Technical and financial planning of underground works. The ADECO-RS method

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Riassunto

Fino a diversi anni fa, la progettazione e la costruzione di opere in sotterraneo non poteva essere affrontata allo stesso modo di altre opere civili di pari importanza.

Questo dipendeva, sostanzialmente, dalla mancanza di adeguati strumenti conoscitivi, progettuali e realizzativi.

Da un lato l'imprevisto geologico sempre in agguato, dall'altro la carenza di strumenti di calcolo adeguati e l'oggettiva difficoltà di affrontare, con le tecniche di scavo disponibili, i terreni cosiddetti *difficili* hanno da sempre collocato le opere in sotterraneo in posizione subordinata rispetto alle analoghe opere in superficie: ad esse si è ricorsi solo quando quest'ultime apparivano impraticabili.

Negli ultimi dieci anni, i progressi fatti in campo geognostico, la disponibilità di più potenti mezzi di calcolo e l'introduzione di tecnologie di scavo innovative avevano creato, però, la premessa per un decisivo salto di qualità.

Oggi, il metodo ADECO-RS ha raccolto in sé tutte queste importanti innovazioni, integrandole tra loro in un sistema di progettazione e di costruzione di nuova concezione che, al contrario dei sistemi fino ad oggi vigenti che offrono soluzioni solo parziali al problema, permette, per la prima volta, di affrontare in maniera omogenea il progetto e la costruzione di gallerie in qualsiasi tipo di terreno elaborandone il progetto completo prima di iniziarne l'esecuzione.

In particolare, minimizzando gli imprevisti ed eliminando le difficoltà di avanzamento che si incontravano in particolari tipi di terreno, esso consente di definire con un elevato grado di precisione, proporzionale alle conoscenze geognostiche acquisite in fase conoscitiva, i tempi ed i costi esecutivi; di conseguenza consente di valutare a preventivo, in manera attendibile, il rapporto costo/beneficio dell'opera in sotterraneo, parametro fondamentale per orientare il progetto decisionale di selezione tra differenti alternative progettuali; a consuntivo poi, il maggior grado di conoscenza garantito dal metodo ADECO-RS permette una precisa definizione dei contenuti dei costi, attraver-

so specifici momenti di controllo eseguiti sistematicamente durante l'esecuzione dell'opera.

Questo significativo risultato, traslato in sede di pianificazione territoriale, pone finalmente le opere in sotterraneo sullo stesso piano di quelle più tradizionali in superficie.

Parole chiave: Galleria, Classificazione, Progetto, Costruzione, Costo.

Abstract

Up until some years ago, the design and construction of underground works could not be dealt with in the same way as other civil engineering works of the same importance.

This was principally due to the lack of adequate survey, design and construction instruments.

Underground construction faces on the one hand, the problems of unexpected geological conditions, always ready to pounce, and on the other hand the inadequacy of computing instruments, not to mention the objective difficulty in dealing with so-called *difficult* ground with available excavation techniques. These problems have always placed underground construction in second place with respect to surface work; underground construction was resorted to only when surface construction seemed impossible.

Over the last few years, progress in the field of geological diagnostics, the availability of more powerful computing instruments and the introduction of innovative excavation technology have provided the conditions for a decisive qualitative transformation.

Today, all these important innovations have been collected together in the ADECO-RS method. They have been integrated in a new conception of design and construction systems. As opposed to the systems used up to now, which only offer partial solutions to the problem, with the ADECO-RS system it is possible, for the first time, to standardize the approach to design and construction of tunnels in any type of ground and complete design and planning of a project can be done before construction begins.

By minimising unforeseen conditions and eliminating tunnel advance difficulties that are met in particular types of ground, this system means that construction times and costs can be forecast with a high degree of precision that is proportional to the diagnostic geological knowledge acquired at the survey stage. Consequently reliable estimates of cost benefit ratios for underground projects can be made at the contract specifications stage. The cost benefit ratio is a fundamental parameter for the decision process of selecting a design from various alternatives. The ADECO-RS system gives a more detailed knowledge of a project by means of specific points of control systematically monitored during construction. Consequently, when the work is finished there is a more detailed breakdown of costs.

The result is significant and when translated into terms of land use and planning, means that underground construction can be placed on the same level as more traditional surface construction.

Key words: Tunnel, Classification, Design, Construction, Cost.

Introduction

Today, all over industrialized world and especially in intensely urbanized areas people are facing two contrasting demands. One is for more and more infrastructures, buildings and living spaces for the functions of community life against which there is that of the growing awareness that the high concentration of these on the surface is inevitably damaging to the natural environment and the quality of life.

For some time now architects and urban planners have identified underground space as a precious source of new spaces and as the only feasible means of finding a definite solution to this problem.

Nevertheless, they often find themselves battling for this space because of the widespread mistrust that administrators and politicians have of underground constructions. These are still today seen as true and genuine works of art constructed by a process of improvisation in which it is impossible to forecast construction times and costs. This mistrust is a legacy of the past. In the past there was a lack of adequate instruments for surveying the ground. Effective instruments for ground reinforcement and therefore cutting systems suitable for all types of rock or soil were non-existent. It was impossible to carry out complex computing operations. All this not only made excavation work difficult and dangerous, it also meant that underground constructions practically had to be designed while they were built.

The design of such projects meant merely defining the vertical and horizontal geometry of the route and some typical cross sections, while excavation methods, stabilization devices and linings were decided during construction as the face advanced.

In this situation any possibility of making forecasts of construction times and costs was ruled out and this justified the fear with which any underground construction was considered.

An example of what is meant here can be seen by looking at the case of the *Traforo del Gran Sasso*. Construction began just over twenty years ago on the basis of a design which today we would call a *feasibility* design. It took ten years to construct running into many difficulties and unexpected conditions of considerable importance with costs soaring from an initial 26 to a final 220 billion lire approximately.

Today, however, one can say that fears of this type of thing happening are no longer justified and this is what we intend to demonstrate here with the help of a few concrete examples.

The problem of planning underground works in different morphological situations and in all types of ground

Underground construction faces difficulties in reliably predicting the geological and mechanical nature of the ground to be tunnelled and it has suffered from a lack of valid excavating instruments and techniques for dealing with the most difficult ground. These are the true weak points of underground construction as far as the planning of works in terms of times and costs are concerned.

It is only in the last few years, and in our country in particular, that important progress has been made in the fields of geological diagnostic techniques and face advance and stabilization systems for all types of ground. This progress represents an indispensable precondition for giving underground construction the same status as any other types of civil engineering project.

One new geological diagnostic technique is the *Pilot Tunnel*, constructed before full face excavation, as a means of surveying the entire length of the route of a planned tunnel. It has been in use in Italy since 1984 and has de facto eliminated unexpected geological conditions, providing important scheduling, contractual and financial advantages. Detailed measurements of geological structure can be made inside a pilot tunnel. Data can be systematically acquired from the behaviour of the cutter during excavation (*RS method* LUNARDI P., 1986) with subsequent processing and checking of this data. Additional data on the mechanical properties of the ground can be obtained using in-situ measurements and tests. Consequently, resulting design models closely fit the real conditions existing along the route of the future tunnel.

