PROCEEDINGS OF THE WORLD TUNNEL CONGRESS '99
OSLO/NORWAY/31 MAY – 3 JUNE 1999

Challenges for the 21st Century

Edited by

T. Alten, L. Backer, P. Bollingmo, E. Broch, K. Holmøy, K.G. Holter & K. Nielsen

On behalf of the Norwegian Tunnelling Society - NFF

OFFPRINT

Investigations, planning and design / Underground space use / Support and lining of tunnels

A.A. BALKEMA / ROTTERDAM / BROOKFIELD / 1999

Challenges for the 21st Century, Alten et al. (eds) © 1999 Balkema, Rotterdam, ISBN 90 5809 063 9

The Bologna to Florence high speed railway line: Progress of underground works

P. Lunardi
Lunardi's Geo-engineering Design Office, Milan, Italy

A. Focaracci
Rocksoil S.p.A., Milan, Italy

ABSTRACT: The construction of the Bologna to Florence high speed railway line constitutes one of the most important civil engineering feats cast into the 21th Century. The project as a whole involves the construction of tunnels for a total length of 73 kilometres. On completion of the project more than 90% of the route will be underground! The paper describes the main characteristics of the underground works, looking in detail at how three particular zones typical of the Apennine chain were crossed.

1 INTRODUCTION

Large mountain chains constitute natural barriers that are difficult to cross and since the beginnings of the history of mankind, the construction of major transport routes through them has always involved the accomplishment of epic feats for all civilisations that have attempted to equip themselves with efficient transport networks.

In this context, the crossing of the Apennines has played a prime historical and cultural role since the time of the Roman consulates. In the cultural and social evolution of the Italian peninsula the creation of new transport routes has always been accompanied by an ever increasing and committed use of technology in civil works, once any tangible development has been achieved

Today, on the threshold of the third millennium, the "High Speed Train" (T.A.V.) project was conceived of to meet the need to integrate the national rail network into the European High Speed rail network. The T.A.V. project redesigns the Italian rail system and increases major lines fourfold with new routes of which the Bologna to Florence line still today constitutes the greatest design and construction commitment.

In order to meet the specifications of a "high capacity", high technology line, constructed with rigorous respect for the environment, this line travels for more than 90% of its length, 73 km, underground through 9 sections of tunnel with only 5 km of the line above ground (not including the terminals in Bologna and Florence which are also mainly underground) (Fig. 1).

The design approach, in which the option to construct underground is prevalent, was unthinkable until only a few years ago. Today it is made possible by the development of new design and construction technologies which make precise and accurate use of large and more and more powerful equipment to industrialise tunnel advance in conditions of safety and keeping to tight production schedules.

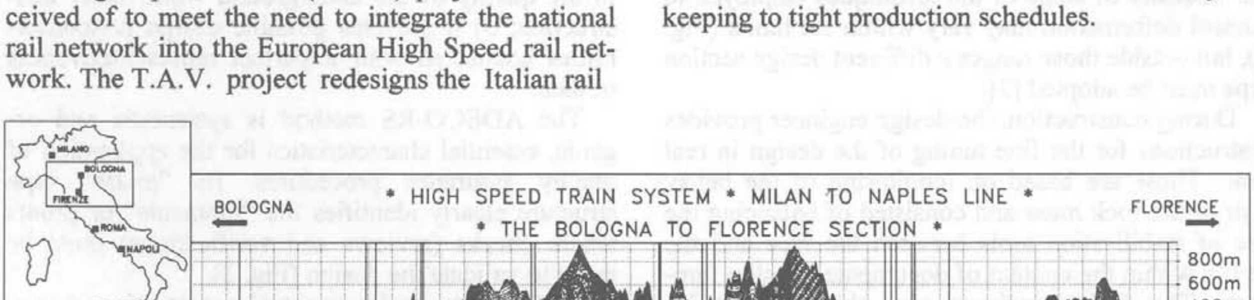


Figure 1. Bologna to Florence High Speed Railway Route: longitudinal section

The geology along the Apennine route is complex. A variety of rock masses are crossed ranging from flyschoid formations, clays and argillites to loose ground. The design engineers from Fiat Engineering and Rocksoil employed the latest technologies to tackle such heterogeneous conditions and made particular use of a variety of ground improvement techniques according to type of ground. It was considered that the specific characteristic of underground works lies in the fact that in order to construct them, ground must be removed from the face and a structural lining placed.

The long and short term behaviour of a tunnel depends on how the ground reacts to the combined action of tunnel advance and the placing of stabilisation structures.

A design engineer must therefore identify advance systems and methods and rhythms and intensity of stabilisation intervention according to the type of ground. They must be varied so that the ground around the excavation is already stable during tunnel advance thus allowing a single method of tunnel construction to be employed.

Design work, which began in 1992, was based on the ADECO-RS approach and aimed particularly at the attentive introduction of the innovative technologies available today [1],[2]. A design was drawn up which in concrete form involved the division of the tunnel into sections with uniform geomechanical behaviour belonging to three different categories: category A, stable face; category B, face stable in the short term; and category C, face unstable. It also involved the selection of a certain number of structural design section types and the relative ranges of application.

The description of a given design section type, though made on the basis of the most probable geological-geomechanical reconstruction of the rock mass, is unique within the range of types of intervention and quantities employed, leaving nothing undecided for implementation on site. Admissible ranges of deformation are specified for each design section type and for each section of tunnel in which it is to be used. For each of these deformation ranges the intensity of some of the techniques employed to control deformation may vary within set limits (Fig. 2), but outside those ranges a different design section type must be adopted [3].

