Tunnelling under the Via Appia Antica in Rome

Professor Eng. Pietro Lunardi, Lunardi Consulting Engineers, Milan, reports record advance rates for tunnelling under this Roman consular road in the course of widening the Rome Ring Road.

The Appia Antica tunnel was finished at the end of June 1999, completing one of the most important projects for the 2000 Jubilee year. The tunnel is an essential part of the operation to widen the three lanes of both carriageways of the Grande Raccordo Anulare (GRA), the large motorway ring road around Rome, an improvement which had become crucial given current traffic demands (Fig 1).

The 600m twin tunnel passes just a few metres below the Via Appia Antica, which is crossed by the ring road mentioned above, and has enabled the original environment of the ancient Roman road to be restored. It is one of the widest, longest and most modern urban road tunnels in the world, with the singular characteristic that the fabric of an ancient landscape has been reconstructed above it.

To complete this project, the consulting engineers in charge of the construction design (Rocksoil of Milan) and the contractor (Società Italiana per Condotte d'Acqua) were obliged to work under very severe constraints. The Jubilee 2000 deadline itself imposed a tight schedule and, in addition, the requirement to provide three lanes and an emergency lane meant constructing two tunnels with a width of 20.7m and a height of 12.5m, having an excavation cross section of 204m^2. The design and construction methods adopted had to ensure extremely high production rates and, at the same time, guarantee safety.

It was decided that traditional design and construction methods would not be able to complete the tunnel on schedule while maintaining acceptable safety standards. The construction method provided by the original design involved prior excavation of side tunnels and casting of sidewalls. It was employed for a short stretch at portals 1 and 2, but, due to the lack of space in the narrow side drifts, it was impossible to exceed advance rates of 0.5m/day for each face. Even top heading and bench advance, although allowing more room for mechanised methods, would have posed serious problems for removing the bench and, in any case, did not guarantee tunnel stability.

It was therefore decided to change the design and continue construction of this difficult tunnel using the Analysis of Controlled Deformation in Rocks and Soils approach (ADECO) [1], already employed with success in other complex situations [2, 3, 4]. This approach involves full face advance even in the poorest ground and ensures the stability of the face (the only critical zone with this type of advance) by means of appropriate ground reinforcement. The advantages afforded by this method and the working space it provides for a high degree of mechanisation made it possible to complete the project safely within budget and on time.

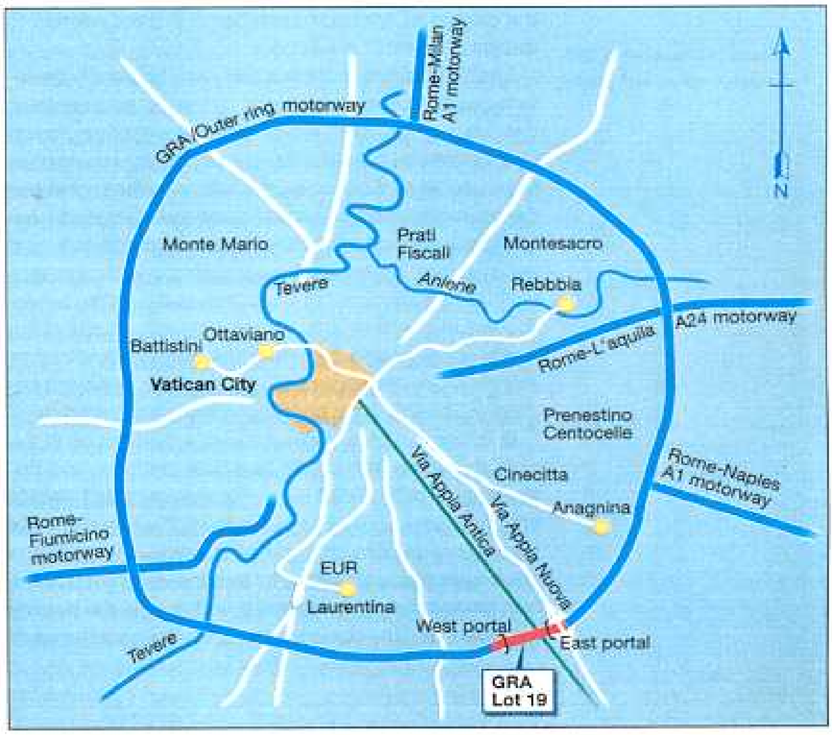

Fig 1. View of the 'Appia Antica' old Roman road and its relationship with Rome's GRA outer ring motorway

Geology

The section of the Grande Raccordo Anulare, where the tunnel under the Via Appia Antica is located, runs through the NW sector of the volcanic body of the Colli Albani, which rises between the platform carbonatic ('Laziale - Abruzzese' series) and the transition ('Umbro - Sabina' series) structures and, with the Sabatino and Vulsino bodies, forms part of the so-called 'Vulcano Laziale'. The geological history of this 'Vulcano' began 800 000 years ago and is divided into distinct phases.