This new way of using a pilot tunnel has found widespread use in tunnel projects over recent years, with more than 100 km of tunnel being built with the method. Two tunnels in particular are worthy of mention. The *Prato Tires* tunnel, forming part of the new route of the Verona Brennero mainline railway, where a pilot tunnel was constructed along the whole 13 km length and the *Marborghetto* tunnel on the Udinese Tarvisio railway where, despite difficult sections requiring complete armouring of the pilot tunnel to prevent its collapse, estimated time and cost targets were kept to satisfactorily (cf. Fig. 1).

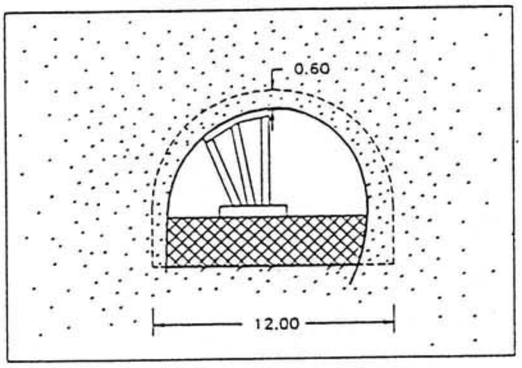
In the field of construction systems, *conservative systems* FOCARACCI A., 1991 are special face advance systems for advancing in the worst type of ground with the same advance rate and safety levels obtained in good quality ground such as rock (industrialization of tunnel excavation).

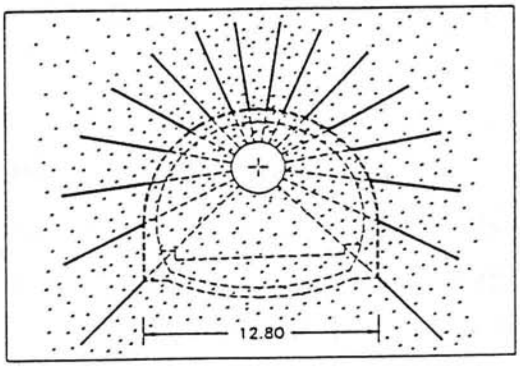
The following are worthy of note (Fig. 2):

- sub-horizontal jet-grouting systems designed for the excavation of tunnels in non cohesive or almost non cohesive ground (used for the first time in the world on the *Campiolo* tunnel on the Pontebba-Tarvisio railway line LUNARDI P., 1992);
- mechanical pre-cutting systems, for systematic excavation of cohesive and semi-cohesive ground, even under the water table (first used in Italy in 1985 on some of the tunnels along the Sibari Cosenza railway line LUNARDI P. *et al.*, 1989 - ARSENA F.P. *et al.*, 1991);
- systems consisting of pre-reinforcement of the core ahead of the face using glass resin nails for the excavation of ground susceptible to extrusion (used for the first time in the world in 1988 on the *Talleto* and *Caprenne* tunnels along the section connecting the new Rome Florence

PILOT TUNNEL

TRADITIONAL ADVANCE	ADVANCE WITH PILOT TUNNEL





	PROJECT	
Genoa Ventimiglia F.S. railway		Udine Tarvisio F.S. railway
	MAIN CONTRACTOR	
COGEFAR S.p.A.		CARNIA Consortium
	SPECIALIST CONTRACTOR	
RODIO S.p.A.		ILBAU
	DESIGN CONSULTANTS	
—		ROCKSOIL S.p.A.
	GROUND	
Clay shales and marl shales		Dolomites, limestones, clay shales

Of metric magnitude in the elastic–plastic range	DEFORMATION PHENOMENA	Considerable for the pilot tunnel, absent during widening
From meter No. 2,180 to No. 2260	COLLAPSE OR NEAR COLL.	None
5 months for repair of near collapse section	CONSTRUCTION TIMES	Pilot tunnel 20 m/day Widening 10 m/day
8,000 ($/metre)	ESTIMATED COST	11,400 ($/metre)
26,700 ($/metre)	ACTUAL COST	12,700 ($/metre)

Fig. 1 - Pilot Tunnel.

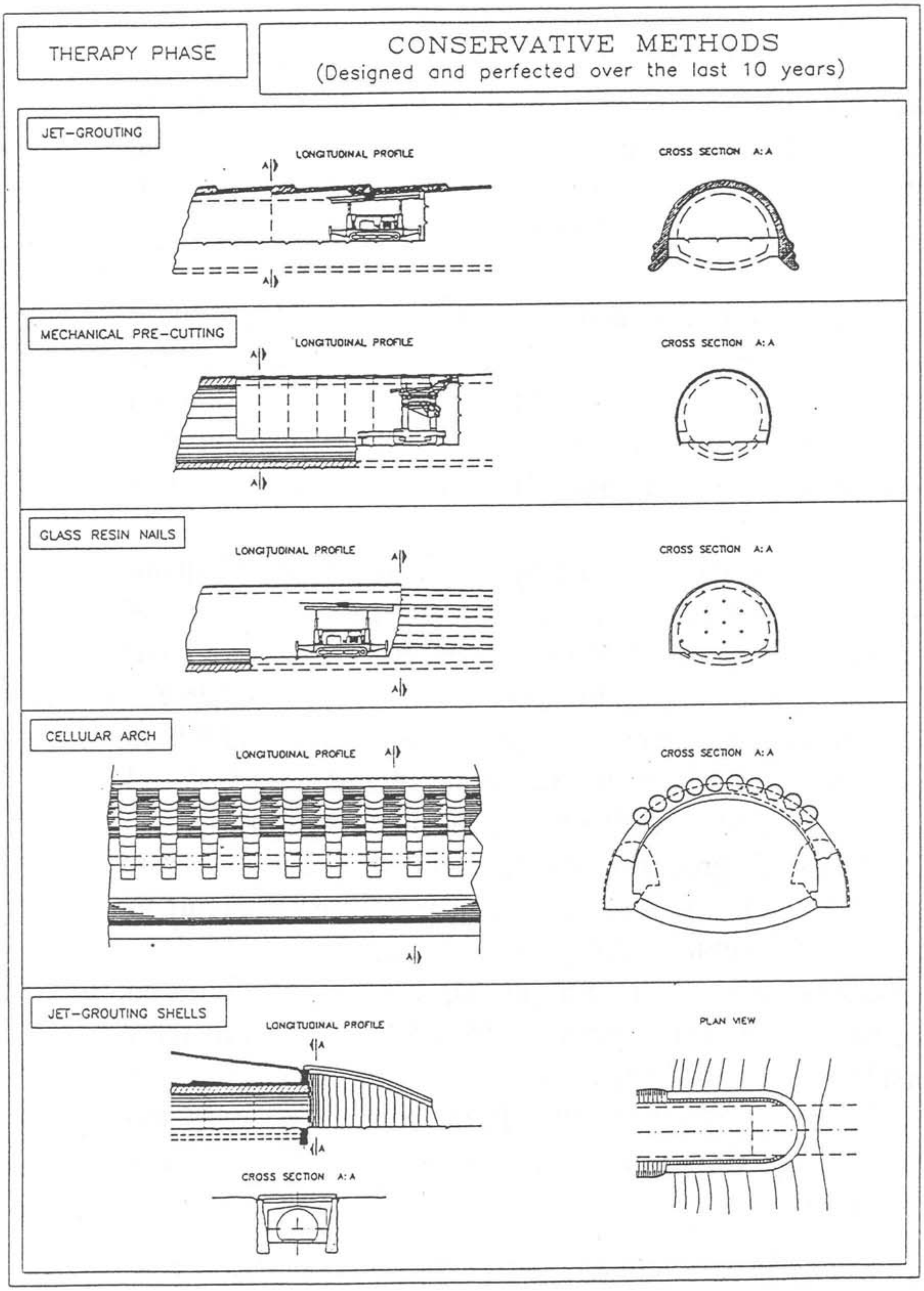


Fig. 2 - Conservative methods (designed and perfected over the last 10 years).