During construction, the design engineer provides instructions for the fine tuning of the design in real time. These are based on monitoring of the behaviour of the rock mass and consisted of balancing the use of stabilisation tools between the face and the cavity within the context of documented design forecasts. The design engineer may give different instructions on the basis of a comparison of forecast and actual data: 1) the most probable forecast conditions correspond to the actual conditions → continue with the specified design section type; 2) actual conditions are slightly different from those forecast as most probable, but fall within the forecast behaviour type and variation range → use one of the design section sub-types; 3) forecast ground conditions correspond to actual conditions, but at different points along the route → employ the correct design section types in the sections of the route to which they actually correspond; 4) actual conditions are considerably different from those forecast for the section → review the design and redesign the section. This method of working allows three results to be achieved: 1) it gives a sufficiently detailed design which fits the actual characteristics of the rock mass; 2) it eliminates all leeway for discretion with regard to the quality of the underground work under construction; 3) it prevents possible design nonconformities connected with imperfect representativeness of data.

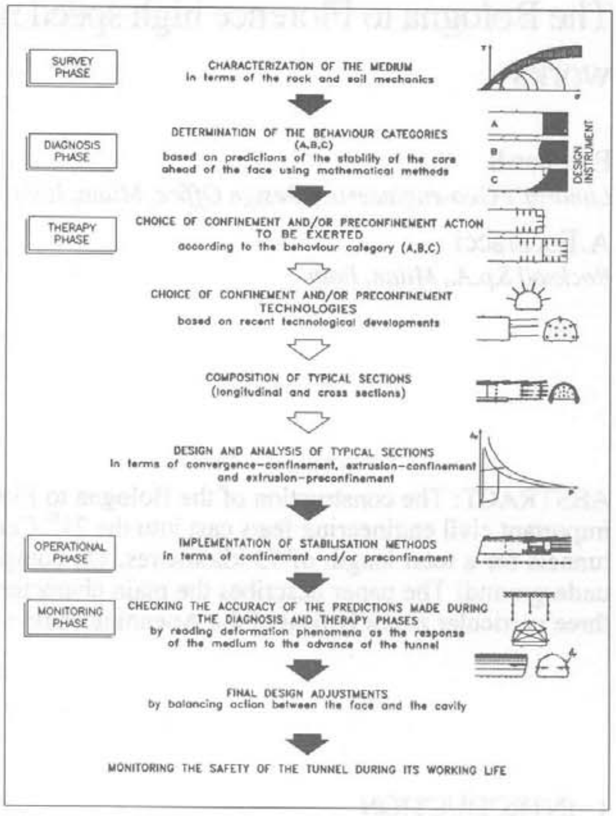


Figure 2. Sommary of the approach based on the analysis of controlled deformation in rock and soil (ADECO-RS).

The ADECO-RS method is systematic and organic, essential characteristics for the application of quality assurance procedures. Its "phase" type structure clearly identifies the "moments" or points where checks (reviews and verifications) must be made to validate the design (Fig. 2).

Furthermore, as far as actual construction is concerned, the method of tunnel advance proposed (full face, with a tunnel cross section of approximately 120 - 140 sq. m) affords the considerable advantage of allowing the works to be industrialised. At the same time, closing the structural ring with the tunnel invert immediately behind the face provides considerable benefits in terms of the long and short term stability of the tunnel.

2 THE UNDERGROUND WORKS

Design work finished in July 1995 and at the same time the contract between the client T.A.V. and the general contractor Fiat/CAVET for construction of the tunnel was signed with work commencing immediately. A description of the main tunnels is given below with attention being paid to particular sections, nevertheless characteristic of the Apennines, encountered in the excavation of three of the 26 faces currently advancing. These sections include advance through a zone affected by the presence of gas, a large zone affected by land slip/slide and a zone under the water table under pressure. These three particularly strait-crossingdifficult sections currently constitute the most problematic encountered so far.

2.1 *Pianoro Tunnel*

The Pianoro Tunnel (10,705 m in length) (Fig. 3) passes through mountains to the East of the Futa state road with maximum overburdens of 170 m

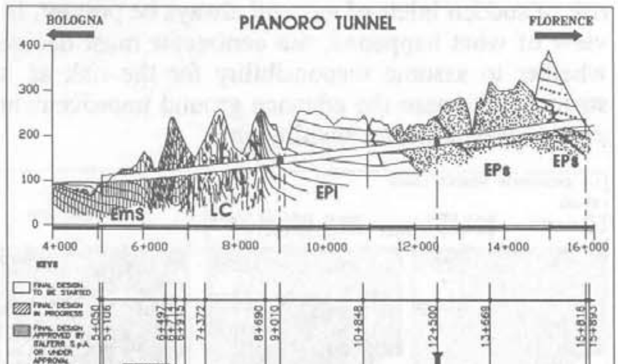


Figure 3. "Pianoro" tunnel: longitudinal geological section.

(average of 90 m). From the North, the ground encountered consists initially of marls (EMS), then the argillites of the Chaotic Complex (LC) and belonging, in the remaining part, to the lower and upper intra-Apennine Pliocene series.