During the course of the Tuscolano - Artemisio phase in particular, four distinct pyroclastic flows were deposited, most of which reached Rome. The part of the route through which the tunnel runs is affected mainly by the most recent pyroclastite deposits of the fourth flow, the last of the Tuscolano - Artemisio phase - the middle Pleistocene. These 'pyroclastites and volcanic cemented scoriae' deposits consist of well stratified pyroclastites. The 'Lava di Capo di Bove' (phonolithic tephrites and leucites) overlies the pyroclastites. It is fissured and constitutes the longest flow of the group, reaching well into the city.

These materials have completely filled the pre-existing Paleo depressions, which are configured radially with respect to the ancient crater and run across the tunnel route. Subsequently, erosion modified the local morphology further, the different phases and volcanic products which have gradually filled and modified the previous morphology, producing extreme complexity in the stratigraphic interfaces.

Design aspects

The ADECO design process is carried out in three main stages known as the survey, diagnosis and therapy phases. The survey phase for the tunnel under Via Appia Antica took the form of a thorough, in-depth geological survey to provide a geological, stratigraphic and geotechnical picture as close to reality as possible, the degree of approximation being in strict relation to design demands for reliability.

The first objective of the survey was to identify the interfaces between the different deposits and between the 'Lava di Capo di Bova' and the underlying pyroclastic material in particular, whose position would have a determining influence on the statics of the tunnel and the methods of construction to be considered. A second objective was to identify the predominantly silty and sandy zones, as their make-up determines the geomechanical behaviour of the rock mass. As a third objective, the survey had to furnish greater knowledge of the hydro-geology and ascertain the strength and deformation characteristics of the ground with sufficient accuracy. The following operations were performed :

- 30 vertical boreholes, some with destruction of the core and some with continuous core sampling and determination of the RQD index (for the pyroclastic material especially), drilled to a depth of 20-30m to below tunnel level at 50m intervals on average. Five sections were surveyed, with two or three surveys for each of the twin tunnels. Particular attention was paid to the base of the sidewalls. The surveys employed inclinometers and settlement gauges in such a way that they could continue to be used for monitoring during construction.
- Five 'down hole' seismic tests for full-scale assessment of the deformation properties of the pyroclastic ground
- 15 pressiometric tests (eight along the outer tunnel and seven along the inner tunnel) to measure the strength and deformation characteristics of the ground directly and to calibrate the seismic tests mentioned above
- Four Lefranc falling head permeability tests to measure the permeability of the ground in situ at tunnel depth
- 61 SPT tests to estimate the strength properties of the material in situ

Table 1.

GROUND	γ (kN/m³)	c' (MPa)	φ (°)	E (MPa)	ν	k (cm/s)
Basalt TL	27	20	45	8.000	0.25	/
Sandy-gravelly pyroclastites PS-PG1.	18.5	0.01	35	110	0.35	25x10-4
Silty-clayey weak sandy pyroclastites PA	20.4	0.03	24	100	0.35	7.5x10-5
Pseudo cohesive TS pyroclastites (Tufo Lionato)	18	0.2	35	200	0.35	/

The tunnel was to pass exclusively through ground from the Tuscolano-Artemisio phase, running mainly through the pyroclastic deposits of the fourth flow (pozzolanic pyroclastites, weathered at times, consisting of scoriae and lapilli with granulometry classification: silty clayey PA, sandy gravelly PG and sandy silty, weakly gravelly PS) and only marginally, in the invert area, through the pseudo-cohesive pyroclastites ('Tufo Lionato'TS) of the third flow, consisting of scoriae, pumices, lithic lava and phenocrystals of leucites, pyroxenes and mica. The basalt, Tl, of the 'Lava di Capo Bove', produced by the Faete phase would constitute the overburden above the tunnel.

The water table would always remain below the extrados of the tunnel invert and, consequently, any seepage of water during excavation would be exclusively due to the percolation of rainwater following short paths of infiltration in locally very permeable materials.

Numerous laboratory tests were performed on samples taken during the surveys to characterise the geomechanics of the various materials. Unfortunately, the nature of the ground meant that only a small percentage of undisturbed samples was obtained and it was impossible to shape suitable test pieces for triaxial tests. As a result, only direct shear tests were performed, which overestimate values for the angle of friction.

