Quality Assurance in the Design and Construction of Underground Works

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ABSTRACT: The design and construction of underground works possess a particular characteristic that distinguish them from all other engineering works: the construction materials consist of the ground through which tunnels are driven and design engineers must adapt design and construction systems to the materials found *in situ*. It is for this reason that the application of quality assurance models to the field of underground construction is particularly complex: on the one hand there is the difficulty of producing a sufficiently precise design and on the other the requirement to deal efficiently with the numerous “product nonconformities” which arise while work is in progress. The problem appeared to be considerably great for the design of the Florence to Bologna section of the High Speed Train system in Italy given the complexity of the project. The adoption of a new design and construction approach known as ADECO-RS and the employment of a specially designed quality system allowed these difficulties to be overcome.

1 INTRODUCTION

For some years now the need to operate under quality assurance regimes has emerged for the design and construction of underground works following requests from various important clients. So far quality systems for design activity have been widely employed in fields such as nuclear, aeronautical, mechanical, electrical design and so on, in which the materials used have known physical properties and the product, its geometry and tolerances are well defined. In the underground construction field, however, the principal construction material is the ground itself and its physical and mechanical properties and the initial states of stress that act on it are difficult to predict and determine and vary over space and time. Consequently, it may happen that the forecast strength and deformation parameters used for design do not correspond to the actual geomechanical characteristics that are found during construction and which, what is more, have a considerable effect on the long and short term behaviour of the excavation. Procedures for managing design and production must therefore be designed in such a way as to prevent product nonconformities (i.e. discrepancies between the design and the construction) that oblige partial redesign from arising each time a change in tunnelling conditions requires minor changes to the design. New design and construction criteria were developed in Italy for the construction of the Milan to Naples High Speed Train system and in particular for the Bologna to Florence section crossing the Apennines where more than 80 kilometres of the route is in tunnel. These criteria allow ISO 9000 quality assurance standards to be successfully applied even in the field of underground construction. The goal was achieved by:

1) formulating and implementing an appropriate quality system for both the design group and the contractors;
2) the adoption of a new integrated design and construction approach known as ADECO-RS. This has the particular characteristic of allowing a complete and reliable design to be drawn up before construction actually commences, independently of the type of ground and the overburden involved;
3) the development of specific criteria for a standardized management of probable variabilities which occur during construction, the position and definite size of which cannot be forecast at the design stage.

A discussion is first given below of why it is worthwhile adopting a quality system in the field of underground works followed by a brief explanation of the basic concepts of the ADECO-RS approach and how it is used in conjunction with a quality system.

2 ECONOMICAL AND PRACTICAL ASPECTS OF THE ADOPTION OF A QUALITY SYSTEM FOR THE DESIGN AND CONSTRUCTION OF UNDERGROUND WORKS

The ISO 9004 standard states that the introduction of a quality system in an enterprise may produce very positive effects in economic terms over the long term even if it necessarily involves incurring greater initial costs for planning and implementing the system. Costs connected with quality can be classified as: a) costs relating to prevention, which are inherent in the implementation of a quality system; b) costs relating to assessment, resulting from quality system conformity verification; c) costs of internal and external failures, found respectively before release within the design organisation or after release by the client. Studies performed by various authors (Mirandola et al. 1989) have identified the tendencies shown in Figure 1 for these costs. Figure 1A shows how verification costs decrease with the implementation of an effective quality system. On the other hand, Figure 1B shows that in the absence of prevention the discovery of internal defects increases as a direct function of an increase in verification activity (increase in relative costs) while external defects decrease (decrease in connected costs): this means that verification alone without prevention leads merely to a transfer of costs from outside to inside the organisation. An increase in prevention activity, however, results in a decrease in the importance of both verification (and therefore also of the connected costs) and of the costs incurred for “product” defects (Fig. 1 A and C). Furthermore, the curve for total costs plotted on the same graph (Fig. 1C) shows the existence of an optimum minimum level for quality costs.

