ON THE OBSERVATIONAL METHOD IN TUNNELLING

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ABSTRACT

Continuous observations made during the driving of a tunnel have always been taken for granted, just like keeping one's eyes on the road when driving a car. Therefore, the term 'observational method' often produces a reaction of surprise among tunnelling engineers in practice. Even if it is explained that 'observation' in the narrow sense of the word really means 'monitoring', doubt and misunderstanding still remain. In the first part of the paper the term 'observational method' as introduced by Peck and redefined by Eurocode is examined critically. The problems encountered in tunnelling are usually so diverse and complex that monitoring can be usefully applied in many different ways. In the second part of the paper a case study is described in which Peck's ideas are followed.

INTRODUCTION

The term 'observational method' was introduced into geotechnical engineering by Peck (1969) in his Rankine lecture. He was following here Terzaghi, who already in the 1940s tentatively proposed a method, which he alternatively called 'experimental method' and 'learn-as-you-go method'. Terzaghi's considerations revolved around the question: how and according to what criteria a project during its development can be economically executed based on an increasing knowledge of the properties and behaviour of the ground. Terzaghi thought that such a method was most likely to be successful in overcoming the set-backs encountered. In this connection Peck (1969) spoke of a 'best-way-out-application'. Terzaghi and Peck realised that taking into account experience and observation during the execution of a project was in no way new and corresponded in fact to common sense. The oldest report on the so-called 'learn-as-you-go' method in geotechnical engineering comes from Herodot. In the Seventh Book he describes the construction work (480 B.C.) on the 30 m wide Xerxes canal on the peninsula Chalkidike as follows:

"These are the towns situated on Athos; and the foreigners dug as I shall show, dividing up the ground among their several nations. They drew a straight line near to the town of Sane; and when the channel had been dug to some depth, some stood at the bottom of it and dug, others took the material as it was dug out and passed it to yet others that stood higher on steps, and they again to others as they received it, till they came to those that were highest; these carried it out and cast it away. With all except the Phoenicians the steep sides of the canal broke and fell in, doubling the labour thereby; because the Phoenicians made the span with the same skill as everything else they do; having taken in hand the portion that fell to them, they so dug as to make the topmost span of the canal as wide again as the canal was to be, and narrowed it continually as they wrought lower, till at the bottom their work was of the same span as what the rest had wrought." (based on the translation by A.D. Godley, 1922).

Observation and experiment characterise every scientific method in all the natural sciences and thus also those of applied geotechnical engineering. Their interaction with theory is always present and diverse. Terzaghi did not attempt to formulate clear rules, in particular regarding what can be experienced and reflected upon, suppositions and facts with regard to problems occurring in day-to-day engineering practice which are supposed to influence decision making. Peck attempted this in his Rankine Lecture. In retrospect he wrote in 1984: *"I was not altogether happy with the results at the time, and I still feel that my efforts to formalise the observational method were too contrived, too rigid."* These remarks of a self-critical nature are a distinguishing feature of the high scientific standards of Peck. Unfortunately, this aspect of his work was subsequently paid little attention. Instead in many circles one still hoped to arrive at such a rigid method,

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rather than tackling the variety of problems posed individually in practice, and likewise with field measurements.