Direttissima line and the old line at Montevarchi LUNARDI P., 1991 - LUNARDI P. *et al.*, 1992);
- *Cellular Arch* systems for the excavation of shallow, wide span cavities in urban areas with non cohesive or almost non cohesive soils causing almost no surface subsidence (used for the first time in the world for the *Venezia* station of the Milan Link Line railway LUNARDI P., 1990);
- sub-vertical jet-grouting systems for the excavation of portal accesses in detritus slopes without jeopardising stability (used for the first time in the world in Italy for the Pontebba portal of the *San Leopoldo* tunnel on the Pontebba Tarvisio railway line LUNARDI P., 1991).

It would take too long to give a detailed description of these methods here. Fig. 3, however, reports one of the many examples of the application of conservative systems and gives a comparison of its use with the application of traditional systems used in the same tunnel and under similar geo-mechanical conditions.

All the necessary instruments both for obtaining an adequate knowledge of the ground before beginning construction and for dealing with all types of ground have therefore been available now for some years. The design stage could have been separated already at that time from the construction stage and this is an indispensable condition for the planning of underground works and the industrialization of excavation operations.

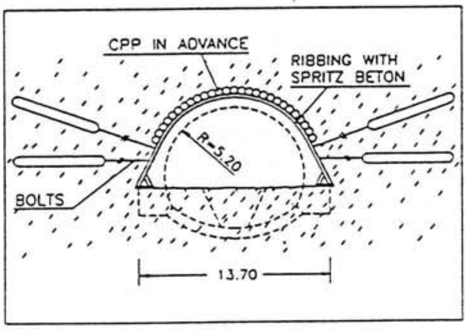
Despite this, underground constructions continue to be considered as different from other civil constructions: difficult to construct and impossible to design in advance.

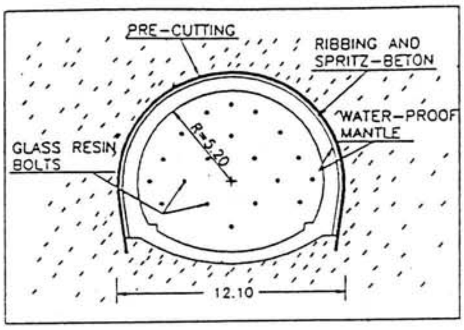
This conviction is no longer justified but is perpetuated because customers and contractors, often badly advised by their own consultants and badly guided by no longer adequate regulations and contract specifications, do not apply the new technologies correctly. Common inadequacies of such regulations and specifications are:

- references to incomplete and partial geo-mechanical classification systems (Rabcewicz, Barton, Bieniawski), that are,

MECHANICAL PRE–CUTTING AND PRE–REINFORCEMENT OF CORE AHEAD OF THE FACE USING GLASS RESIN BOLTS

TRADITIONAL SYSTEMS	CONSERVATIVE SYSTEMS





TRADITIONAL SYSTEMS		CONSERVATIVE SYSTEMS
"Direttissima" F.S. railway line Stretch of line Arezzo S.–Figline V.	PROJECT	"Direttissima" F.S. railway line Stretch of line Arezzo S.–Figline V.
FE.S.P.I. Consortium	MAIN CONTRACTOR	FE.S.P.I. Consortium
RODIO S.p.A.	SPECIALIST CONTRACTOR	RODIO S.p.A.
—	DESIGN CONSULTANTS	ROCKSOIL S.p.A.
Limy, clayey, sandy	GROUND	Limy, clayey, sandy
Yield of decimetric magnitude, convergence up to 2 m	DEFORMATION PHENOMENA	Maximum convergences of 2–5 cm disappearing after casting of the inv.
Collapse of "Del Poggio" tunnel Near collapse of "Tasso" tunnel	COLLAPSE OR NEAR COLL.	None
0.50 (m/day)	ADVANCE RATE	2.75 (m/day)
18,700 ($/metre)	ESTIMATED COST	20,000 ($/metre)
22,700 ($/metre)	ACTUAL COST	20,000 ($/metre)

Fig. 3 - Mechanical pre-cutting and pre-reinforcement of core ahead of the face using glass resin bolts.

at the most, only valid for rock masses with good mechanical properties;
- the absence of precise guide lines on the correct use of the modern methodologies for diagnosis and therapy in the design of underground works making it impossible to provide the necessary technical guarantees;
- lack of instructions or precise directives on how methods are to be applied and works carried out;
- a complete and total absence of quality control systems for completed works.

All these inadequacies translate into wide margins of discretion for making modifications to the design during construction (necessarily provided for in contract specifications themselves to make up for the above inadequacies) with consequent frequent conflict between customer and main contractor over the considerable price increases that result from these design modifications and construction changes.

The resultant difficulty in the technical management of a contract has obvious effects on costs and financial aspects.

Fig. 4 is based on a considerable amount of final data relating in particular to the Rabcewicz classification system. It shows how the intrinsic inadequacies of this system lead to the concentration of 90% of the length of the tunnels excavated into just three rock classes each with a very different cost per linear metre (the cost of a section in class Va is actually three times higher than that of a section in class III). This produces a very steep unit cost curve. In this situation it is easy for a main contractor to take advantage of the vague indications provided by Rabcewicz and attribute poorer rock classes to tunnels than those given in cost estimates.

It is these negative results have that have had the effect of making the technical progress that has been achieved, in term of survey technologies and face advance systems, worthless. Furthermore, they have perpetuated, amongst those involved, the mistaken conviction that it is impossible to construct underground to the same standards of quality and safety as can be achieved with other civil engineering works.