Clearly, with civil works the quality and validity of the design with respect to the actual conditions encountered play a fundamental role in guaranteeing the effectiveness of prevention costs with respect to final construction costs. If the design for such works is not sufficiently well defined it is probable that many nonconformities will be detected during construction with consequent additional costs which may be considerable. It follows that if the design is not sufficiently well-defined, then the advantages of adopting a quality system are lost. This is what happens in the tunnelling field where the limitations of traditional design approaches do not allow a complete and reliable design to be produced before construction commences. For example methods based on geomechanical classifications (generally developed on the basis of the design engineers experience and not transferable to geological contexts in which he/she has not worked before) give little weight to or even completely ignore the influence of important parameters such as the original stress state of the medium, the geometry and dimensions of the theoretical cross section of the cavity and so on and this inevitably leads to designs which only define the general characteristics of the construction. Even empirical methods like the NATM, which undoubtedly constituted a considerable step ahead when it was introduced, although they emphasise the importance of systematically measuring and interpreting the deformation response, they are not suitable for use in conjunction with a quality system because design is performed while construction is in progress and

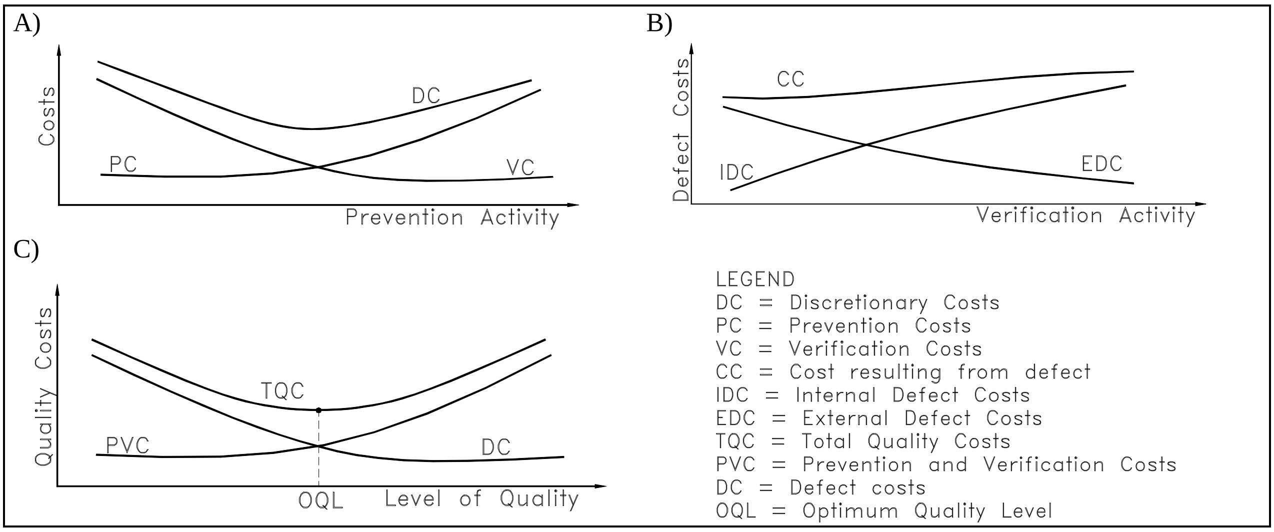


Fig. A: Quality cost curves [1]:

A) Prevention and verification costs as a function of prevention activity;

B) Internal and external defect cost curves as a function of verification activity;

C) Total quality costs as a function of the level of quality achieved.