This, together with the results of the survey campaign as a whole, was taken into account and the parameters summarised in Table 1 were attributed to the various types of ground.

The diagnosis phase

Here, the designer uses the information from the survey phase to predict the stress-strain behaviour of the tunnel in the long and short term under the hypothesis of no stabilisation intervention. It is well known that this behaviour is closely connected with the formation of an arch effect and its presence and position with respect to the surfaces of the tunnel are signalled by the deformation response of the medium to the action of excavation.

Analysis of controlled deformation in rocks and soils shows that the central element to be considered for correct assessment of how deformation develops and thus of the ultimate stability of the proposed tunnel is the stress-strain behaviour of the advance core in the absence of intervention to stabilise it. This behaviour is conditioned by:

- The strength and deformation properties of the rock mass, which is connected with the various geological structures through which the tunnel passes
- The loads resulting from the overburden and stresses of tectonic origin
- The size and shape of the cross section excavated
- The method of tunnel advance

There are three different possible types of behaviour: Category A - Stable face; Category B - Face stable in the short term; Category C - Unstable face.

The study carried out for this tunnel discovered unstable face behaviour in the portal zones, where the very shallow overburden would not have allowed any natural formation of an arch. There was short-term face stability behaviour in the rest of the tunnel, where an arch effect would have been formed close to the perimeter of the tunnel, which would then have gradually shifted away from it as the ground began to plasticise. This phenomenon would inevitably have been triggered with negative consequences for the long-term stability of the tunnel and overlying structures.

Therapy phase

In the therapy phase, the design engineer decides on the basis of the predictions made in the diagnosis phase which type of action to employ and the intervention required to achieve complete stabilisation of the tunnel. In addition, as part of this phase it was decided how the action was to be implemented and how tunnel advance would proceed to ensure long- and short-term stability. The procedure selected for the portal zones was different from that for the running tunnel because of the different type of behaviour forecast.

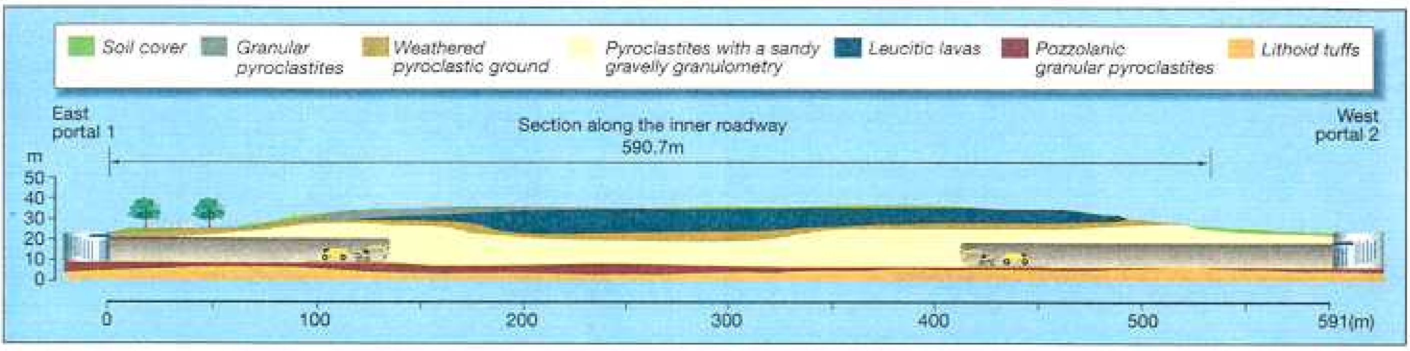

Fig 2. Geological profile along the inner roadway

Portal zones

In order for advance to take place safely under unstable face conditions, it is imperative to employ methods that will create an artificial arch effect ahead of the face in the place of a natural arch which cannot be formed because of the particular stress-strain conditions that exist. This is necessary to guarantee the integrity of both the face and the ground around the excavation.

While excavation works at portals 1 and 2 (inner carriageway) were tackled without great success using the multiple drift technique of the original design, the new design specified full face advance for portals 3 and 4 (outer carriageway) after first reinforcing the advance core and the ground around the cavity with fibre glass structural elements and horizontal jet grouting respectively.

The excavation would then be stabilised with a preliminary lining consisting of a 250mm layer of shotcrete reinforced with HEB 200 steel ribs and wire mesh and then closed with the kickers and the tunnel invert at a distance of not more than 14m from the face. Placing the waterproof lining and casting the final lining in reinforced concrete would then follow.