In the section between kilometre 6+497 and 6+914, the connection with the existing Florence to Bologna "Direttissima" line starts and requires the construction of two large access chambers. At kilometres 9+015 and 12+500 the line is joined by two access tunnels (Emilia 1 and Emilia 2) of 182 m and 307 m respectively.

2.2 *Sadurano Tunnel*

At the end of the Pianoro Tunnel, the line crosses the Rio Laurenziamo incision, the Rio Crocione and again passes underground at kilometre 16+601.

The Sadurano Tunnel (3,778 m in length) (Fig. 4) begins here with maximum overburdens of 250 m (average of 80 m). the ground belongs to the Upper Pliocene (EPS) and consists of lightly cemented sandstones and conglomerates.

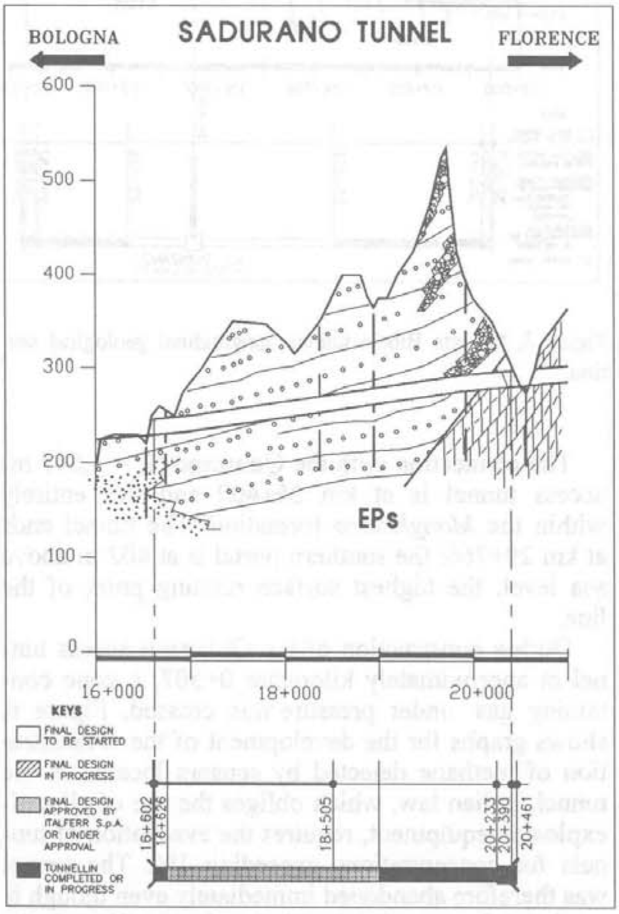


Figure 4. "Sadurano" tunnel: longitudinal geological section.

2.3 *Monte Bibile Tunnel*

At the exit of the Sadurano Tunnel the line crosses the Rio dei Cani incision with a box-shaped girder bridge and returns under ground for a further 9,243 m (Monte Bibele Tunnel). The Monte Bibele Tunnel (Fig. 5) runs under the mountain of the same name with overburdens ranging between 50 m and 280 m

The ground encountered from the North as far as approximately km 24+700, belongs to the Miocene formation consisting of the *Marne di Bismantova* interbedded from around km 23+000 with fine grain sandstones; the *Monghidoro Formation* (LaM) is then crossed for a length of around 5 km This formation, belonging to the *Ligure Successione* has the characteristics of a heavily tectonised flysch, incorporating pockets of water and gas (CH_4) under pressure.

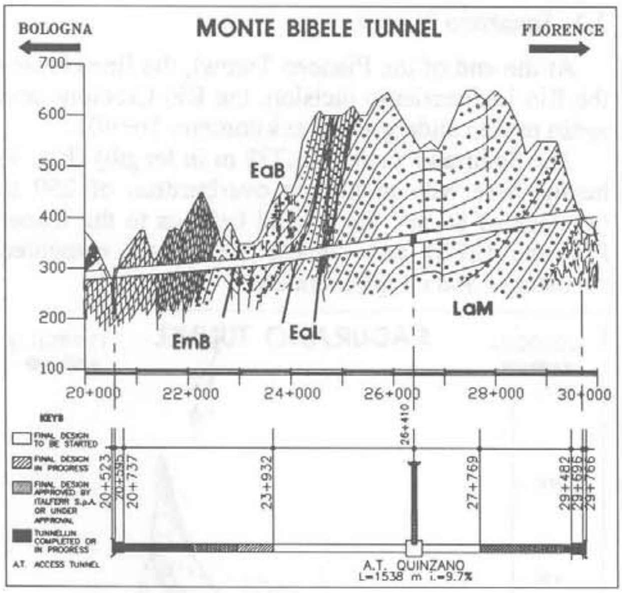


Figure 5. "Monte Bibele tunnel: longitudinal geological section.

The connection with the Quinzano (L = 1,547 m) access tunnel is at km 26+400 and lies entirely within the *Monghidoro* formation. The tunnel ends at km 29+766: the southern portal is at 402 m above sea level, the highest surface running point of the line.

During construction of the Quinzano access tunnel at approximately kilometre 0+507, a zone containing gas under pressure was crossed. Figure 6 shows graphs for the development of the concentration of methane detected by sensors located in the tunnel. Italian law, which obliges the use of all anti-explosion equipment, requires the evacuation of tunnels for concentrations exceeding 1%. The tunnel was therefore abandoned immediately even though it needed to be completed with the placing of steel ribs and a shotcrete lining.