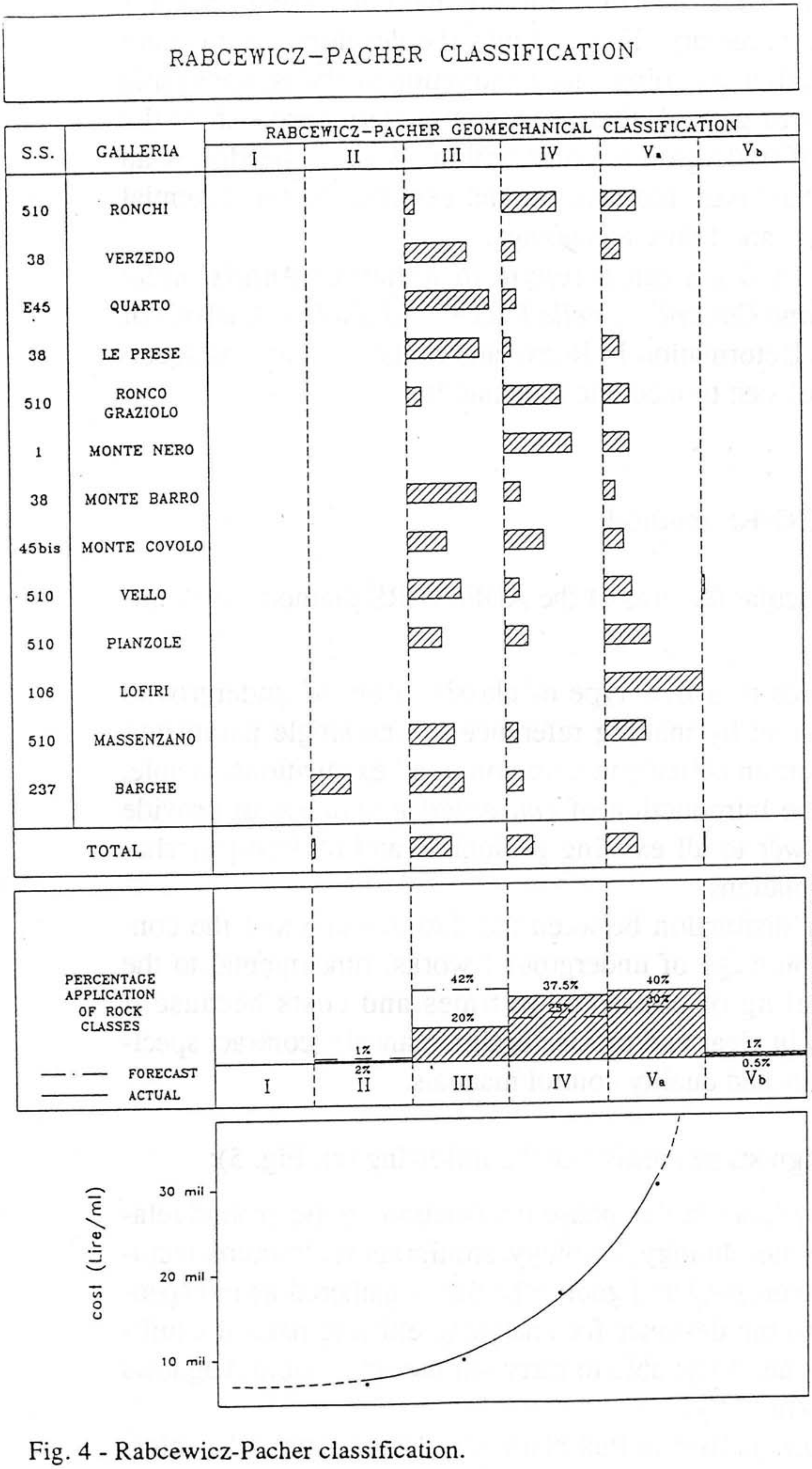


Fig. 4 - Rabcewicz-Pacher classification.

A complete overhaul of the traditional contractual formulas is therefore necessary. This assumes the development of more adequate design, planning and construction methods, applicable to all types of ground, that provide a modern approach to the problems of underground construction. What is needed is an approach that takes into account and exploits the full potential of all present and future technology.

The ADECO-RS (an acronym in Italian of *Analisi delle Deformazione Controllate nelle Rocce e nei Suoli* - Analysis of Controlled Deformation in Rocks and Soils) system was specifically developed to meet these demands.

The ADECO-RS method

The particular features of the ADECO-RS method are as follows:

- reference to a new type of classification of underground works that by making reference to one single parameter, stress-strain behaviour, common to all excavations, is able, with the introduction of *conservative systems*, to provide an answer to all existing geological and rock/soil mechanics situations;
- a clear distinction between the design stage and the construction stage of underground works, fundamental to the scheduling of construction times and costs because it results in clear and precise design manuals, contract specifications and quality control manuals.

The **design stage** consists of the following (cf. Fig. 5):

- *survey phase*: in this phase information on the ground relating to morphology, lithology, stratigraphy, structure, tectonics, hydrology and geomechanics is gathered as indispensable to the designer for analysing existing natural equilibriums and to be able to carry out the subsequent diagnosis phase correctly;
- *diagnosis phase*: in this phase the designer uses the infor-

TUNNEL DESIGN AND CONSTRUCTION
ADECO – RS SYSTEM

STAGE	PHASE	ACTIVITY
DESIGN	– SURVEY	– analysis of naturally existing equilibriums
	– DIAGNOSIS	– study and forecast of deformation phenomena
	– THERAPY	– control of deformation phenomena in terms of choice of stabilization systems
CONSTRUCTION	– OPERATIONAL	– implementation of stabilization instruments for the control of deformation phenomena
	– MONITORING DURING CONSTRUCTION	– monitoring and readings of deformation phenomena as a response of rock mass during tunnel advance (surface and at depth measurement of convergence)
	– DEVELOPMENT OF THE DESIGN	– interpretation of deformation phenomena – balancing of stabilization systems between face and the perimeter of the excavation

Fig. 5 - Tunnel design and construction Adeco - RS system.

mation collected during the survey phase to make accurate predictions concerning the behaviour of the future tunnel during excavation. The predictions must be made in terms of genesis, localization, development and size of probable deformation phenomena that will be triggered at the face and as a consequence in the band of ground around the excavation. The choice of stabilisation instruments and consequently the success of the project will depend on these predictions;

- *therapy phase*: in this phase, after predictions of the type, localisation and size of deformation phenomena at the face and around the excavation have been made during the diagnosis phase, excavation systems, rates and stages are decided and above all stabilization systems are chosen and the balance of these between the face and the perimeter of the tunnel is decided.

The **construction stage** consists of the following:

- *operational phase*: in this phase construction is carried out and stabilisation intruments are implemented according to design predictions. These are adapted if necessary according to the actual response of the rock mass and checked following clearly laid down quality control procedures;
- *monitoring phase*: in this phase the accuracy of the predictions made during the diagnosis phase for implementation during the operational phase, is checked by means of an appropriate campaign of surface and depth convergence measurements. When the tunnel is completed and in use, systematic monitoring is continued for safety purposes throughout the life of the tunnel.

In following this conceptual and operational scheme, the ADECO-RS method, by making use of the results of a detailed study of the dynamic development of excavation, offers designers a simple guide for the classification of underground works based on longitudinal sections each having a uniform stress-strain behaviour. Standard cross sections are assigned to these longitudinal sections together with initial and final stabilisation works. Times and costs are defined (cf. Fig. 6).

The introduction of the ADECO-RS method to guidelines and contract specifications has two immediate and obvious main consequences:

a) the design stage becomes more important, because the designer can make reliable technical proposals before the contract for the works is awarded. These also constitute an effective instrument for control and are of great help in managing the project during construction and during the subsequent quality control phase;
b) the cost estimates of underground works are much more accurate, being subject to very modest percentage error.

For the first time reliable estimates of construction costs can be made.

On the other hand it is only rigth that a fair and adequate price be paid for a well designed, carefully constructed and thoroughly inspected project.