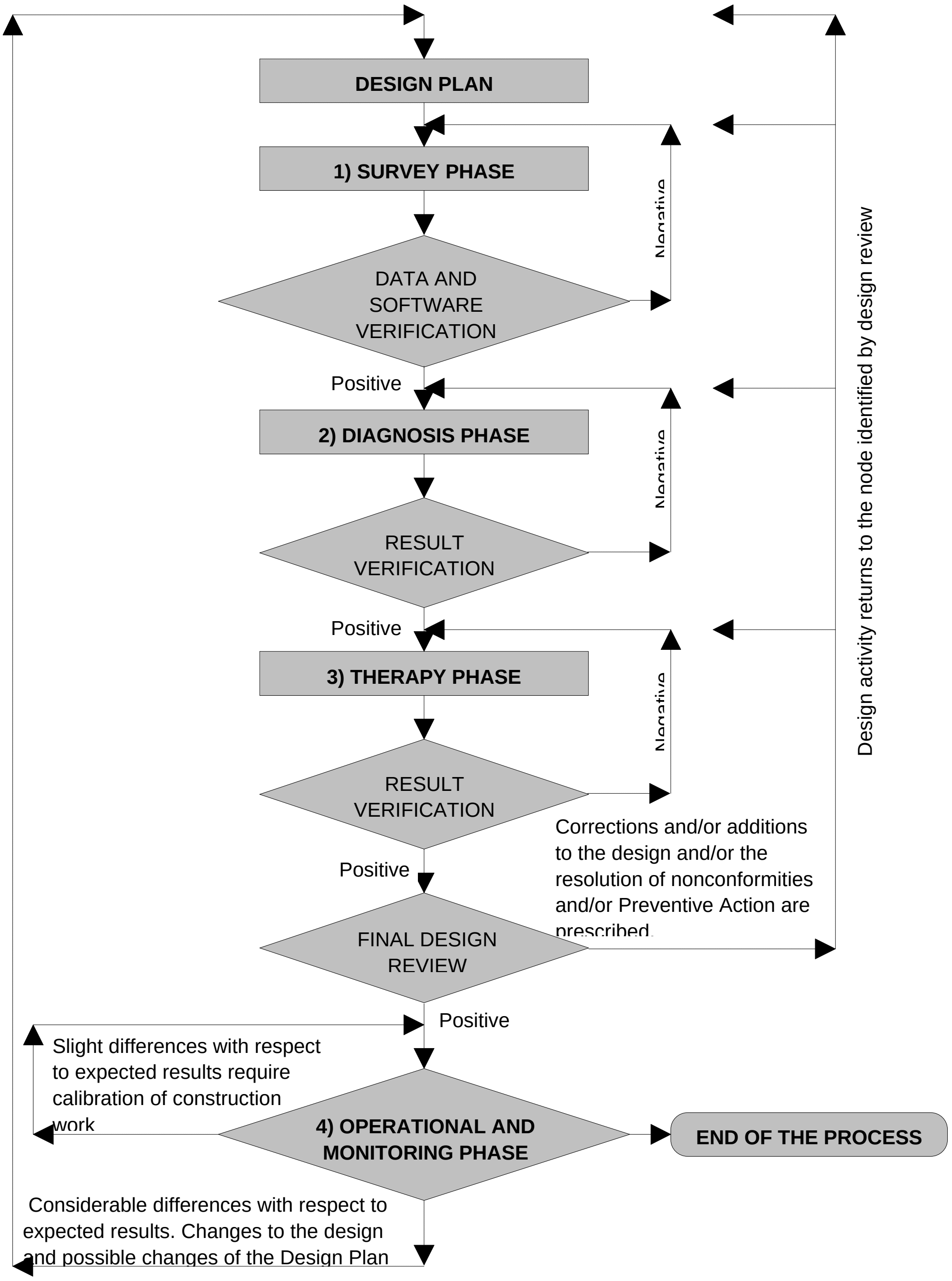


Fig. B: Flow chart for the design phases of the ADECO-RS approach.

consequently does not produce well defined designs before construction commences. In addition, these methods are not really applicable to all types of ground and all stress-strain conditions since they generally do not take account of new excavation technologies based on conservation or improvement of the rigidity of the advance core, indispensable for operating successfully in difficult stress strain conditions.

Because of the above mentioned limitations these methods lead to:

1) uncertain definition of the characteristics of the construction at the design stage, leaving margins of discretion that are too wide at the construction stage;

2) improvised use of monitoring data during construction for design purposes and not as indispensable feedback for the fine tuning and validation of an existing and complete design;

3) not allowing, as a consequence, sufficient planning and scheduling of construction activity, nor providing reliable forecasts of construction times and costs;

4) the inevitability of numerous product (discrepancies between design and actual construction), process (failure to observe plans and schedules) and system (the cause of the preceding nonconformities lies in the design method) nonconformities.

In order to be able to successfully employ a quality system in the design and construction of underground works, a new design and construction approach therefore had to be developed. It is based on the analysis of controlled deformation in rocks and soils and has already been used with success in numerous difficult situations.

3 DESIGN QUALITY AND THE ADECO-RS APPROACH

The Analysis of COntrolled DEformation in Rocks and Soils (ADECO-RS) is an integrated design and construction approach for underground works which allows final design specifications to be drawn up before construction commences with a high degree of reliability independently of the type of ground or the overburden involved (Lunardi 1993, 1994, 1995, 1996).

For this purpose reference is made to one single parameter (the deformation response of the medium to excavation), first using theoretical tools to predict and control it and then using experimental techniques to measure and interpret it for the fine tuning of the design during construction. As has already been mentioned, the approach involves a clear distinction between the “moment” or stage of design and that of construction. During the first stage (see Fig. 2) the survey, diagnosis and therapy phases of design are performed, while the second stage involves the operational and verification phases. In the survey phase the design engineer characterises the medium to be tunnelled in terms of rock and soil mechanics; this is indispensable to be able to perform the subsequent diagnosis phase. The diagnosis phase is based on the data collected during the survey phase; appropriate mathematical tools are employed to forecast the deformation response of the ground to excavation and the tunnel is then divided into sections showing uniform stress-strain behaviour on the basis of three main face behaviour categories: category A (face stable), category B (face stable in the short term) and category C (face unstable). In the therapy phase the design engineer decides, given the predictions of the diagnosis phase, the type of action to be exerted (preconfinement or simple confinement, if it works ahead or behind the face) and the necessary intervention, within the behaviour category that has been identified, required to achieve complete stabilisation of the tunnel. The composition of the longitudinal and cross section types is then defined, designing them and testing their effectiveness using mathematical tools. In addition, whenever the project must be carried out under quality assurance regime the design engineer has to evaluate the admissible ranges of deformation