Since the rock mass was heavily tectonised with a decidedly elastic-fragile behaviour, the primary and secondary linings needed to be placed rapidly to ensure the stability of the cavity (category B, face stable in the short term). Because in this particular case it was not possible to do this, almost 200 cu. m of ground fell into the cavity within about an hour. As can be seen from Fig. 7, after reaching the limit of its strength, the behaviour of the ground shows a sharp fall to residual values. This is why the modest failure that is usually produced in the roof and sides of the tunnel tends, if it is not promptly confined, to become a large zone stressed in the plastic range as a consequence of the increase in deformation at constant loads. An examination of the changes in volumes shows how the relaxation of the rock mass around the tunnel develops; these volumes flow in-

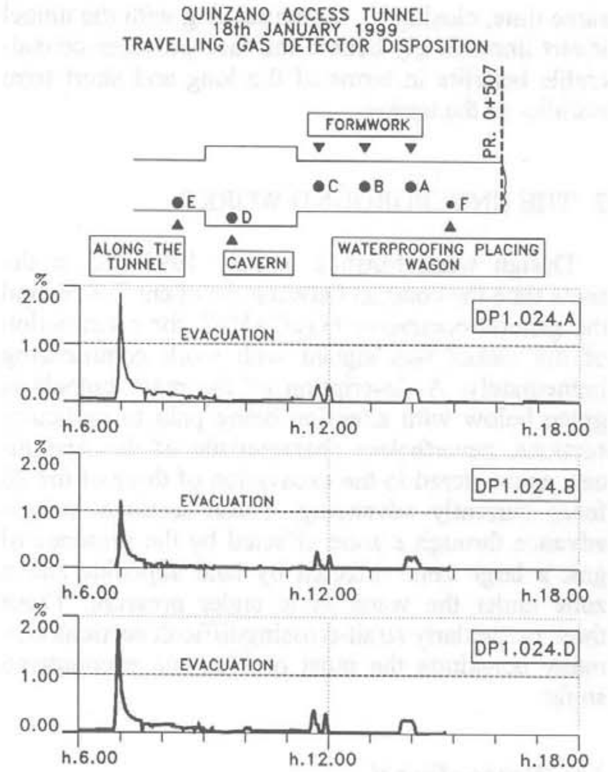


Figure 6. "Quinzano" access tunnel: Gas monitoring at Km 0+507.

evitably into the tunnel if they are not confined. The risk of sudden inlets of gas will always be present. In view of what happened, the contractor must decide whether to assume responsibility for the risk as it stands or increase the advance ground improvement to guarantee a greater standby time.

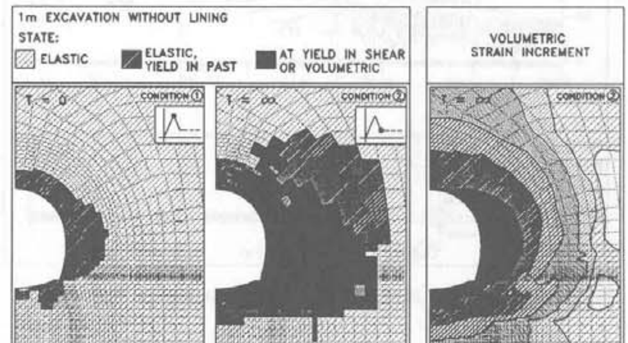


Figure 7. "Quinzano" access tunnel: FLAC analysis of tunnel cross section stability near the front.

2.4 *Raticosa Tunnel*

The Raticosa Tunnel, (10,450 m in length) (Fig. 8), starts at km 29+982. The highest point on the Bologna to Florence line is reached in this tunnel at 413.5 metres above sea level. From the North, for a length of almost 5 km., the ground tunnelled belongs to the Chaotic Complex (LC); this consists of intensely fractured and tectonised argillites. It is the first time in the world in which ground of this type with such large overburdens and therefore stress states is being tunnelled. The remaining section of the tunnel passes through flysch of the *Marnoso-Arenacea* formation (RMA).

The Osteria (L = 1,325 m) and Castelvecchio (L = 1,150 m) access tunnels connect to the tunnel at km 32+515 and km 35+325 respectively.

The section at the North portal passes through an

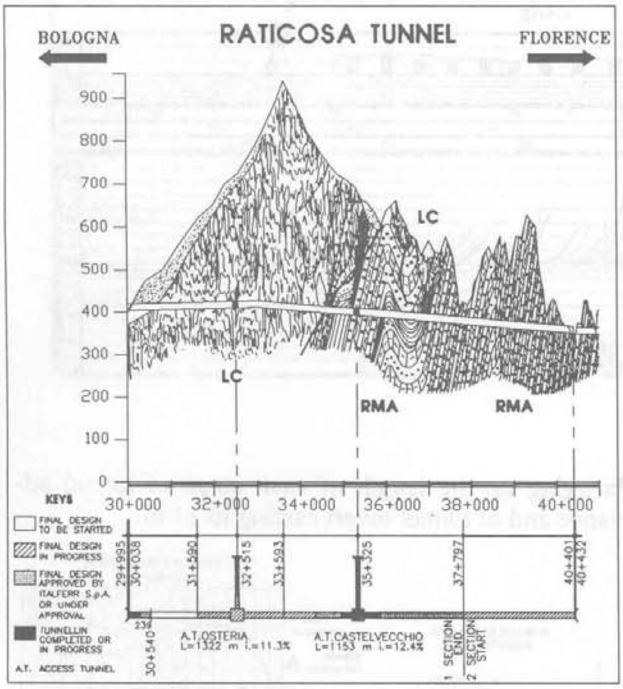


Figure 8. "Raticosa" tunnel: longitudinal geological section.

extensive area of paleo-landslide consisting of argillite debris incorporating calcareous blocks of modest dimensions (1 cu. m). The landslide zone affects about 500 m of the tunnel and consists of a succession of flows, the deepest and oldest going back to 3,000 years ago and the most recent to the beginning of the century. Studies of flows conducted by Fiat Engineering since 1995 allow three bands of movement classified according to different velocities of the solifluction to be identified (Fig. 9).