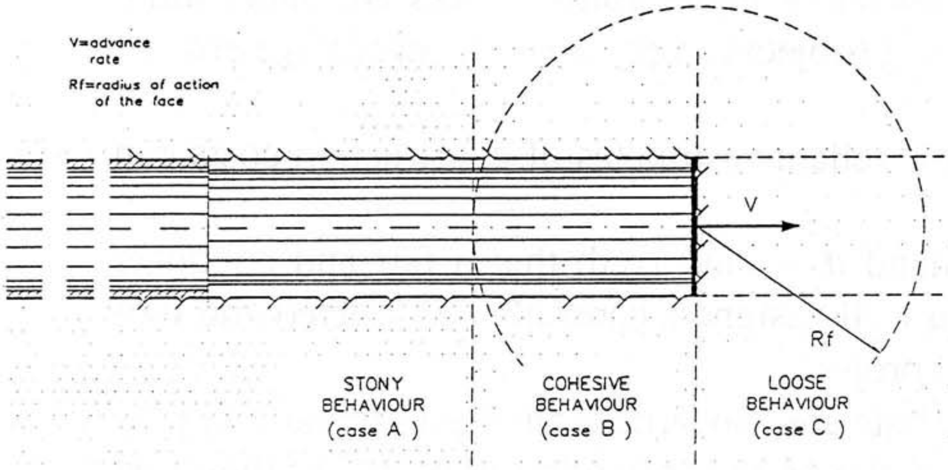
As far as price lists are concerned, amongst the various possible working hypotheses the following is probably the most feasible for ease of contract management. A unit price per linear meter of completed tunnel is set, based on cross section types specified at the design stage and on an analysis of market prices, with certain operations for pre-reinforcement and pre-containment of excavations treated separately and paid for per unit of measurement with relative price lists appropriately discounted for quantities in excess of forecast estimates until only cost prices are paid. As such special operations do not have a great effect on the cost of cross section types, used with the ADECO-RS method (cf. Fig. 7), the greater part of the price, as stipulated at the moment of awarding the contract, will be guaranteed, while increases will be limited to pre-reinforcement and pre-containment of the excavation and these will have only a small percentage effect on the total price of the project.

It is finally worth noting that if the market value of the cross section types defined by the ADECO-RS system are calculated,

THERAPY PHASE

TUNNEL DESIGN AND CONSTRUCTION
ADECO – RS SYSTEM

CHOICE OF STABILIZATION INSTRUMENTS FOR THE COMPOSITION OF CROSS SECTION TYPES



FACE		STABLE		STABLE IN THE SHORT TERM			UNSTABLE			
		A1	A2	B1	B2	B3	C1	C2	C3	C4
STABILIZATION INSTRUMENTS	RADIAL BOLTS	●		●						
	REINFORCED SPRITZ-BETON	●	●	●	●		●	●	●	●
	GROUND REINF. OF FACE				●		●	●		
	TUNNEL INVERT			●	●	●	●	●	●	●
	PRE-CUTTING					●	●			
	RADIAL GROUND REINFORC. FROM PILOT TUNNEL								●	
	JET-GROUTING							●		
	INJECTIONS IN ADVANCE									●
	DRAINAGE		●	●	●	●	●	●		
	PILE DRIVING		●							
DEFORMATION PHENOMENA		CENTIMETRIC		DECIMETRIC			UNACCEPTABLE			

SECT. C2

Fig. 6 - Tunnel design and construction Adeco - RS system.

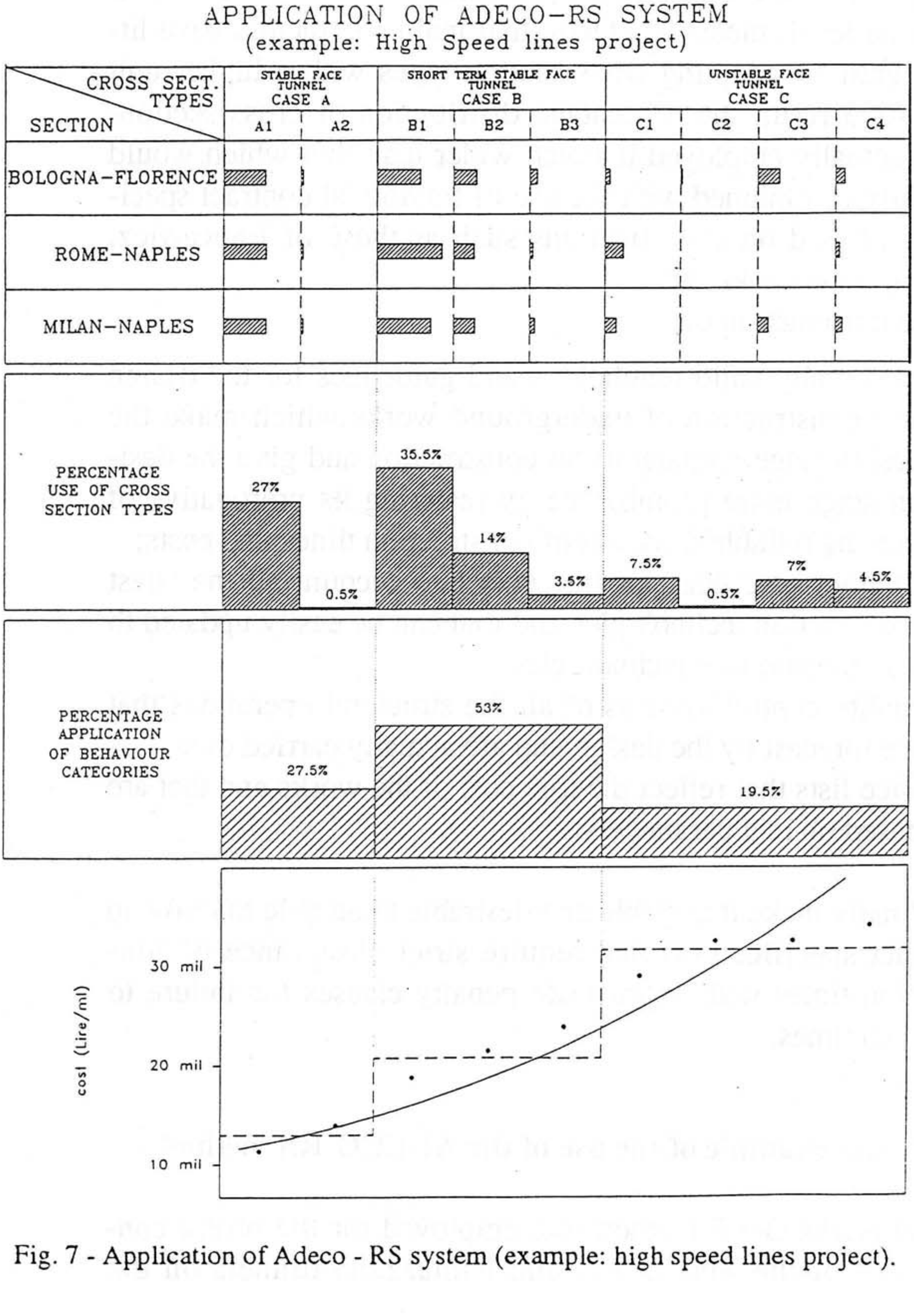


Fig. 7 - Application of Adeco - RS system (example: high speed lines project).

the result is a unit cost curve which is rather flat. This is a consequence of the system being applicable to all types of ground and taking into account all types of technologies in use to date. This curve, calculated for 100 Km of tunnel to be excavated under extremely varied conditions, is given in Fig. 7. The more gradual gradient of the unit cost curve, which from a financial viewpoint puts the different rock behaviour categories all on the same level, means, de facto, that main contractors have little to gain by adopting cross section types with a higher unit cost. As a result the percentage distribution of cross section-types actually employed is much wider than that which would normally be obtained with the use of traditional contract specification based on classifications such as those of Rabcewicz, Barton, Bieniawski, etc.