The difficulty pointed out by Peck of trying to formalise the use of field measurements in geotechnical engineering, applies already to the first sentence of his work today. It runs: *"Observational methods have always been used by engineers working in the fields now included in applied soil mechanics, but observational method is a term having a restricted meaning"*. In the first part of this sentence it is claimed that in applied soil mechanics there is more than one kind of observational method, whereas in the second part however we see that by this term something quite specific is to be understood. Since the meaning of observational methods, which it appears have always been used in applied soil mechanics, remains something of a mystery and a unique definition has not been found, a confusion of definitions has arisen. This is the real reason why today the term observational method is given so many different meanings. Some would interpret it as that described above in the construction of the Xerxes canal, while others speak of it only when during the execution of the work a change is made to the project as a result of previously calculated and measured values. In underground construction one comes across a further very specific concept of the observational method, which has nothing at all to do with that of Peck. This is the so-called New Austrian Tunnelling Method (NATM), which according to its advocates epitomizes the observational method. What are we dealing with here? According to its protagonists, the central idea of NATM is to minimise rock pressure acting on the lining by means of a specific ground response curve and measurements. We refer here to the published material of the authors of the NATM, i.e. L. Rabcewicz, L. Müller and F. Pacher (often referred to as the 'fathers' of the NATM). Pacher proposed in 1964 a special trough-shaped ground response curve having a minimum. It is then a simple matter to choose the position and shape of the lining characteristics in such a way as to intersect the ground response curve of the rock at its lowest point. Rabcewicz (1972) claimed that *"with the aid of measurement, one is in the position to keep the forces under control and the lining resistance can be chosen accordingly, until an optimum value is achieved."* In the last 35 years the protagonists of NATM have published a great number of papers with case histories showing the success of their 'observational method'. The Austrian National Committee of the International Tunnelling Association is still distributing a document (1978) world wide, explaining the essence of the NATM by referring to the Pacher curve in combination with deformation measurements.

It has been shown, that the optimisation of the lining resistance following NATM, i.e. based on monitoring, is fundamentally flawed. The trough-shaped rock ground response curve thus required according to Pacher cannot be explained theoretically and has never been verified by measurements or numerical simulations (Kovári, 1994). In fact, it can be shown that Pacher's concept violates the fundamental principles of the conservation of energy in the same way the idea of the perpetuum mobile (perpetual motion) does. Therefore, NATM as an observational method can be disregarded.

In the following, firstly the original definition of Peck and that of Eurocode 7 are briefly considered. Then we conclude the general considerations, in order in the second part to report on the successful application of field measurements in a difficult tunnelling project, the methodology of which comes very close to Peck's ideas.

THE OBSERVATIONAL METHOD ACCORDING TO PECK AND EUROCODE 7

For the briefest and at the same time clearest presentation of the ideas of Peck we are indebted to Nicholson (1996):

„Peck's observational method involves developing an initial design based on most probable conditions, together with predictions of behaviour. Calculations are made and these are used to identify contingency plans and trigger values for the monitoring system. Peck proposed that construction work should be started using the most probable design. If the monitoring records exceeded the predicted behaviour, then the predefined contingency plans would be triggered. The response time for monitoring and implementation of the contingency plan must be appropriate to control the work."

In Eurocode 7 the definition is as follows:

„*1. Because prediction of geotechnical behaviour is often difficult, it is sometimes appropriate to adopt the approach known as ‚the observational method‘, in which the design is reviewed during construction. When this approach is used the following four requirements shall all be made before construction is started:*

- *the limits of behaviour which are acceptable shall be established.*
- *the range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits.*
- *a plan of monitoring shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage; and with sufficiently short intervals to allow contingency actions to be undertaken successfully. The response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system.*
- *a plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits.*

2. During construction the monitoring shall be carried out as planned and additional or replacement monitoring shall be undertaken if this becomes necessary. The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put in operation if this becomes necessary."

Thus the formulation according to Eurocode 7 does not proceed from the 'most probable and most unfavourable conditions', in order to predict the behaviour of the structure via calculations. The necessity of carrying out calculations is not mentioned at all. In the text only 'monitoring' and not observations is mentioned. This word only appears in the description of the method. The definition of Eurocode 7 can hardly be criticised. In any case it is made in such general terms that one must speak - as for the 'learn-as you-go' method of Terzaghi - rather of 'sound engineering' than of an independent method.

In order to illustrate the degree of uncertainty of the method proposed by Peck in regard to tunnelling, we only have to consider the word 'conditions' more closely. In practice so many different aspects are understood like geology and hydrogeology, the mechanical properties of the ground as well as the effectiveness of constructional measures. Thus it is clear that the general expression 'condition' is unsuitable as a basis for a planned procedure (method).

