

# THE ADECO-RS APPROACH IN THE DESIGN AND CONSTRUCTION OF THE UNDERGROUND WORKS OF ROME TO NAPLES HIGH SPEED RAILWAY LINE: A COMPARISON BETWEEN FINAL DESIGN SPECIFICATIONS, CONSTRUCTION DESIGN AND “AS BUILT”

Prof. Ing. Pietro Lunardi, Lunardi's Geo-engineering Design Office, Milan, Italy

SUMMARY: 22 tunnels with a total length of 21.8 km on the new High Speed rail Rome-Naples line have been designed and constructed on the basis of the ADECO-RS approach which makes a clear distinction between the construction and the design stages or moments and allows execution times and costs of underground works to be planned accurately. The paper first illustrates the design principles followed and then at the end discusses the results, which were in line with forecasts, in terms of times and costs.

## 1 GENERAL BACKGROUND TO THE WORKS

The new Rome-Naples railway is part of the High Speed Train Milan-Naples line which in turn represents a southern terminal of the European High Speed network.

The line has been divided up into lots with differing costs. Construction contracts were awarded to five contractors belonging to the IRICAV UNO consortium (the general contractor for this part of the line) and namely Pegaso, Icla, Italstrade, Vianini and Condotte.

The total length of the line, currently being completed, is 204 km and 28.3 km of this (equal to 13% of the total length) runs through underground tunnel.

Design and construction of the parts of the tunnel designed by Rocksoil is discussed below and these account for 77% of the underground works for a total of 21.8 km and 22 tunnels.

Figures 1 to 4 show the longitudinal geological profiles of the 22 tunnels: the *Colli Albani* tunnel (Pegaso lot, 6,361 m.) is the longest tunnel on the entire line while the *Collatina* tunnel (Italstrade lot, 53 m.) is the shortest.

The underground route runs through ground which can basically be classified as having two different types of origin:

- pyroclastic ground and lava flows, generated by eruptions of the volcanic complexes of *Latium*, of *Valle del Sacco* and of *Campania*;

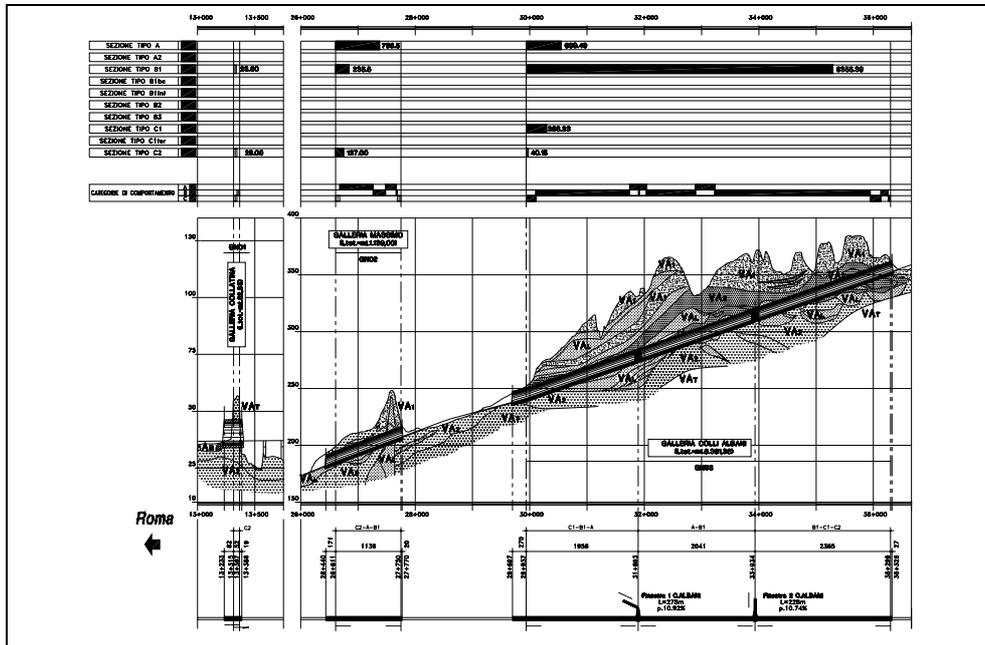


Figure 1. Longitudinal profiles of the tunnels: Collatina, Massimo, Colli Albani.