The introduction of:

- universally valid regulations and guidelines for the design and construction of underground works which make the design stage preparatory to construction and give the design stage more prominence by restoring its prerogative of making reliable forecasts of construction times and costs;
- contract specifications that take into account all the latest construction technologies and that can be easily updated to accomodate new technologies;
- quality control systems of all the structural operations that are forecast by the design and are actually carried out;
- price lists that reflect the true cost of the works and that are based on real parameters;

will finally make it possible and desirable to be able to draw up contract specifications that require strict observance of construction times with appropriate penalty clauses for failure to meet deadlines.

A pratical example of the use of the ADECO-RS method

The ADECO-RS method was employed for the recent construction of the Malenchini and Rimazzano tunnels on the

Livorno Cecina sections of the Livorno Civitavecchia motorway currently under construction.

Geological and geotechnical picture (survey phase)

The area through which the route passes underground is characterized by outcrops of loose and stony ground.

The geotechnical and mechanical properties of the lithotypes encountered were determined by means of in-situ and laboratory tests during the geological diagnostic survey. The laboratory tests were carried out on undisturbed and dislocated samples taken from drill holes.

They furnished good indications of the values for strength and deformation parameters of the ground.

These values would govern the behaviour of the ground when excavated.

Predictions of the response of the ground to excavation (diagnosis phase)

The response to excavation of the ground through which the tunnels were to pass was predicted on the basis of the data furnished during the survey phase. The most up-to-date and reliable mathematical computing instruments were used and the resulting predictions were used to decide on precise advance methods and on the most suitable stabilization techniques to be employed.

The predictions were closely related to a study of the stress-strain conditions that would result in the ground around the tunnel, following excavation, and were used to divide the route into sections each having uniform mechanical behaviour. These are listed below:

a) tracts with low and medium overburden (20 - 25 m max overburden) in the presence of non cohesive or almost non cohesive ground for which essentially unstable conditions were forecast at the face (tunnel with unstable face behaviour, category C);

b) tracts with low and medium overburden (25 - 35 m max overburden) in the presence of cohesive ground of a clayey nature where instability phenomena in the core of ground ahead of the advance face could be considered as exhibiting elastic-plastic behaviour due to the decompression it would be subject to and to the swelling effect following chemical and physical alteration (tunnel with short term stability face behaviour, category B).

Stabilization operantions (therapy phase)

All the above considerations were taken into account in order to define stabilization operations for each section exhibiting uniform mechanical behaviour and the relative operational phases (cross section types) to be adopted for the construction of the tunnel with the aim of guaranteeing short and long term stability of the walls of the excavation.

Cross sections:

- cross section type 1 (horizontal jet-grouting) adopted for longitudinal sections belonging to behaviour category C;
- cross section type 2A (sub-horizontal reinforcement of the core of ground ahead of the face using glass resin nails and full face excavation with the construction of a tunnel invert within two to three diameters of the cutting face) adopted for longitudinal sections belonging to behaviour category B.

Monotoring and measurement (operational and monitoring phase)

All excavation and advance operation were carefully monitored during the construction of both tunnels.

This involved systematic measurements of convergence and topographical measurements to check for displacements of the primary lining in shotcrete. For the Rimazzano tunnel, surface extensometer measurements were carried out to evaluate deformation phenomena occurring in the ground as the face approached. The results of the measurements, read and processed in real time, were initially used to rate design formulations and later to check the validity of the techniques adopted.

The Direction of Works continuously carried out checking of all work. Although these checks did not use criteria typical of quality control systems, the systems used were very similar.

Cost analysis

Estimates

On completion of the previous design phases, cost and construction planning of the works was carried out. Construction times of 14 and 20 months and total costs of 23.5 and 39.95 thousand million lire were estimated for the construction of the Malenchini and Rimazzano tunnels respectively.

Considerations concerning actual construction times and costs

The above estimates, when compared with actual construction times and costs on completion of the works, show an underestimate of a few percentage points.

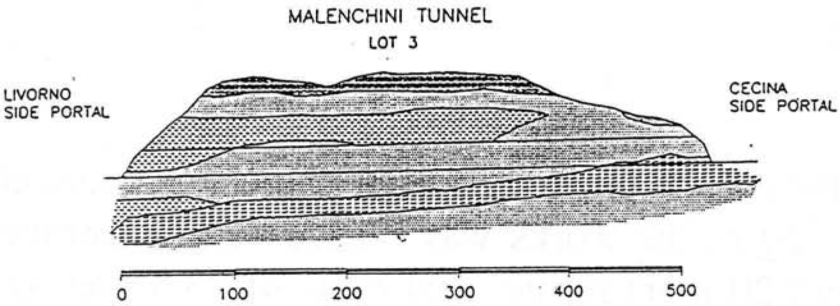
As far as construction costs in particular are concerned, Figg. 8 and 9 give a comparison of both the total cost for each tunnel and the unit costs for the main operational phases (ground reinforcement, excavation and lining).

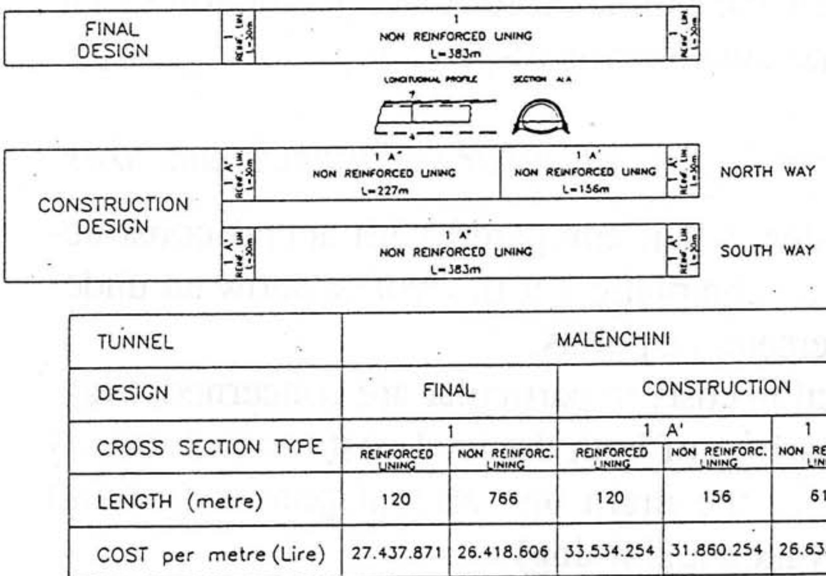
The increase in the total cost of the works as compared to the forecast cost was equal to 7.3% in the case of the Malenchini tunnel and equal to 3.1% for the Rimazzano tunnel.

