not be stable without adequate works to stabilise it. Convergence of the cavity would continue towards infinity as internal confinement pressure diminishes.

At the face, however, the tunnel would be stable in the short term, since the characteristic line for the core (C) intersects with that for the face (B) in the elastic plastic range. In fact, equilibrium would be reached at the face in the short term, with radial preconvergence equal to Δr_O. Even if a lining ring with a given rigidity were installed immediately behind the face, it could only counter deformation that occurs after it is in place. Consequently, the characteristic line that describes it (D), starting from the radial preconvergence Δr_O that has already occurred, would intersect that for the cavity, giving a confinement pressure P.

If tunnel advance were effected using the Pretunnelling method, however, the tunnel lining would already be functioning several metres ahead of the arrival of the face and would be able to intercept deformation much earlier, when radial preconvergence was still at $\Delta r'_O$. In addition, there is the fact that the preconfinement action exerted by the Pretunnel shell on the ground surrounding the future tunnel would fully prevent even temporary removal of the minor principal stress σ_3, and consequently prevent the decay of its strength and deformation properties. This translates into a flatter curve for the characteristic line for the cavity, which would remain in the elastic range for a significantly longer section of its length.

As a result, a lining with the same rigidity as a traditional lining but placed using Pretunnel methods, starting from radial preconvergence that has already occurred $\Delta r'_O$, would intercept the characteristic line of the cavity (A'), calculated taking into account the preconfinement effect produced by the system, with a confinement pressure P' lower than P. At the same time, the core of ground ahead of the face would be subject to preconvergence $\Delta r_O << \Delta r'_O$, would remain much more stable, and extrusion at the face would be significantly reduced.

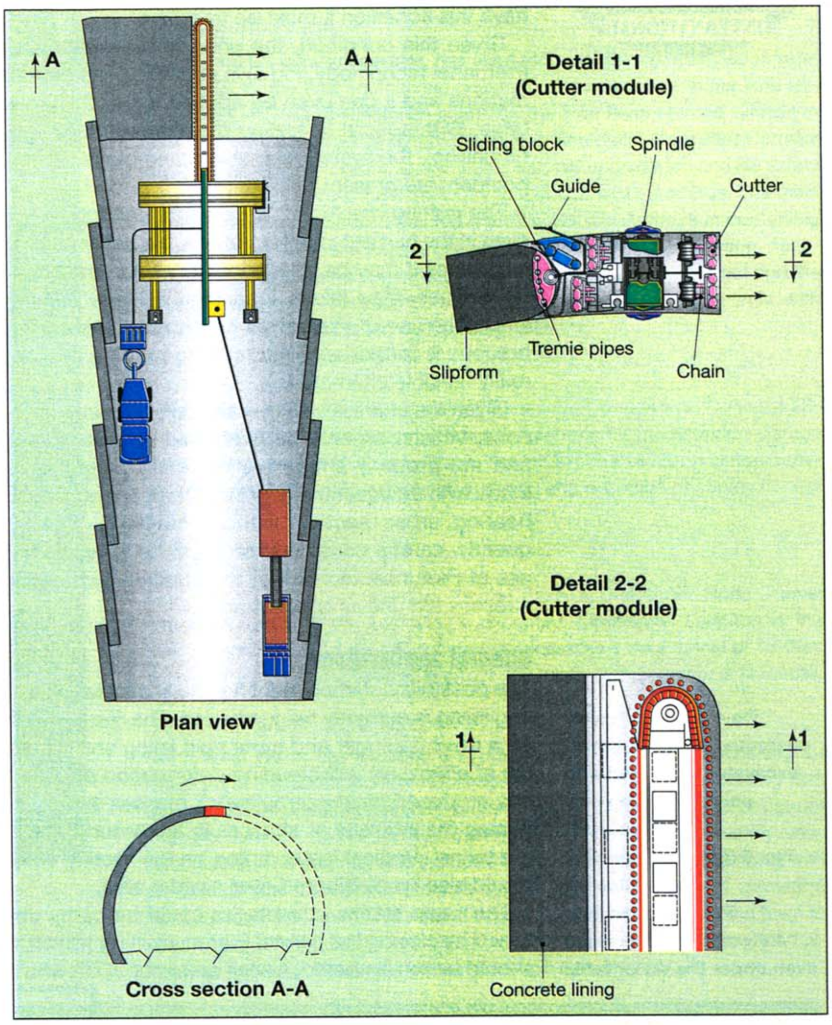


Fig 3. The cutter module is fitted with a series of blocks which normally remain fixed into the side of the cutters