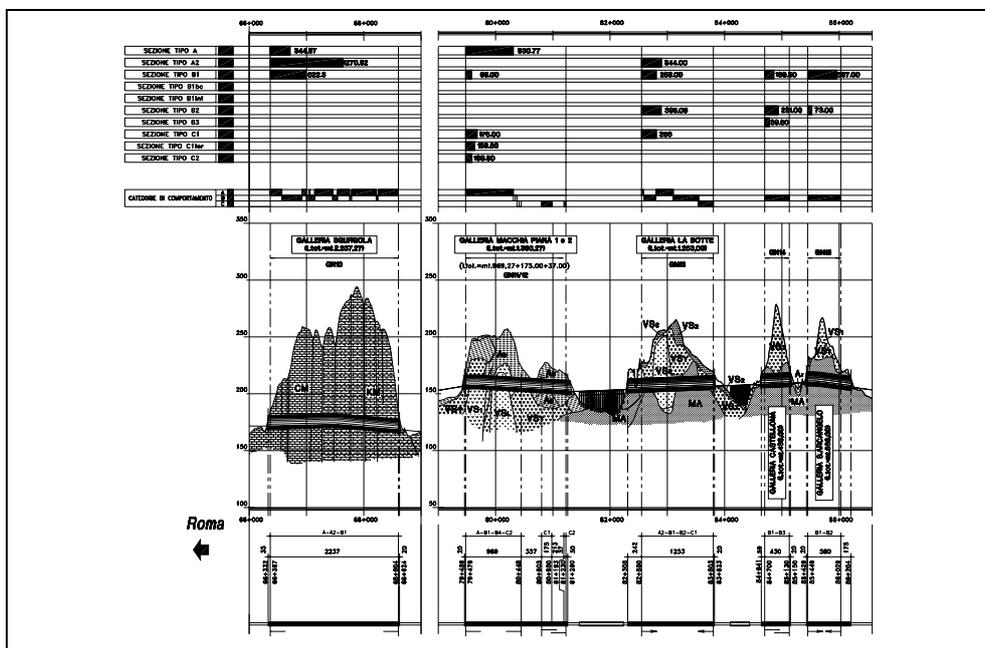


Figure 2. Longitudinal profiles of the tunnels: Surgola, Macchia Piana 1 and 2, La Botte, Castellana, S. Arcangelo.

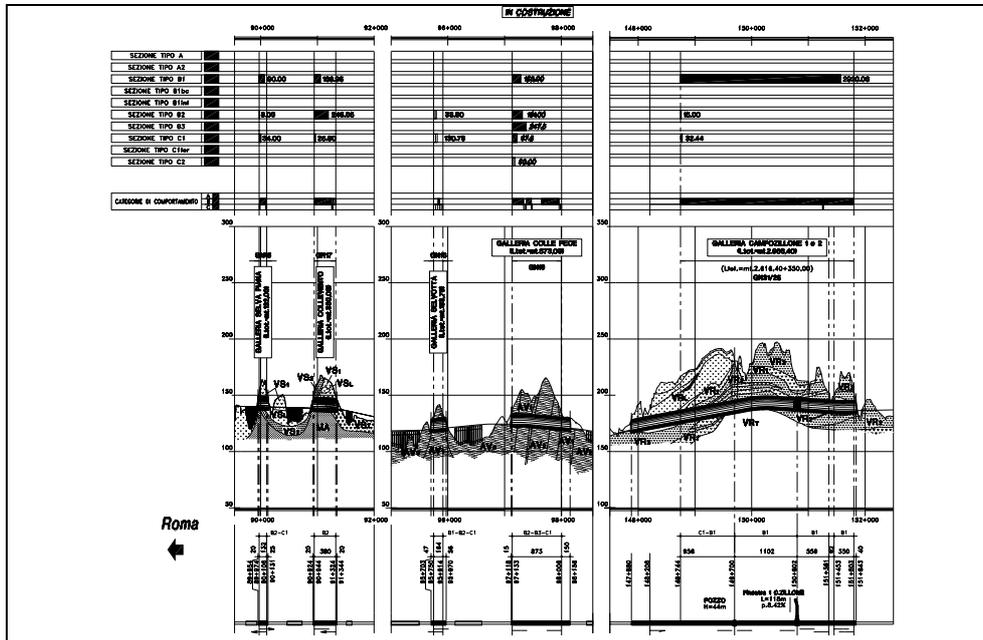


Figure 3. Longitudinal profiles of the tunnels: Selva Piana, Collevento, Selvotta, Colle Pece, Campo Zillone 1 and 2.