A similar increase (5 - 6%) was found for construction times and this demonstrates that the two factors are closely related one to the other. An analysis of the cost summary tables and unit cost curves in Fig. 10 shows that these increases are totally due to soil improvement work. Excavation and lining opera-

TUNNEL DESIGN AND CONSTRUCTION

FIRST EXAMPLE OF THE APPLICATION OF THE ADECO-RS METHOD
FOR THE TUNNELS OF THE LIVORNO-CIVITAVECCHIA MOTORWAY
ON THE LIVORNO-CECINA SECTION



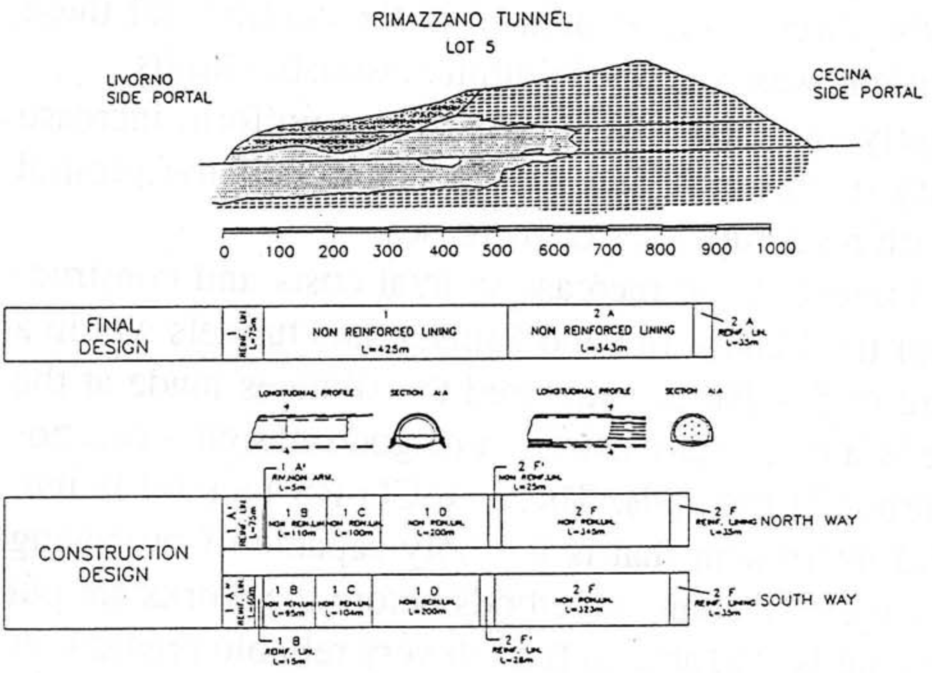


TUNNEL	MALENCHINI				
DESIGN	FINAL		CONSTRUCTION		
CROSS SECTION TYPE	1		1 A'		1 A"
	REINFORCED LINING	NON REINFORC. LINING	REINFORCED LINING	NON REINFORC. LINING	NON REINFORC. LINING
LENGTH (metre)	120	766	120	156	610
COST per metre (Lire)	27.437.871	26.418.606	33.534.254	31.860.254	26.635.494
EXCAV. COST per m (Lire)	3.284.000	3.284.000	3.284.000	3.284.000	3.284.000
LINING cost per meter (Lire)	9.447.000	7.773.000	9.145.000	7.471.000	7.276.000
REINFORCEMENT cost per meter (Lire)	14.732.000	15.094.402	21.105.000	21.105.000	16.075.000
TOTAL COST (Lire) (exclusive of portal)	23.530.000.000		25.244.310.000		
DIFFERENCE	7.3%				

Fig. 8 - Tunnel design and construction.

TUNNEL DESIGN AND CONSTRUCTION

FIRST EXAMPLE OF THE APPLICATION OF THE ADECO–RS METHOD
FOR THE TUNNEL OF THE LIVORNO–CIVITAVECCHIA MOTORWAY
ON THE LIVORNO–CECINA SECTION



TUNNEL	RIMAZZANO													
DESIGN	FINAL				CONSTRUCTION									
CROSS SECT. TYPE	1		2 A		1 A'		1 A'	1 B		1 C	1 D	2 F'	2 F	
	REINFORCED LINING	NON REINF. LINING	REINFORCED LINING	NON REINF. LINING	REINFORCED LINING	NON REINF. LINING	REINFORCED LINING	REINFORCED LINING	NON REINF. LINING	NON REINF. LINING	NON REINF. LINING	NON REINF. LINING	REINFORCED LINING	NON REINF. LINING
LENGTH (metres)	150	850	70	686	75	5	60	15	205	204	400	53	70	646
COST per metre (Lire)	27.437.571	28.056.833	20.475.730	18.491.246	31.456.898	29.782.896	30.177.396	31.383.522	29.709.322	27.986.472	28.756.196	20.077.716	18.924.156	17.250.154
EXCAV. COST per m (Lire)	3.284.000	3.284.000	7.758.000	7.758.000	3.145.500	3.145.500	3.145.500	3.093.750	3.093.750	3.162.570	3.184.800	7.069.440	7.069.440	7.069.440
LINING cost per metre (Lire)	9.447.000	7.773.000	10.385.000	8.721.000	9.392.536	7.718.536	9.392.536	9.377.536	7.703.536	7.325.538	7.324.154	7.875.276	9.549.276	7.875.276
REINFORCEMENT cost per metre (Lire)	14.732.000	14.732.000	1.943.000	1.943.000	18.919.360	18.919.360	17.639.360	18.919.360	18.919.360	17.239.360	18.250.784	5.133.000	2.303.440	2.303.440
TOTAL COST (Lire) (exclusive of portals)	39.952.081.070				41.203.662.000									
DIFFERENCE	3.1%													

Fig. 9 - Tunnel design and construction.

tions do no show any appreciable increase in unit costs with respect to those forecast and have modest effects on total costs according to the behaviour category of the ground concerned.

While lining operations have practically no effect on total cost as far as the different categories of mechanical behaviour of the ground are concerned, excavation operations lead to decreasing costs with poorer quality (and therefore easier to dig), ground although the latter means greater construction difficulties.

Under these conditions special operations for the containment and pre-containment of the excavation become important and have an appreciable effect on the total cost of the works.

Despite this, good executive design meant that the percentage error in the forecasts as stipulated in the contract for these special operations was contained within reasonable limits.

Consequently, the total cost curve shows a uniform increase as the quality of the rock and soil mechanics of the ground decreases, with no abrupt rises or increases.

The containment of the increase in total costs and construction times for the Malenchini and Rimazzzano tunnels within a limited figure of 5 - 7% as compared to estimates made at the design stage is a clear demonstration of good design, operational and contractual methods. The ADECO-RS method is therefore a valid instrument that is not only capable of proposing more than adequate technical methods before the works are put out to tender, but is also able to furnish very reliable predictions of unit costs with very modest margins of percentage error.