Pretunnel technology was developed predominantly for excavation of tunnels in difficult stress-strain conditions. However, the technique is only feasible if the soil has a minimum of cohesion so that the ground is self supporting during the first cut and at least until the formwork has been inserted and the casting of the lining begun. If the ground does not

Operational advantages

There are clear operational advantages to be added to the statics advantages:

- total elimination of overbreak;
- elimination of the need for filler injections and/or pressurisation of the ground behind the tunnel lining;
- elimination of temporary stabilisation works thanks to immediate construction of the final lining;
- significant reduction in the thickness of the lining required to achieve long- and short-term stabilisation of the tunnel as a result of the preconfinement action exerted;
- almost complete mechanisation of the works, with regular and constant tunnel advance. There are considerable and favourable repercussions for site economies and production rates (approximately 2m of finished tunnel /day), while operational flexibility is maintained since the same equipment can be used for tunnels of different diameter and in different ground with different geomechanical properties;
- energy savings: consumption is minimised because the cut is made only for the thickness of the lining;
- construction site times are shorter than with other mechanised systems (shields for example), with consequent increase in profitability, allowing the the system to be used even for short tunnels.

have this cohesion it must be treated.

Given this condition, the principal application for Pretunnel technology (Fig 5) is in heterogeneous formations and it can even be applied under the water table. With special operating procedures (Point Pretunnelling), the system can also be employed where boulders are present.

The cutting machinery is powerful enough to use even in the hardest rock formations. However, in such conditions it may be uneconomical, since traditional techniques may prove less costly. Nevertheless, where the use of explosives or the production of vibrations is forbidden, Pretunnelling may be the only really feasible alternative.

Given the characteristics of the concrete lining sections, which can only be reinforced with steel fibre and not properly armoured, the lining cannot bear loads with an eccentricity greater than 1/6 of its load bearing cross section without cracking. Consequently, careful consideration must be given to the use of Pretunnel technology in conditions where the stresses are unevenly distributed.