In addition, Powderham and Nicholson (1996) have raised some further important questions with respect to Peck's terms and stress that: *"a clear, acceptable definition of the observational method is required"*. With the Eurocode the clearest possible definition has been achieved and it turns out that more restricted definitions, as Peck has already emphasised, are doomed to failure.

In many places the false impression prevails that field measurements can only be employed meaningfully within the framework of the observational method. In tunnelling however there is a whole range of problems for which field measurements are of considerable value without limiting ourselves to Peck's ideas. (Kovári and Amstad, 1993). A recent case history from Italy is dealt with in detail below. For its theoretical background we refer to Lunardi (2000).

THE USE OF MONITORING TO PASS UNDER THE MUGELLO MOTOR RACING CIRCUIT (FIRENZUOLA TUNNEL)

Introduction to the Case History

The underground works for tunnelling under the Apennines on the Bologna to Florence section of the Italian High Speed rail system without any doubt constitute one of the largest tunnelling project in the world today. To cover the 90 km of the route that connects the two cities, the project involved the construction of 11 tunnels with a 140 sq.m cross section and a total length of 84.5 km. To these another 18 km must be added for the 13 tunnels giving access to the line and the 'Ginori' service tunnel. The ground tunnelled, as is known, is extremely complex and heterogeneous ranging from flyschoid formations to clays, argillites and loose soils. The overburdens vary between 0 and 600 m. Despite the difficult context, the contract for the entire project was awarded on a 'turnkey' basis in which the general contractor, obviously having felt that the design was sufficiently complete and reliable, agreed to accept all the risks, including the geological risks. The current state of progress of works, started in 1996, has now passed the 35% point and full face tunnel advance is proceeding simultaneously on 32 faces fully on schedule and within budgets. Average production rates are around 1,600 m/month of finished tunnel (Lunardi, 1998 and 1999).

One of the problems faced so far was that of passing under the Mugello international motor racing circuit with a shallow overburden (Figures 1 and 2). This particularly interesting case has been used to illustrate the application of the observational criteria used in the new approach to calibrate and optimise design during tunnel construction.

Figure 1 : View of the Mugello International Motor Racing Circuit

The Geological, Geotechnical and Hydrogeological Picture (Survey Stage)

The area in which the tunnel passes under the race circuit is located in the Mugello Basin and crosses the valley created by the Bagnone river at an angle. From a geological viewpoint the ground to be tunnelled belongs to the Clays of Mugello Basin *(Argille del Bacino del Mugello)* formation (aBM) which consist of Pleistocene fluvial-lacustrian deposits with sub-horizontal stratification. They are clayey silts, slightly sandy and grey-blue in colour, with a compact structure, neither weathered nor oxidised, with scattered peaty blackish and level lentils or lentils of fine sand mixed with silt. An alluvial or eluvial deposit consisting of sands, gravels and thick conglomerates of fan-shaped structures covers the surface (Figure 3).