Running tunnel

Under 'face stable in short term' conditions, to ensure that an arch effect is formed and maintained as close as possible to the walls of the excavation, it is essential to take action to contain plasticisation of the ground that occurs at the face and around the excavation, and the deformation that results from it (extrusion of the core and convergence of the cavity).

For this tunnel, account was taken of the characteristics of the ground; the overburden and the resulting stress states in play; the type and entity of the deformation phenomena to be contained as forecast during the diagnosis phase; and the need to limit surface subsidence to avoid disturbance to the remains of the ancient Roman road above.

It was then decided to advance full face in steps of 1m, with a cross section of 194m², after first reinforcing the advance core with fibreglass structural elements and rendering the face concave in shape. This was to be followed by immediate placing of the preliminary lining, consisting of steel ribs and shotcrete, and then the kickers and tunnel invert at a short distance from the face itself. The aim was to ensure a gradual and consistent passage from the original statics conditions of the ground, confined before excavation by the presence of a rigid advance core, to the conditions of the ground when contained by the preliminary lining after excavation. Placing the waterproofing and final lining would then complete the tunnel.

Design calculations

After initial calculations conducted using simplified methods, intervention to stabilise the tunnel was checked by employing two and three dimensional finite element models in the non-linear field and found to be correct. The calculations not only confirmed that the approach considered was both correct and feasible but also furnished valuable long- and short-term predictions of deformation behaviour (extrusion, convergence, surface subsidence) and stress states in the linings for different operational procedures (e.g. placing the tunnel invert at different distances from the face). It was thus possible to design the tunnel completely in every operational and geometric detail (shape of the cross section, operating cycles, tunnel advance steps, etc.).

The final design developed for the running tunnel was as follows:

- to control the deformation response of the ground ahead of the face: the placing of 76 fibre glass structural elements, 24m long, with a minimum overlap of 10m
- to control the short-term deformation response back from the face: the placing of a preliminary lining

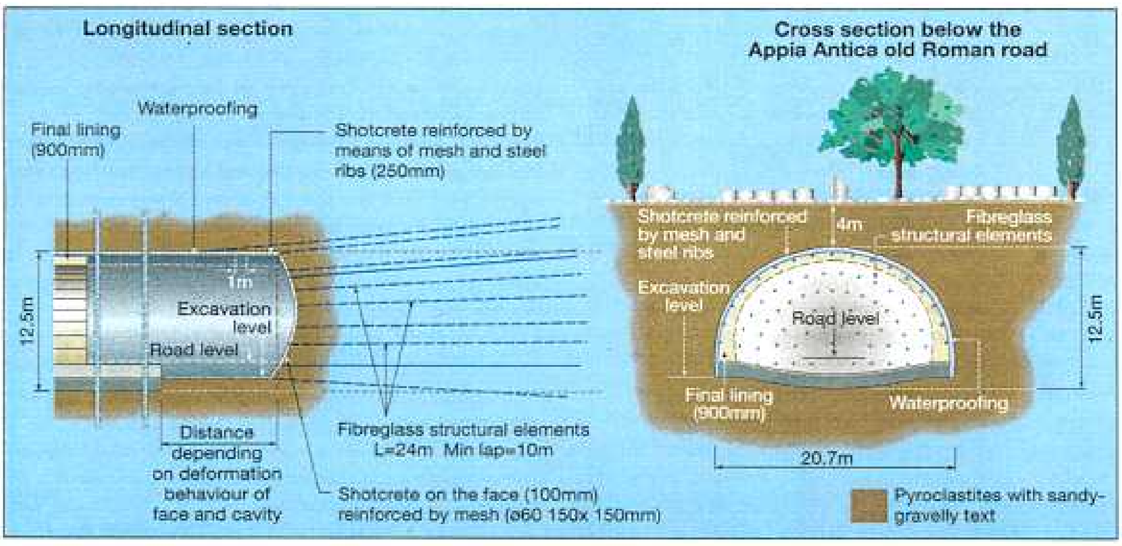

Fig 3. The full face construction method as used on the Appia Antica Tunnel

consisting of double IPN220 steel ribs and a 250mm layer of shotcrete reinforced with wire mesh, completed with a tunnel invert in reinforced concrete, 1.20m. thick, placed at a distance from the face of 14-38m. from it, to be decided by the design engineer on the basis of actual face extrusion values measured

- to provide long-term stability: a final lining in concrete with a minimum thickness, in the crown, of 0.9m.