A more superficial band with a horizontal velocity of more than 4 mm per year, an intermediate band with a velocity of between 4.0 and 1.5 mm per year and a base band with a velocity of between less than 1.5 mm and 0.0 mm per year. In such delicate conditions (tunnel with face unstable), a design section type was selected involving a considerable increase in the rigidity of the core of ground ahead of the face using fibre glass structural elements and the placing, immediately after excavation, of a primary lining in the roof and a tunnel invert consisting of steel ribs and fibre reinforced shotcrete.(Fig. 10) Casting of the side walls and tunnel invert in reinforced concrete followed at approximately 6 m from the face and that of the crown at a distance of approximately 50-60 m Ground reinforcement of the advance core consisted of approximately 100 fibre glass structural elements 22 m in length, repeated every 12 m of tunnel advance.

Figure 9. "Raticosa" tunnel: Steel reinforcement placing of invert

In this delicate situation, systematic measure of extrusion at the face was crucial for defining the length of the stages of tunnel advance. The aim was to maintain deformation of the ground within the range beyond which its strength would fall to residual values, which in this specific case would lead to collapse of the face. It was therefore necessary to place an extrusion measuring device "sliding deformeter" type (length = 30 m) at each stage of tunnel advance to measure longitudinal deformation of the ground in the advance core at the face. In this way the extrusion measured with a new metre is added to that already measured by the old metre to give total actual extrusion (Fig. 11). Similarly total differential extrusion between two extrusion bases placed 1 m apart is calculated. The deformation measured must always remain below the 5% limit above which strength values will fall (Fig. 12). By using these criteria it was possible to regulate the length, inten-

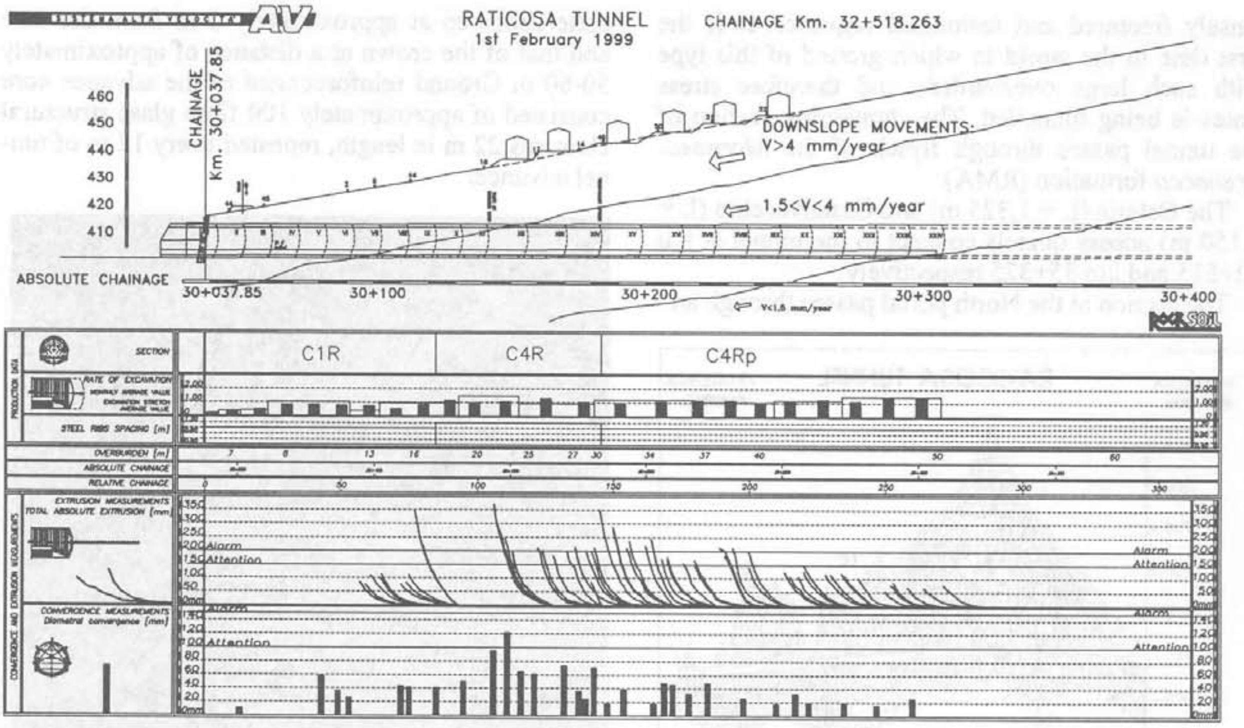


Figure 10. "Raticosa" tunnel: North portal - monitoring

sity and overlap of the ground reinforcement for each new tunnel advance as well as the length of each stage of tunnel advance and of tunnel invert casting. As the landslide zone was entered it was possible to gradual reduce the degree of stabilisation bringing up the length of each stage of tunnel advance and of tunnel invert casting to 11 m.