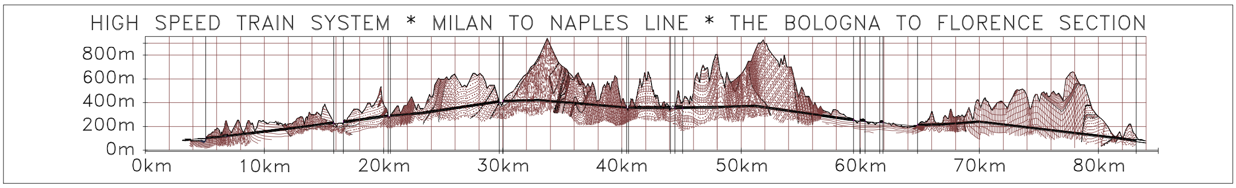


Fig. C: Longitudinal profile of the entire length of the Bologna to Florence section of the High Speed System.

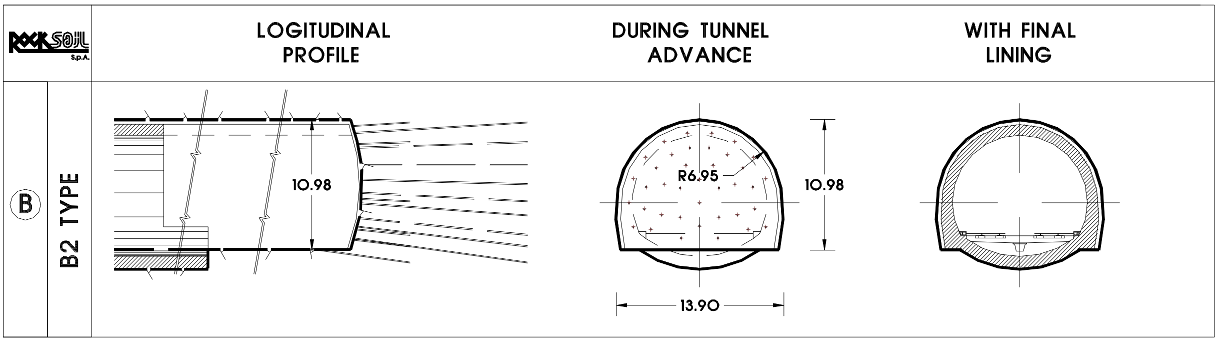
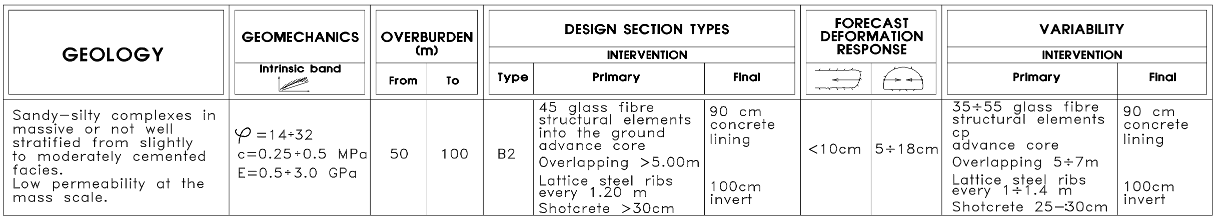


Fig. D: B2 type, longitudinal and cross sections.



GEOLOGY	GEOMECHANICS	OVERBURDEN (m)		DESIGN SECTION TYPES			FORECAST DEFORMATION RESPONSE		VARIABILITY	
				INTERVENTION					INTERVENTION	
	Intrinsic band	From	To	Type	Primary	Final			Primary	Final
Sandy–silty complexes in massive or not well stratified from slightly to moderately cemented facies. Low permeability at the mass scale.	φ =14÷32 c=0.25÷0.5 MPa E=0.5÷3.0 GPa	50	100	B2	45 glass fibre structural elements into the ground advance core Overlapping >5.00m Lattice steel ribs every 1.20 m Shotcrete >30cm	90 cm concrete lining 100cm invert	<10cm	5÷18cm	35÷55 glass fibre structural elements cp advance core Overlapping 5÷7m Lattice steel ribs every 1÷1.4 m Shotcrete 25–30cm	90 cm concrete lining 100cm invert