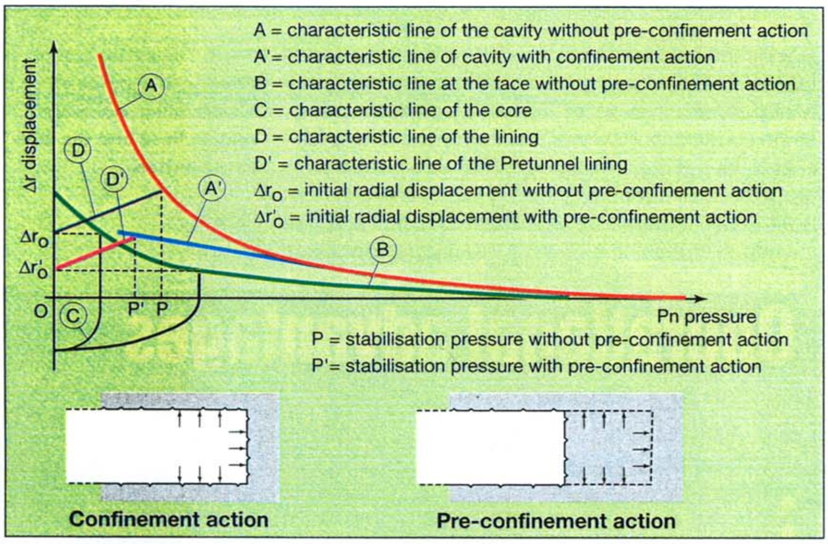
Special applications

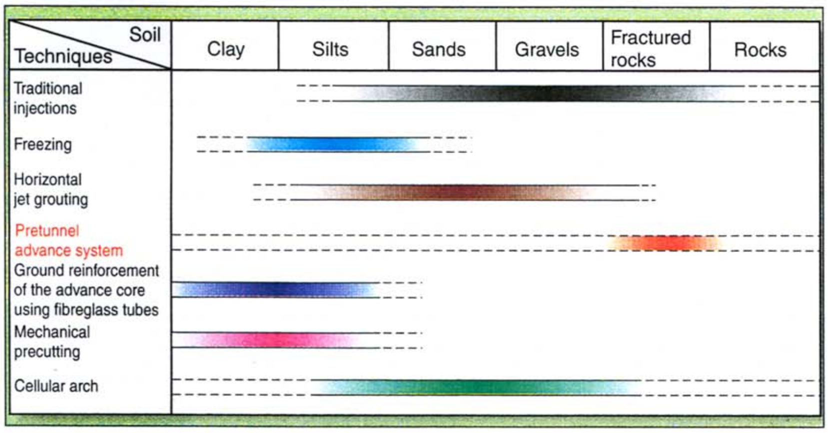
The possibility of implementing a fully circular closed ring lining is currently being studied. The result would be a much stronger and more rigid lining shell capable of effectively withstanding deformation phenomena produced by anisotropic rock masses and of reducing the intensity of stresses in the ground below the tunnel. Vertical loads acting on the footing walls would also be distributed over a wider area.

The same statics advantages could be partly obtained by closing the normal Pretunnel lining (which, it should be remembered, traces an arc of 270°) with a series of concrete buttresses laid on the floor of the tunnel. Experimentation regarding this particular special application is at an advanced stage.

Fig 4 (below). Typical characteristics of a tunnel excavated in ground with poor geomechanical properties

Fig 5 (bottom). Principal application for Pretunnelling is in heterogeneous ground, even under the water table





Trevi holds the patent for the Pretunnel system and has tested it on a short experimental tunnel. The ground chosen consisted of a calcareous-sandstone complex fractured to a varying extent. Laboratory measurements on the rock matrix of the strength properties of the rock were as follows:

Resistance to unconfined compression was 37MPa and resistance to tensile stress (Brazilian test)was 3MPa, with an index of hardness according to Knoop equal to 1,645MPa at right angles to the stratification and 1,073MPa parallel to it.

The experiment consisted of laying an 8.5m long concrete lining section with a circular cross section of constant radius and completion of the tunnel with removal of the enclosed soil. The radius of the cross section increased from 3.7m. at the face to 4.4m at the end of the run.

The machine was fitted with instrumentation to measure and record the following parameters:

- depth reached by the cutter module;
- speed of rotation of the chains;
- pressure in the hydraulic circuit of the jacks;
- pressure of the concrete in the casting chamber;
- angle of inclination of the cutter module;
- deformation at the end of the cutter module;
- deviation at the end of the cutter module;

The first half of the lining starting at the foot of the right wall and continuing up to the peak of the crown was installed using the Continuous Pretunnel technique and the second, left-hand, half with the Point Pretunnel technique by cutting and casting as the cutter is extracted to produce seven panels stretching from the foot of the left-hand wall up to the crown.

Results of the experiments show that advance rates of 1.5-2m/day can be achieved in practice, depending on the characteristics of the cross section and of the ground to be tunnelled.

On completion of the test, the results were checked by Georadar measurements, which showed the excellent uniformity of the thickness of the lining and the absence of unevenness in the concrete and of separation between the lining and the rock behind it. Tests on samples taken from the lining after 28 days gave strength values higher than 30MPa.

Conclusions

Pretunnel technology involves creation of a protective shell around the advance core and is therefore entitled to classification as one of those tunnelling technologies that regulates deformation of the face and the cavity by acting on the rigidity of the core. It thus functions in accordance with the most recent orientations concerning the design and construction of tunnels to provide design and construction engineers with an innovative advance system that is highly industrialised and reliable and is capable of producing fast (approximately 2m of finished tunnel/day) and constant advance rates in a wide range of soils.

The system is already being employed with success in construction of the Colleferro Tunnel on the high-speed Rome-Naples railway line and its use is planned for some of the tunnels on the Bologna-Florence high-speed railway line. In the motorway field, the Pretunnel system is soon to be used for widening the Nazzano Tunnel from two to three lanes in both directions without closing the tunnel to traffic as part of improvements to the A1 Milan-Naples motorway to meet increased traffic demands. T&T