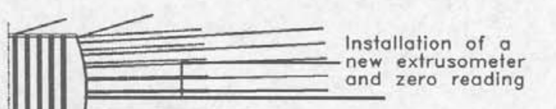


Figure 11. Plots of total extrusion of excavation face

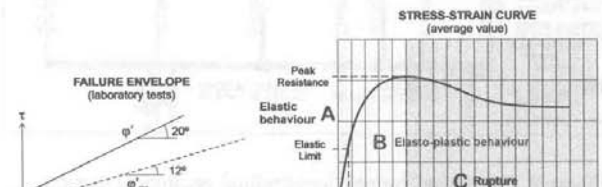


Figure 12. Extimating the plastic zone with extrusion measurements

2.5 *Scheggianico Tunnel*

On exiting from the Raticosa Tunnel, the line crosses the deep incision of the Diaterna river by viaduct. The Scheggianico tunnel (Fig. 13) starts at km 40+542, is 3,558 m in length and has overburdens up to 300 m lying entirely within the *Marnoso-Arenacea* formation. The Brenzone (L.= 140 m) and the Brentana (L. = 237 m) access tunnels connect with it at km 41+170 and km 43+250 respectively. At the exit, at approximately km 44+100, the tunnel passes under the Imolese state road with approximately 1 m of overburden.

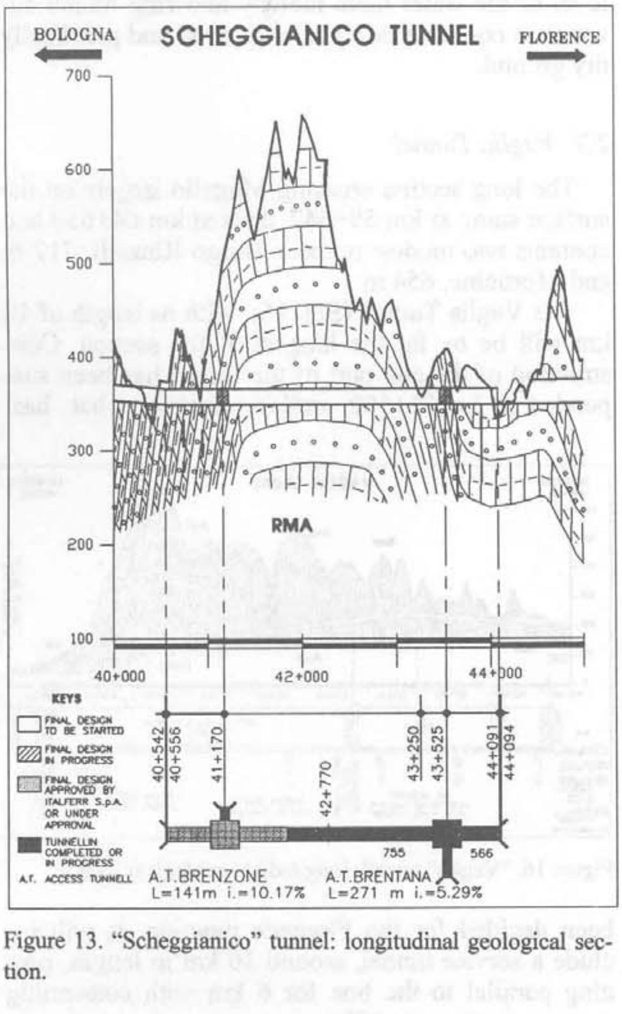


Figure 13. "Scheggianico" tunnel: longitudinal geological section.

2.6 *Firenzuola Tunnel*

The exit of the Scheggianico Tunnel looks over the Santerno river, which is crossed by viaduct. At the end of the viaduct, the line enters *S. Pellegrino Siding* at km 44+279 halfway between Florence and Bologna and runs through the Firenzuola Tunnel for 740 m After *Siding* the tunnel runs under the Rovigo river and reaches the Southern portal by the Mugello motor-racing track. The maximum overburdens are over 500 m. The ground tunnelled belongs to the *Marnoso-Arenacea* formation up to km 55+000 and is followed in rapid succession by the Tuscan sedimentary series, consisting of sandstones, siltites, argillites and marls belonging to the *Castel Guerino* (TMG), the *Marne Varicolori* (TVM) and *Macigno del Mugello* (TMM) formations. The last three kilometres pass through the lacustrine deposits of Mugello. There are four access tunnels along this tunnel: the Rovigo access tunnel, 555 km in length at km 45+800; the Osteto access tunnel, a good 1,503 km in length at km 51+000; the Marzano access tunnel, 1,112 km in length at km 54+450; the S. Giorgio access tunnel, 383 km in length (Fig. 14).