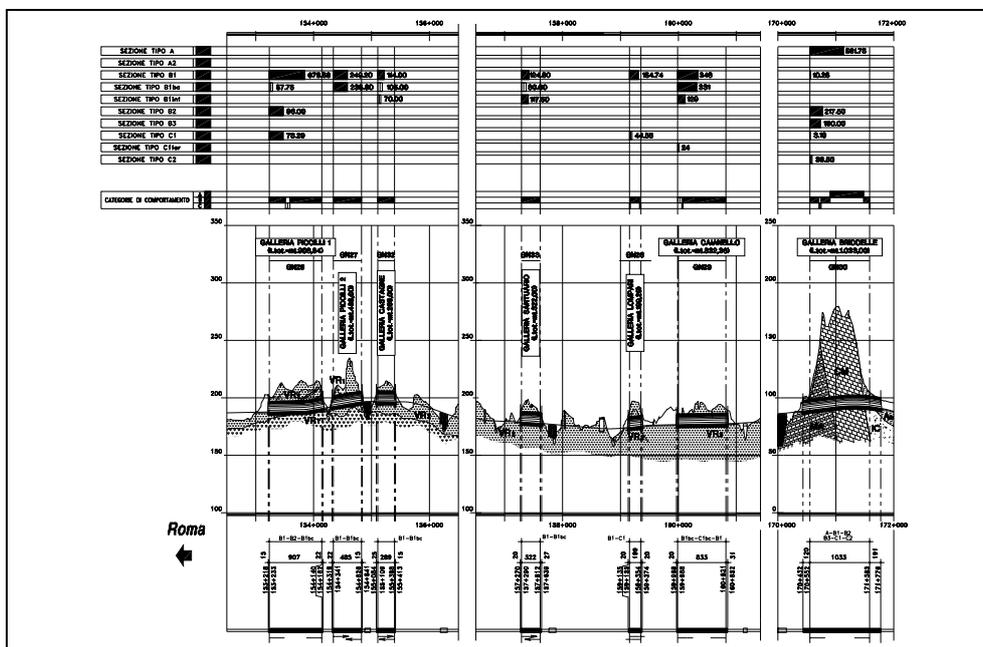


Figure 4. Longitudinal profiles of the tunnels: Piccilli 1 and 2, Castagne, Santuario, Lompari, Caianello, Bricelle.

- sedimentary rocks of the flyschoid and carbonatic type (marly and limy argillites) belonging to the Apennine system.

The overburdens vary greatly but never exceed 110 m., while they are often very shallow at the portals.

The final and construction design of the tunnels was performed using the Analysis of Controlled Deformation in Rocks and Soils approach (ADECO-RS), valid for all types of ground and stress-strain conditions [Lunardi 2000].

According to this approach, the design and construction of an underground project is performed in the following stages:

- a survey phase, a diagnosis phase and a therapy phase, in the design stage or moment;
- an operational phase and a monitoring phase during construction in the construction stage or moment.

## 2 GEOLOGICAL AND GEOTECHNICAL BACKGROUND (SURVEY PHASE)

As mentioned above, many of the tunnels pass through ground of volcanic origin. The activity of the volcanic bodies concerned began in the Pliocene period and developed mainly in the Pleistocene period from upper *Lazio* down to the *Vesuvian* region dying out about 100,000 years ago. The volcanological development of the active centres passed through three different phases, which occurred in almost the same order in all the centres of activity: the phase of the volcano-stratum, the phase of great ignimbritic expansion and the phase of the construction of ash and lava cones.

Two important centres of eruption are identifiable along the route of the line, one in the *Lazio* area (*Colli Albani*) and the other (*Roccamonfina*) in the *Campania* area near the end of the route. There is a smaller volcanic body near the *Sacco* river (*Valle del Sacco*). Between the two major volcanic “domains”, in the central part of the route, often interdigitating with the volcanic products of the *Valle del Sacco* volcanic body, there are outcrops of sedimentary rocks of the Apennine backbone of the Cretaceous and Miocene periods, in carbonatic, flyschoid and clayey-marly facies.

From a hydrogeological viewpoint, the route lies practically entirely above the regional water-table and consequently the tunnels are not subject to large heads of pressure; there are, however, some localised exceptions, for example in the *La Botte* tunnel of the *Italstrade* lot, and the *Castellona* tunnel of the *Vianini* lot, where the marly-arenaceous complex provides an impermeable bedrock to the overlying pyroclastites, favouring the formation of suspended water-tables with modest heads of pressure or at the northern portal of the *Colli Albani* tunnel where the water-table that supplies a fountain in the *Vetrice* area is intersected.

From a geotechnical viewpoint the lithotypes given in table I were identified in the geological complexes. The parameters for them with the variation in the geotechnical characteristics are given in the same table I.

## 3 STRESS-STRAIN BEHAVIOUR PREDICTIONS (DIAGNOSIS PHASE)

It became immediately clear in the diagnosis phase that the tunnels to be driven, either because of the geotechnical characteristics of the ground or because of the varying overburdens, would be subject to extremely different stress-strain conditions.