Conclusions

The good results obtained with the application of the ADECO-RS method for the construction of tunnels in difficult ground, such as that encountered by the Malenchini and Rimazzano tunnels, demonstrate that today, as opposed to a few years ago, it is possible, where the will exists, to deliver finished projects *keys in hand* even in the case of civil engineering works that depend heavily on the morphology of the ground, its

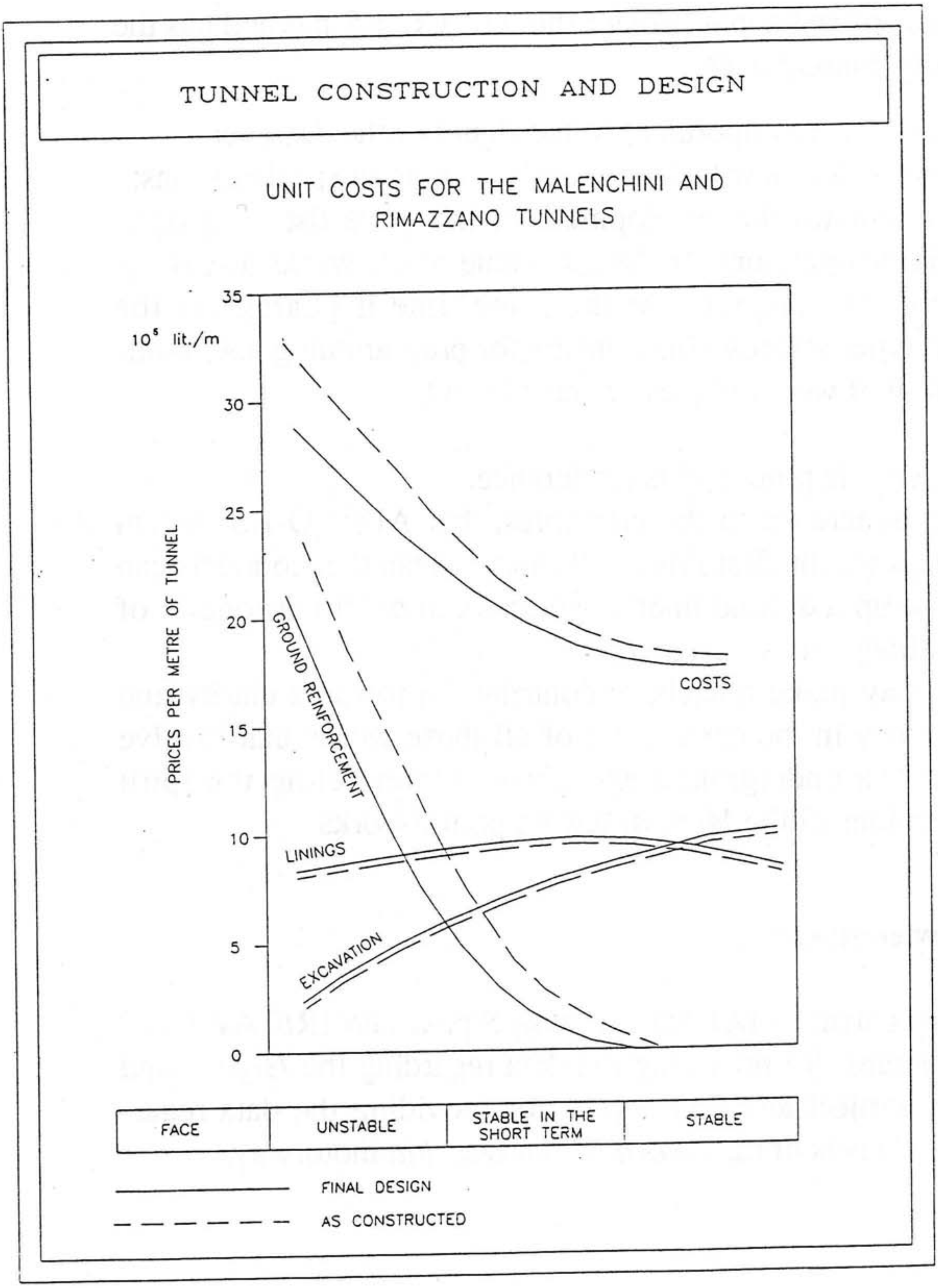


Fig. 10 - Tunnel construction and design.

geology and hydrological conditions, as is the case with underground works. This is, at this present time, persuading ANAS and the *Societa Autostrade* (Motorway Company) to re-examine its contract specifications for the construction of underground works and to replace the old regulations with newer and more adequate ones.

In this context application of the ADECO-RS method has the following consequences:

- it gives more importance to the figure of the designer;
- it introduces new technologies into contract specifications;
- it stimulates the development of fair price lists that compensate operators for the true value of the works according to real parameters. At the same time it guarantees the customer effective instruments for programming and monitoring of works as they are carried out.

As such it is proposed as a reference.

Strict adherence to the principles, that ADECO-RS system introduces for the first time, will finally mean that contracts can be drawn up that bind main contractors to strict observance of the deadlines set by designers.

This may make a decisive contribution towards clarity and transparency in the contracting of all those works that involve construction underground and towards interpreting the spirit and intentions of the *Merloni* law on public works.

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Bibliography

ARSENA F.P., FOCARACCI A., LUNARDI P., VOLPE A., 1991 - *La prima applicazione in Italia del pretaglio meccanico.* International Conference on *Soil and Rock Improvement in Underground Works*, Milan, II: 549, 556.

FOCARACCI A., 1991 - *Interventi conservativi: aspetti riguardanti l'impresa specializzata.* International Conference on *Soil and Rock Improvement in Underground Works*, Milan, II: 531,545.

LUNARDI P., 1986 - *Lo scavo delle gallerie mediante cunicolo pilota.* Atti del primo ciclo di conferenze di meccanica e ingegneria delle rocce, Politecnico di Torino - Dipartimento di Ingegneria Strutturale, Torino, IV: 1,47.

LUNARDI P., BINDI R., FOCARACCI A., 1989 - *Nouvelles orientations pour le project et la construction des tunnels dans des terrains meubles. Etudes et experiences sur le preconfinement de la cavite et la preconsolidation du noyau au front.* Colloque International *Tunnels et micro-tunnels en terrain meuble*, Paris.

LUNARDI P., 1990 - *Un noveau systeme constructif pour la realisation de tunnel de grande portee dans terrains non coherents: l'Arc Cellulaire.* Colloque International *Les fondations des grands ouvrages*, Paris, I: 227, 237.

LUNARDI P., 1991 - *Aspetti progettuali e costruttivi nella realizzazione di gallerie in situazioni difficili: interventi di precontenimento del cavo.* International Conference on *Soil and Rock Improvement in Underground Works*, Milan, II: 567, 580.

LUNARDI P., 1991 - *L'impiego del jet-grouting per l'attacco di gallerie in terreni soffici.* International Conference on *Soil and Rock Improvement in Underground Works*, Milan, II: 227, 234.

LUNARDI P., 1992 - *Il consolidamento del terreno mediante jet-grouting.* Quarry and Construction, Parma, 3.

LUNARDI P., FOCARACCI A., GIORGI P., PAPACELLA A., 1992 - *Tunnel face reinforcement in soft ground design and controls during excavation.* International Congress on *Towards New Worlds in Tunnelling*, Acapulco, II: 897, 908.