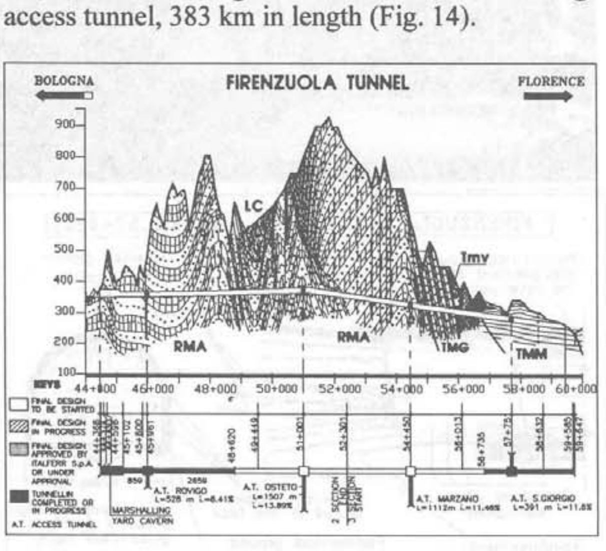
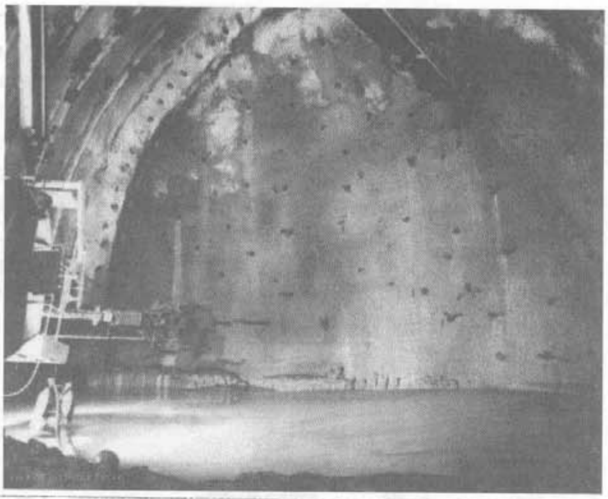


Figure 14. "Firenzuola" tunnel: longitudinal geological section.

The stretch of the Firenzuola Tunnel from the San Giorgio access tunnel up to around km 56+730 passes through the lacustrine deposits of the Mugello basin consisting of sandy silts with sandy interbedding. At km 57+484 one of these sandy strata with a thickness of about 10 m had to be tunnelled under the water table with a pressure of approximately 3 bar. Tunnel advance was against the dip, so that the sandy bank, inclined at an angle of 10° to the horizontal, was first encountered by the bottom of the face and gradually rose up it. As the thickness of the sand at the face increased, the flow of water into the tunnel also increased rising gradually to reach 6 litres per sec. These concentrated inflows of water caused erosion with the transport of sand in suspension and as a consequence gravitational fall-in along the walls of the tunnel during excavation.

These events recommended immediate suspension of excavation to change to behaviour category C and the adoption of a design section type suitable for the actual conditions encountered. After a few borehole drillings in advance at various angles, the geometry of the sandy stratum was reconstructed and it was decided to take the following action ahead of the face and immediately behind it (Fig. 15):

- Ground reinforcement ahead of the face using fibre glass structural elements which were fitted with *"canne manchettes"* type valved tubes for



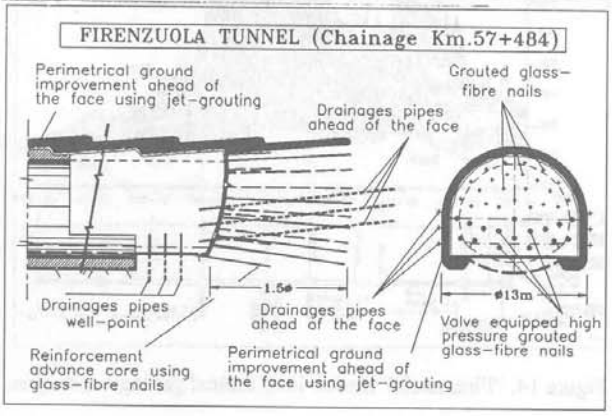


Figure 15. "Firenzuola Tunnel: longitudinal and cross section at Km 57+484.

the sandy section (lower half of the tunnel cross section). Jet grouting was used to maintain the hole stable during drilling and cementation stages. Mixes under pressure and appropriate injection parameters were employed in the return stage (drill-rods extraction). A few hours after the introduction of the valved fibre glass elements, the grout under pressure was injected, valve after valve, starting with those closest to the face and moving gradually to those most distant from it. Also the drillings closest to the centre of the face were injected first gradually moving outwards. This system was used to keep water out of the core of ground ahead of the face.

- Advance ground improvement around the tunnel using overlapped columns of jet-grouting.
- Sub-horizontal drains 25 m in length, 15 m of which perforated and protected with a special non woven fabric recommended for fine grain soils and 10 m of which sealed and cemented in place.
- Ground improvement of the sands to a thickness of 5 m below the tunnel invert, still to be excavated, at the face. To further reduce the water pressure and to resume tunnel advance under conditions of safey, a pumped drainage system was employed using wellpoints in 5+5 vertical holes driven 6 m below the level of excavation.

Given the effectiveness of the pumped drainage system, the drains placed in advance of the face were subsequently also connected to centrifuge pumps.

The method of advance ground improvement described was applied for the whole of the section through sand for a length of 60 m. The results were excellent because the water was drained without the transport of material and .lowering the piezometric level of the water table thereby allowing tunnel advance to continue safely in omproved and practically dry ground.