Construction aspects

When the ADECO-RS approach is employed, construction must not begin until the entire design procedure is complete. The construction aspects consist of the operational and monitoring phases.

The operational phase: construction began at portal No. 1 (Fig 2) in November 1998 and, from January 1999 onwards, tunnel advance proceeded simultaneously from all four portals in order to meet the completion deadline. Apart from the first few metres driven using the side drift system as specified in the original design (27m at portal No. 1 and 13.6m at portal No. 2), work was performed in cycles according to the full face approach following the procedure illustrated in Fig 3.

Tunnel excavation in 1m steps was performed by a ripper mounted on an excavator, making sure to maintain the correct shape of the face. Total advance rates were equal to 70m/week of finished tunnel, an average of 2.5m/day on each face, and this was maintained from start to end of work, with peaks of 3.3m/day/face. The marked improvement in advance rates achieved by passing from the original to the full face design method can be seen from the different slopes of the relative tunnel advance curves in Fig 4.

Little more than six months was required to excavate the 1242m and one inner carriageway was opened to traffic in September 1999. The outer carriageway was opened at the end of November 1999 and the whole tunnel went into service at the beginning of January 2000 with the opening of the third lane.

Particular attention was paid during excavation to maintaining the correct distance between the face and the point at which the tunnel invert was placed, calibrating it on the basis of extrusion measures as tunnelling proceeded. This operation confers rigidity on the ring of the lining, and, if it had been delayed too long on a tunnel span of 20m, not only would the advantages obtained from full face advance with a rigid core have been lost and admissible values for surface subsidence exceeded, but the stability of the whole tunnel could have been put at risk!

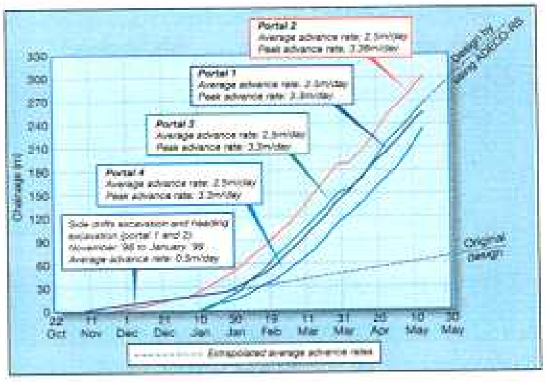

Fig 4. Graph showing the relative tunnel advance curves

Monitoring during construction: In order to verify that the stress-strain behaviour of the face and the cavity during construction actually corresponded to that predicted by the calculations performed during the design phase, an intensive monitoring campaign was carried out involving measurement of extrusion, convergence and surface subsidence. Comparison of predicted and actual deformation allows the reliability of the design to be ascertained immediately as well as appropriate calibration and fine tuning of crucial parameters to be performed during construction, within the limits set in the design (e.g. distance from the face at which the tunnel invert and kickers were placed).

The results of monitoring are of some interest. While full face advance was employed on a tunnel cross section of 194m^2 and a tunnel span of 20.6m, maximum extrusion and convergence values were in the order of 15mm, while surface subsidence, despite the extremely shallow overburdens and poor quality of the ground, never exceeded 20-25mm as against the 50mm measured during the few metres of tunnel advance when the original design was employed. These values were absolutely in line with those predicted by calculations at the design moment and they confirm that the ground remained almost totally in the elastic range, thanks to the preconfinement exerted by the advance core which had been stiffened by advance ground reinforcement. The result was excellent advance rates achieved in absolute safety.

Conclusions

When the extremely poor ground conditions, very shallow overburdens and the exceptional nature of the geometry and width of the tunnel cross section are considered, the excellent results achieved during construction of the tunnel under the Via Appia Antica demonstrate just how extremely flexible, reliable and, in the final analysis, universal the approach based on the controlled analysis of deformation in rocks and soils is. The construction principles of this approach (full face advance, after first improving the ground in the advance core, even in the most difficult ground) were found to be completely sound even for the excavation of an urban tunnel, like that under the Via Appia Antica, over 20m wide under a very shallow overburden without any appreciable surface subsidence. Considerable advantages were also gained in terms of time schedules and budgets. Rigorous application of these principles achieved what seemed to be impossible using traditional systems: excavation of a tunnel with a total cross section of 204m^2 at an average speed of 2.5 m/day and linearity of advance rates never before achieved. It is not difficult to deduce from the advance rate curves in Fig. 4 that if tunnel advance had continued using multiple-drift excavation according to the original design, as they started to do at portals 1 and 2, the work would not have been completed until 2003!

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