The geological, geotechnical and hydrogeological information acquired and the results of calculations performed using analytical and/or mathematical methods were therefore

	VOLCANIC COMPLEXES (Vulcaniti dei Colli Albani, Vulcaniti della Valle del Sacco, Vulcaniti di Rocca Monfina)			CARBONATIC COMPLEX (Calcari dei Monti Lepini)	FLYSCHOID COMPLEX (Argille Varicolori, Complesso Marnoso-Arenaceo)	
	Pyroclastites	Tuffs	Lavas	Stratified limestones	Scaly clays	Clayey marls with arenaceous layers
$\gamma$ [t/m <sup>3</sup> ]	1.4 ÷ 1.6	1.6 ÷ 2	2.6 ÷ 2.7	2.5 ÷ 2.7	2.0 ÷ 2.1	2.2 ÷ 2.4
C [Mpa]	0 ÷ 0.1	0.1 ÷ 0.5	0.5 ÷ 5	0.5 ÷ 1	0.01 ÷ 0.05	0.2 ÷ 0.4
$\varphi$ [°]	25 ÷ 35	20 ÷ 25	30 ÷ 35	35 ÷ 40	18 ÷ 23	28 ÷ 33
$\sigma_{gd}$ [Mpa]	1 ÷ 5	/	/	1 ÷ 4	/	/
E [Mpa]	50 ÷ 100	300÷600	2000÷5000	10,000 ÷ 12,000	50 ÷ 100	200 ÷ 400
$\nu$	0.35	0.3	0.25	0.25 ÷ 0.3	0.35	0.3

Table I. Summary of the characteristics of the ground.

employed to divide the underground route into sections of uniform stress-strain behaviour as a function of face stability in the absence of intervention to stabilise the tunnel:

- face stable (behaviour category A);
- face stable in the short term (behaviour category B);
- face unstable (behaviour category C).

Category A comprised all those sections of tunnel in which mathematical calculations predicted that:

- the stress state of the ground at the face and around the cavity would not have exceeded the natural strength characteristics of the medium;
- an “arch effect” would have been created close to the profile of the tunnel;
- deformation phenomena would have developed in the elastic range, having an immediate effect in the order of a few millimetres;
- as a consequence, the face as a whole would have remained stable.

This category was found in lava, lithoid tufo and slightly fractured limestone sections, materials which generally present good strength properties relative to the stresses mobilised by driving tunnels with the specified overburdens.

Category B, however, included all those sections of tunnel where mathematical calculation predicted that:

- the stress state at the face and around the cavity during tunnel advance would have exceeded the natural strength characteristics of the medium, in the elastic range;
- an “arch effect” would not have been formed close to the profile of the tunnel, but at a distance equal to the size of the band of plasticised ground around the cavity;
- deformation phenomena would have developed into the elastic-plastic range with the effect deferred in time and in the order of centimetres;
- as a consequence, the face would have remained stable in the short term at normal tunnel advance rhythms, with observable extrusion of the core at the face but not

sufficient to affect the short term stability of the tunnel since the ground would still be able to generate sufficient residual strength.

This category was found in the flyschoid complexes (*Argille Varicolori* or marly-arenaceous ground) or in the stratified pyroclastites, as long as the overburdens were sufficient to make the natural formation of an arch effect possible.

Finally category C included all those sections of tunnel where mathematical calculation predicted that:

- the state of stress in the ground would have exceeded the strength characteristics of the material considerably even in the zone around the face;
- an “arch effect” would have been formed naturally neither at the face nor around the tunnel since the ground would not have possessed sufficient residual strength;
- deformation phenomena would have developed in the failure range, with the effect deferred in time and of the order of decimeters, giving rise to serious instability such as the collapse of the face and the cavity.
- as a consequence in the absence of intervention to stabilise it the face would have been completely unstable.

This category was found most frequently at portals and in general in sections with shallow overburdens, as well as in sections of clayey ground with a scaly structure belonging to the flysches of the *Argille Varicolori* with geotechnical characteristics close to the lower limits of the range identified (residual values). There is no way in which an arch effect can be formed in these cases except artificially.

#### 4 CONSTRUCTION METHODOLOGY (THERAPY PHASE)

After formulating predictions of the stress-strain behaviour of the ground as a result of excavation, the most appropriate stabilisation techniques were chosen to control, contain or actually anticipate and eliminate deformation for each section of tunnel with uniform deformation behaviour.

The guiding principles on which design of the tunnel section types was based are essentially as follows:

1. always full face advance, especially under difficult stress-strain conditions;
2. containment of changes to and decompression of the ground around the tunnel by immediate application of effective preconfinement and/or confinement of the cavity (sub-horizontal jet-grouting, glass-fibre structural elements in the core and/or in advance around the future tunnel and, if necessary, fitted with valves for cement injections, shotcrete, etc.) of sufficient entity, according to the case, to absorb a significant proportion of the deformation without collapsing or to anticipate and eliminate the onset of any movement in the ground whatsoever;
3. placing of a final concrete lining, reinforced if necessary, and complete with the casting of the tunnel invert when needed to halt deformation phenomena in steps at a short distance from the face.