2.7 *Vaglia Tunnel*

The long section crossing Mugello largely on the surface starts at km 59+647, ends at km 64+650 and contains two modest tunnels: Borgo Rinzelli, 717 m and Morticine, 654 m

The Vaglia Tunnel (Fig. 16), with its length of 18 km will be by far the longest of the section. Construction of the end part of the tunnel has been suspended at km 71+500 until it is known what has

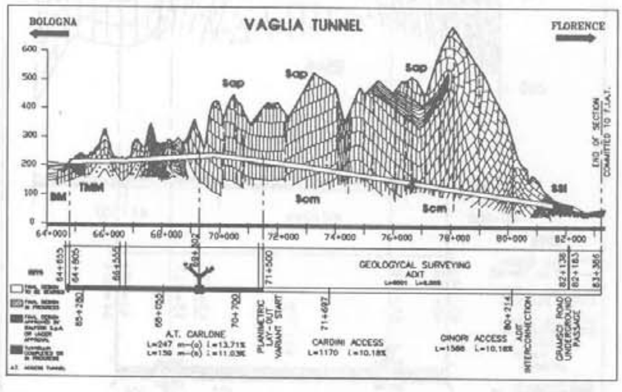


Figure 16. "Vaglia" tunnel: longitudinal geological section.

been decided for the Florence junction. It will include a service tunnel, around 10 km in length, running parallel to the line for 6 km with connecting passages to it every 250 m.

From North to South, the Vaglia Tunnel crosses the lacustrine deposits and then the *Macigno del Mugello* for a length of 2.5 km A length of 900 m then passes through the Siliano formation (Ssi), similar to the Chaotic Complex, and at around km 69+000 almost as far as Castello, the tunnel runs through the *Monte Morello* formation (ScM), consisting of alternating marly limestones and limy marls with marly strata.

The Carlone access tunnel connects at km 69+300 with a length of 261 m for branch a) plus 141 m for branch b).

GEOLOGICAL KEYS		
SUCCESSIONE EPILIGURE EMILIANA	EmB	– Bismantova Formation (marls and arenaceous marls)
	EaL	– Loiano Formation (conglomerates and sandstones)
	EaB	– Bismantova Formation (sandstones)
	EPs	– Pliocene intrappenninico superiore (conglomerates and poorly cemented sandstones)
	EPi	– Pliocene intrappenninico inferiore (poorly cemented sandstones beds and porly cemented sands and/or silts)
	EGSg	– Gessoso–solfifera Formation (gypsum, marly and sily shales beds)
	EmS	– Schlier Marls (silty marls)
SUCCESSIONE UMBRO-ROMAGNOLA	RMA	– Marly and arenaceous formation (sandstones beds, marlsbeds, silty and marly beds)
SUCCESSIONE LIGURE	LC	– Complesso Caotico Formation (shales)
	OL	– Olistostrome
	LaM	– Monghidoro Formation (sandstones, shaly marls and marly shales)
SUCCESSIONE SUBLIGURE ALLOCTONO	SPF	– Pietra forte (sandstones, marly shales, limestones and marly limestones)
	SSI	– Sillano Formation (shales with limestones, marly limestones, calcareous sandstones, marls)
	ScM	– M. Morello Formation (limestones, marly limestones, calcareous sandstones, marls)
	SAP	– Pescina shales
	SVR	– Villa a Radda Formation (shales)
SUCCESSIONE TOSCANA AUTOCTONO	TMM	– Macigno del Mugello (silty beds, silty and marly beds, sandstones beds)
	TM	– Macigno (sandstones with silty and shaly beds)
	Tmv	– Marne varicolori Formation (shales, marly shales and marls)
	TMG	– Castel Guerino Formation (sandstones, marls and silty marls)
BACINI ESTENSIVI	BM	– Bacino del Mugello formation
	aBM	– Bacino del Mugello shales
	cBM	– conglomeratates
	sBM	– sands
	dt	– debris
	dfr	– landslide debris
SYMBOLS		– Overthrust
		– Faults
		– Groundwater piezometric level

3 CONCLUSION

The complexity and size of the investment of money and resources certainly makes the new crossing of Apennines by the Italian High Speed railway system a project of international importance. The paper briefly describes the main characteristics of the underground works, looking in detail at how three particular zones typical of the Apennine chain were crossed: a zone affected by the presence of gas, a large zone affected by landslide and a zone under the water table under pressure. These three particularly difficult zones to cross currently represent the most problematic encountered to date.

ACKNOWLEDGEMENTS

The authors thank N. Meistro, G. Romano, M. Capasso of Rocksoil for their cooperation in writing this paper.

REFERENCES

[1] LUNARDI P., "Progetto e costruzione di gallerie secondo l'approccio basato sull'analisi delle deformazioni controllate nelle rocce e nei suoli" (Article in three parts, in Italian and French), Quarry and Construction, March 1994, March 1995, April 1996

[2] LUNARDI P., "The Bologna to Florence high speed rail connection. Design and construction aspects of the underground works", Gallerie e grandi opere in sotterraneo, No. 54, 1998.

[3] ENRICI R., FOCARACCI A., VALLINO G., "The Bologna to Florence high speed rail connection. The design and construction phese of tunnels", Gallerie e grandi opere in sotterraneo, No. 54, 1998.

[4] LUNARDI P., FOCARACCI A., "Quality Assurance in the Design and Construction of Underground Works", International Congress on "Underground Construction in Modern Infrastructure", Stockholm, 7-9 June 1998