Fig. E: B2 type section and relative variability.

for each type of section and each length of tunnel and, within these ranges, to give the degree of variation of the intensity of intervention designed to control the deformation response to excavation. At the end of the therapy phase it is then possible to draw up a complete and detailed design, which is at the same time sufficiently flexible to be implemented in observance of the regulations of a quality system. Once the design stage is complete, the operational phase in which the tunnel is constructed commences and in which the stabilisation tools prescribed by the design are put into operation. The monitoring phase begins at the same time as the operational phase and involves planned monitoring: deformation is measured and interpreted to verify the validity of the design and to fine tune it adjusting the balance of stabilisation intervention between the face and the cavity. The monitoring phase does not end with the completion of the works but continues during the entire life of the tunnel to constantly monitor safety during operation.

4 THE BOLOGNA TO FLORENCE SECTION OF THE HIGH SPEED TRAIN SYSTEM

As already stated the Analysis of Controlled Deformation in Rocks and Soils approach was adopted for the design and construction of the tunnels on the Milan to Naples line of the High Speed Train system along the section crossing the Apennines between Bologna and Florence (Fig. 3). A very high percentage (more than 90%) of the route runs underground and is characterised by the heterogeneity, complexity and difficulty of the geology, geomechanics and stress-strain conditions to be tackled. Despite this, the adoption of this new design and construction approach allowed a complete design to be drawn up before the works commenced so that no uncertainty remained when construction was performed and precise scheduling of all work was possible with the result that true industrialisation of tunnel advance was possible with certain knowledge of construction times and costs.

At the same time, identification in advance of admissible variation, always however within forecast ranges of deformation, for each design section type according to the actual response of the ground to excavation provided the necessary flexibility required for the successful adoption of a quality assurance system without betraying its fundamental principles. Technical procedures were drawn up for this purpose, described in a manual entitled “Guide Lines for the application of Design Section-Types and Relative Variability”, to facilitate management of the above mentioned variability during construction. Figure 6 shows part of the manual for design section type B2 (Fig. 5) and the relative variability in a particular geological/geotechnical and stress-strain situation.

It is in fact the design engineer who gives instructions in real time for adjusting the balance of stabilisation intervention between the face and the cavity on the basis of the actual stress-strain response of the ground to excavation and in conformity with documented design forecasts. The following situations can be verified by comparing forecast and actual data:

1) the forecast solution satisfies the actual conditions and application of the specified design section type continues;
2) the actual conditions differ slightly from those forecast, but nevertheless fall within the range of variability considered admissible and the design section type is changed to a derived type considered more suitable for the observed conditions;
3) the forecast conditions correspond to the actual conditions but at different points along the tunnel and the correct design section types are applied in the length of tunnel most appropriate for them;
4) the actual conditions differ considerably from forecast conditions and the design is reviewed and the section of tunnel redesigned.

With this method of operation it was possible to:

1) draw up a detailed and reliable design suitable for operating under a quality assurance regime without unresolved questions left to an engineer’s discretion before starting construction;
2) schedule all works to the point where true industrialisation of excavation was achieved with precise forecasts of construction times and costs even in the most difficult grounds and stress-strain conditions;
3) avoid an excessive number of design nonconformities due to slight unavoidable differences between forecast and actual conditions.

5 CONCLUSION

The good results obtained in numerous underground projects over recent years in Italy and Europe in very varied types of ground and stress-strain conditions using the ADECO-RS approach demonstrate that it can be employed to achieve steady and fast advance rates, safety during construction operations and final construction times and costs comparable to those estimated. Its use for the design and construction of more than 78 kilometres of tunnel under quality assurance regime in the difficult and heterogeneous ground of the Italian Apennines is demonstrating that in combination with a specially designed quality system, it also possesses all the necessary requirements for the production of designs of underground works to be constructed under quality assurance regimes.

Despite the well-known difficulty of the Apennine ground through which the tunnel passes, the final design produced for the construction of the new High Speed railway line from Bologna to Florence possesses a degree of definition sufficient to make the characteristics of the tunnel to be constructed completely unambiguous. It was possible to industrialise construction and maintain it within the forecast limits with good approximation. Any changes required to the forecast section types are made in real time under the control of the design engineer according to rules defined before construction actually commenced.

Completion of the works, begun at the end of 1996, is scheduled for 2002 (average advance rates of 36 m./day of finished tunnel.

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