The following tunnel section types were actually designed (fig. 5):

- **for sections of tunnel belonging to behaviour category A (*face stable*)** a type A section was designed consisting of a simple lining with a preliminary lining in shotcrete reinforced with simple steel ribs and a final lining in concrete 60 cm. thick, closed with a tunnel invert also 60 cm. thick.

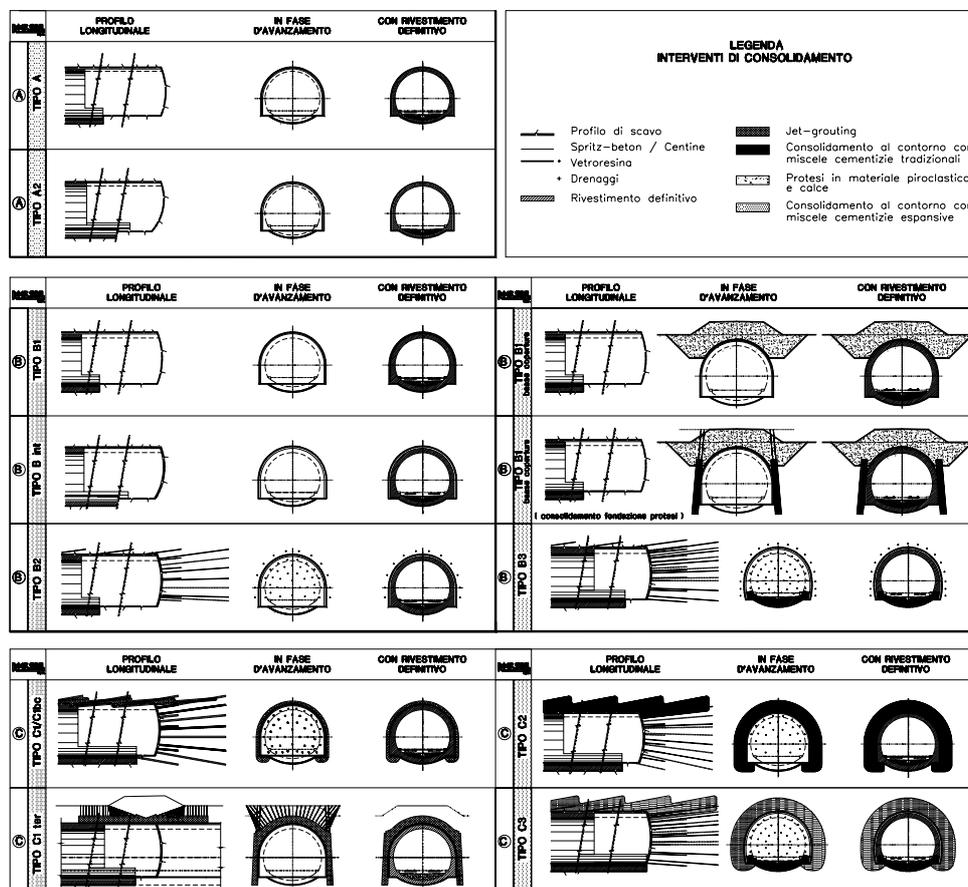


Figure 5. Tunnel section types.

- for sections of tunnel belonging to behaviour category B (*face stable in the short term*) three main tunnel section types were designed:
  - section type B1, consisting of a preliminary lining in shotcrete reinforced with double steel ribs + a final lining of 80 cm. closed with a tunnel invert of 90 cm. cast within 3 tunnel diameters from the face;
  - section type B2, for which reinforcement of the advance core is specified, performed using glass-fibre structural elements + a preliminary lining in shotcrete reinforced with double steel ribs + a final lining of 90 cm. closed with a tunnel invert cast within a distance of 1.5 tunnel diameters from the face;
  - section type B3, for which a geometry with curved tunnel walls is specified in order to withstand horizontal thrusts more effectively along with reinforcement of the advance core (more intensely than for B2 with more reinforcements and a longer overlap) again using glass-fibre structural elements + a preliminary lining in shotcrete reinforced with double steel ribs + a final lining of 90 cm. closed with

a tunnel invert 100 cm thick cast in one piece with side kicker and floor slab in steps of 4-6 m. from the face;

- **for sections of tunnel belonging to behaviour category B (*face unstable*)** two main types of tunnel section were designed:
  - section type C1, consisting of advance reinforcement of the ground around the tunnel using the technique of sub-horizontal jet-grouting + microcolumns of improved ground created using the same technique but in the advance core and reinforced with glass-fibre structural elements (15.5 m. in length with overlap of 3 m.) + a preliminary lining in shotcrete reinforced with double steel ribs + a final lining varying in thickness in the crown from 40 to 130 cm. closed with a tunnel invert 100 cm thick, cast in steps 6 - 12.5 m. in length, 1.5 tunnel diameters from the face;
  - section type C2, consisting of advance ground improvement around the future cavity using high pressure grout injections using valved glass-fibre tubes + reinforcement of the advance core with grouted glass-fibre structural elements (15 m. in length with an overlap of 5 m.) + a preliminary lining in shotcrete reinforced with double steel ribs + a final lining of 90 cm. closed with a tunnel invert 100 cm thick cast in steps 6 - 12.5 m. in length, 1 - 1.5 tunnel diameters from the face.

Finally when the final design specifications were completed the percentages of different tunnel sections types with respect to the total length of the tunnels was as follows:

- section type A: 28.9 %;
- section type B: 60 %;
- section type C: 11.1 %.

In addition to the rail tunnels, the design also involved a few indispensable accessory works. The following are worthy of mention:

- three access tunnels for the passage of vehicles were specified to accelerate advance rates for the longest tunnels, working contemporaneously on several faces: two access tunnels on the *Colli Albani* tunnel (over 6 km in length) and a third access tunnel to the *Campo Zillone* tunnel (around 3 km in length);
- works for portals, which, depending on the morphology and the nature of the ground in question, were designed using the most appropriate technologies (shells of ground improved using jet-grouting methods, “berlin” walls, etc.).

#### *4.1 Statics calculations*

The statics and deformation behaviour of tunnels, both in the construction phases and the final service phase was analysed and verified by a series of calculations on 3 and 2 dimensional finite element models in the elastic-plastic range.

The models were developed to simulate the behaviour of the ground-tunnel system in the different construction phases, as realistically as possible. Particular attention was paid: to the effect of preconfinement treatments of the cavity and reinforcement of the advance core specified in the design; to deformation values to be expected at the constructions stage; to stresses in the preliminary and final linings. The mathematical models were processed on computers using the software package ADINA version 6.0.

## 5 CONTRACT AWARDS

Contracts for all the tunnels, just as for all the other surface works required for construction of the line were of the “all-in, lump sum” type (2,844,644,600 euro, of which 324,231,600

for tunnels only) and awarded on the basis of final design specifications. With this type of contract the General Contractor IRICAV UNO accepted all risks including the geological risk.

## 6 OPERATIONAL PHASE

Construction design began immediately after the contract was awarded, with excavation work underway (May 1995, *Colli Albani* tunnel).

Given the additional survey information available and direct in the field confirmation, the validity of the final design was substantially confirmed at the operational phase and only a few minor refinements were made during construction design:

- in order to specifically tackle the scaly clays characteristics of the *Colle Pece* tunnel, a section type C3 was introduced that is different from C2, due above all to the use of expanding cement mixes for grouting of the glass-fibre structural elements;
- a section type “B1<sub>bc</sub>” for shallow overburdens and a section type “C1<sub>ter</sub>” were designed for tunnel sections with particular design characteristics;
- section types A2 and an “B1<sub>intermedia</sub>”, very similar to A1 and B1 described above, were developed to optimise works in a few particular circumstances;
- admissible variations (e.g. intensity of reinforcement) were specified for each tunnel section type according to the actual deformation behaviour measured during construction as compared to that predicted by design calculations. This was done in order to apply quality assurance norms.

Finally when the construction design was completed the percentages of different tunnel section types were as follows:

- section type A: 22.5 %;
- section type B: 69.4 %;
- section type C: 8.2 %.

To date (December 1999), after 1,100 working days (1,700 total days) approximately 21.6 km of tunnel have been completed, almost all fully lined, equal to about 99% of the underground sections.

Average advance rates were about 20 m./day, not counting excavation performed to open access tunnels, shafts and other accessory works.

Figure 6 shows production graphs for the *Colli Albani* and *Sgurgola* tunnels from which it can be seen that production rates were not only high (around 100 m/month per face) but above all very constant, a sign that the construction design matched actual conditions excellently.

Table II gives a clear comparison of the differences in the distribution of tunnel section types between the final design, the construction design and the “as built”. These differences did not result in any significant change in the overall cost of the works, since the greater percentage of B section types was compensated for by a decrease in A and, above all, in C (by far the most costly) section types.

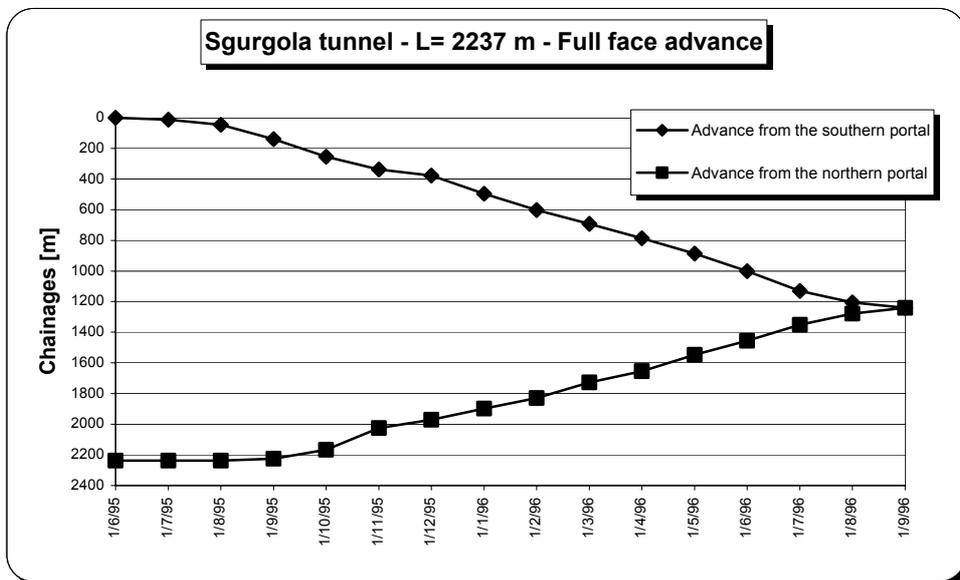
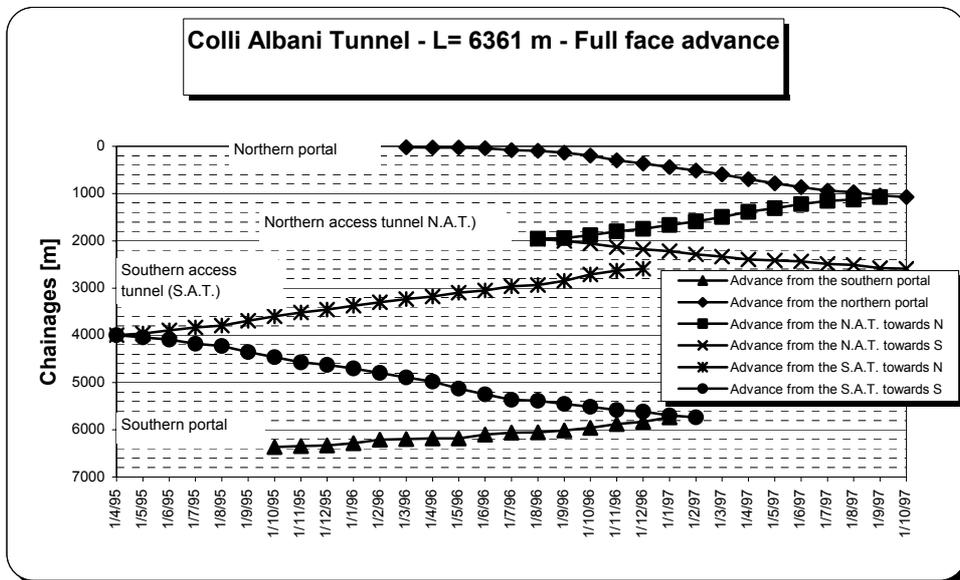


Figure 6. The very distinct linear nature of the curves is a result of the high level of industrialisation achieved.

HIGH SPEED TRAIN - Milan to Naples Line - Rome to Naples Section - SECTION TYPES DISTRIBUTION																																				
WBS	TUNNEL	TUNNEL LENGTH (m)	FINAL DESIGN						CONSTRUCTION DESIGN						AS BUILT (January 2001)																					
			SECTION TYPES (Length in metres)						SECTION TYPES (Length in metres)						Built section			SECTION TYPES (Length in metres)																		
			A	B1	B1 bc	B2	B3	C1	C2	A/A2	B1	B1 bc	B2	B3	C1	C2	(%)	met	A/A2	B1	B1 bc	B2	B3	C1	C2											
GN01	COLLATINA	55						55	53							24								29	100.0	53		24						29		
GN02	MASSIMO	1149	1092					57	1139	664	355													120	100.0	1139	766	236						137		
GN03	COLLI ALBANI	6357	1462	3115				1780	6361	541	5425													355	40	100.0	6361	610	5355					356	40	
GN10	SGURGOLA	2240	560	1680					2237	1987	250															100.0	2237	1615	622							
GN11	MACCHIA PIANA 1	1150	920	230					969	834	63															100.0	969	831	66						72	
GN12	MACCHIA PIANA 2	540	540						212																		100.0	212							175	37
GN13	LA BOTTE	1185	687			379			119	1263	300	348		342												100.0	1263	344	256		395		258			
GN14	CASTELLONA	470	249	221					430	178		173	79													100.0	430		159.5		231	39.5				
GN15	S. ARCAANGELO	580			116	406			58	580	380	200														100.0	580		507		73					
GN16	SELVA PIANA	170	119	51						132		49														100.0	132		90		8				34	
GN17	COLLEVENTO	387			348				39	380	100		239.5	50.5												100.0	380		107	248		25				
GN18	SELVOTTA	173				173				164																100.0	164				33				131	
GN19	COLLE PECE	873			611	175			87	873	253		389	149	42	40										100.0	719		153	181	247.5	87.5	50			
GN21	GAMPO ZILLONE 1	3163		1423		1740				2617	1565		801		251											100.0	2617		2586		15				16	
GN25	GAMPO ZILLONE 2	350				350				350	334				16											100.0	350		334						16	
GN26	PICCILLI 1	845	127	591				127		907	553	58	296													100.0	907		677	58	98				74	
GN27	PICCILLI 2	229		195				34		485	296	219														100.0	485		249	236						
GN28	L'OMPARI	235		189			47			199	155															100.0	199		155						44	
GN29	CAIANELLO	210		168				21	21	832	474	334				24										100.0	832		477	331					24	
GN30	BRICCELLE	1033	424	609						1033	581	10		218	180	4	40									100.0	1033	582	10		218	180	4		39	
GN32	CASTAGNE	0										189	100													100.0	289		184	105						
GN33	SANTUARIO	0								322		242	80													100.0	322		242	80						
<b>TOTAL LENGTH (m)</b>		21394	6190	8472		3717	649	1962	415	21817	4907	11213	791	2729	408	1408	362	99.3	21663	4748	12490	810	1500	467	1245	404										
<b>% SECTION TYPES USE</b>			A	B1	B1 bc	B2	B3	C1	C2		A/A2	B1	B1 bc	B2	B3	C1	C2		A/A2	B1	B1 bc	B2	B3	C1	C2		A/A2	B1	B1 bc	B2	B3	C1	C2			
			28.9	39.6	0.0	17.4	3.0	9.2	1.9		22.5	51.4	3.6	12.5	1.9	6.5	1.7		21.9	57.7	3.7	6.9	2.2	5.7	1.9											
<b>TOTAL SECTION TO BE TUNNELED (%/m)</b>																											0.7									155

Table II. Percentage use of different tunnel section types: a comparison between final design, construction design and “as built”.

## 7 MONITORING PHASE

### 7.1 Monitoring during construction

The adequacy of design hypotheses was verified by geotechnical mapping of the face and monitoring of the stress-strain behaviour of the face and the cavity observed during construction at each stages and sequences specified in the design.

To achieve this a complete monitoring system was devised that included:

1. geological and structural mapping of the face;
2. face extrusion measurements;
3. convergence measurements;
4. extensometer measurements from above;
5. surface levelling measurements (on sections with shallow overburdens);
6. inclinometer measurements (at portals);
7. laboratory tests on samples taken from the face

### 7.2 Final monitoring

Twenty two completely automated permanent monitoring stations for digital recording of data were located along the rail tunnels.

Their purpose was to:

1. verify design hypotheses;
2. monitor the behaviour of the tunnels over time;
3. provide information for maintenance purposes.

The monitoring project currently in progress includes the following:

1. convergence measurements to determine radial deformation;
2. extensometer measurements to assess the development of deformation inside the ground;
3. measurements of total pressure of the ground on the lining;
4. measurements of interstitial pressure within the ground;
5. measurements of stress in structural members;
6. measurements of the temperature of the concrete in the final lining
7. measurements of vibrations induced in structures by the passage of trains.

## 8 CONCLUSIONS

The difficulty of making reliable predictions of the geological and geotechnical characteristics of the ground to be tunnelled when carrying out underground works and the lack of advance tools and techniques valid for all types of ground has always been a weak point in the planning of underground projects both in terms of times and costs.

On completion of the tunnels on the High Speed Rome-Naples line, it can be stated that the design predictions made using the ADECO-RS approach were found to match the reality very closely despite the geological difficulty of the ground tunnelled.

When account is taken of the ground involved and of some objectively difficult conditions that had to be tackled, the fast average advance rates achieved constitute a good indicator of both the high standard of the design and the high degree of industrialisation of the tunnel advance operations achieved on construction sites.

The underground works should be completed on schedule within the first few months of 2001. Construction costs too differ by only a few percentage points from forecasts and there have been no serious disputes between the Contractors and the Owner.

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Work:	<b>HIGH SPEED TRAIN Line Milan to Naples Section Rome to Naples Underground works</b>
Owner:	<b>Ferrovie dello Stato S.p.A.</b>
Concessionaire:	<b>T.A.V. S.p.A.</b>
Supervisor:	<b>ITALFERR-SIS.T.A.V. S.p.A.</b>
General Contractor:	<b>IRICAV UNO</b>
Designer:	<b>ROCKSOIL S.p.A.</b>