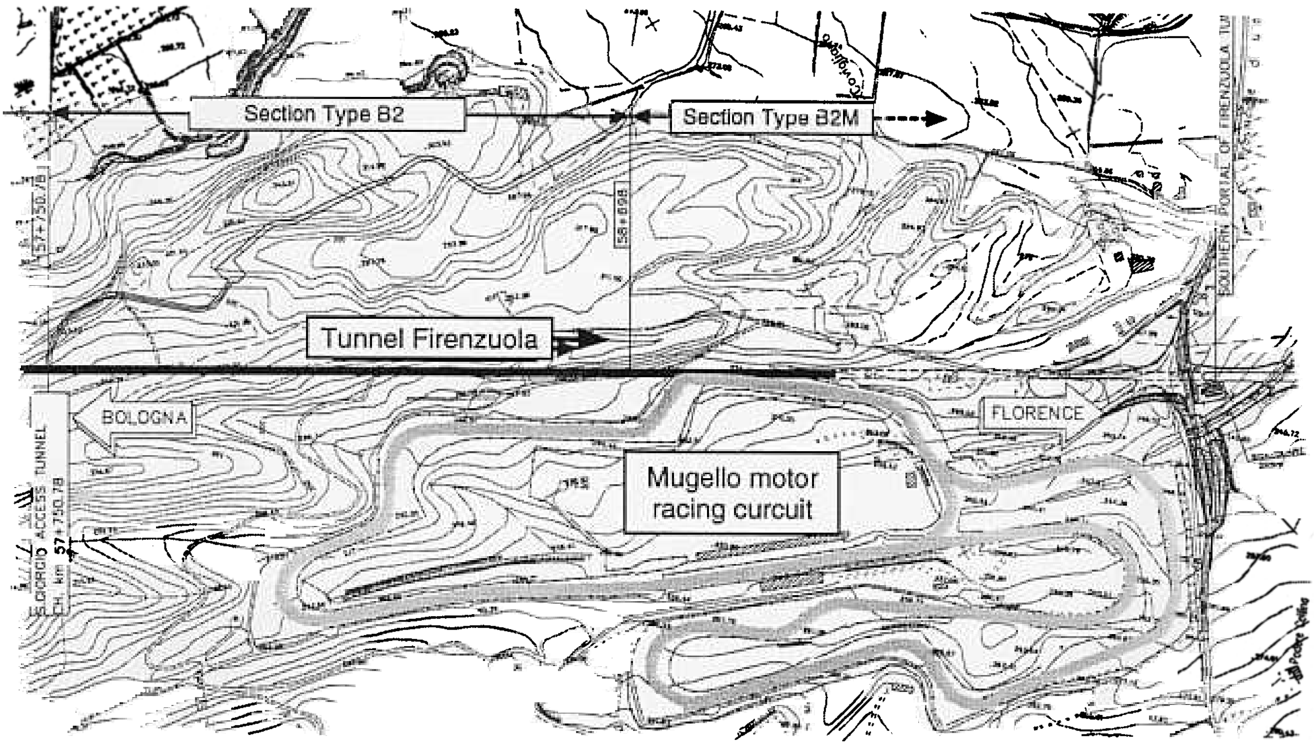

Figure 2 : Firenzuola Tunnel, Passing under the Mugello International Motor Racing Circuit, Chorography

From a geotechnical viewpoint, the Clays of Mugello Basin can be classified as inorganic clays of medium-low plasticity (CL) and good consistency, slightly overconsolidated (OCR between 2 and 5). The strength and deformation parameters of the material were investigated under drained and undrained conditions using simple and triaxial compression tests (CD and CU and UU). These gave values for undrained cohesion which increased with depth and which in any case lay between 0,1 and 0,5 MPa. Under drained conditions the strength of the material under intense stress fell rapidly in two distinct phases:

- when peak strength values were reached, after small relative slipping, the bonds between the particles that confer effective cohesion c' on the material were destroyed, while there was no change in the effective angle of friction with respect to the peak value;
- after greater relative slipping, the angle of friction fell to residual values.

To summarise, the investigations on the first analysis produced the following geotechnical parameters:
- unit weight: 19.9 - 20 kN/m^3
- peak effective cohesion: 0.02 - 0.03 MPa
- residual effective cohesion: 0 MPa
- peak effective angle of friction: 24° - 28°
- residual effective angle of friction: 15° - 18°

The elastic modulus, estimated on the basis of pressure meter tests was linearly proportional to the depth according to the law: $E(z) = 11{,}5 + 3{,}02 \cdot z$ [MPa]

The coefficient of consolidation (C_v), obtained using consolidation tests was also found to vary with depth ranging from $5 \cdot 10^{-7}$ and $3 \cdot 10^{-7}$ m^2/s.

Finally a few extrusion tests were performed in a triaxial cell; the results are given in Figure 4.

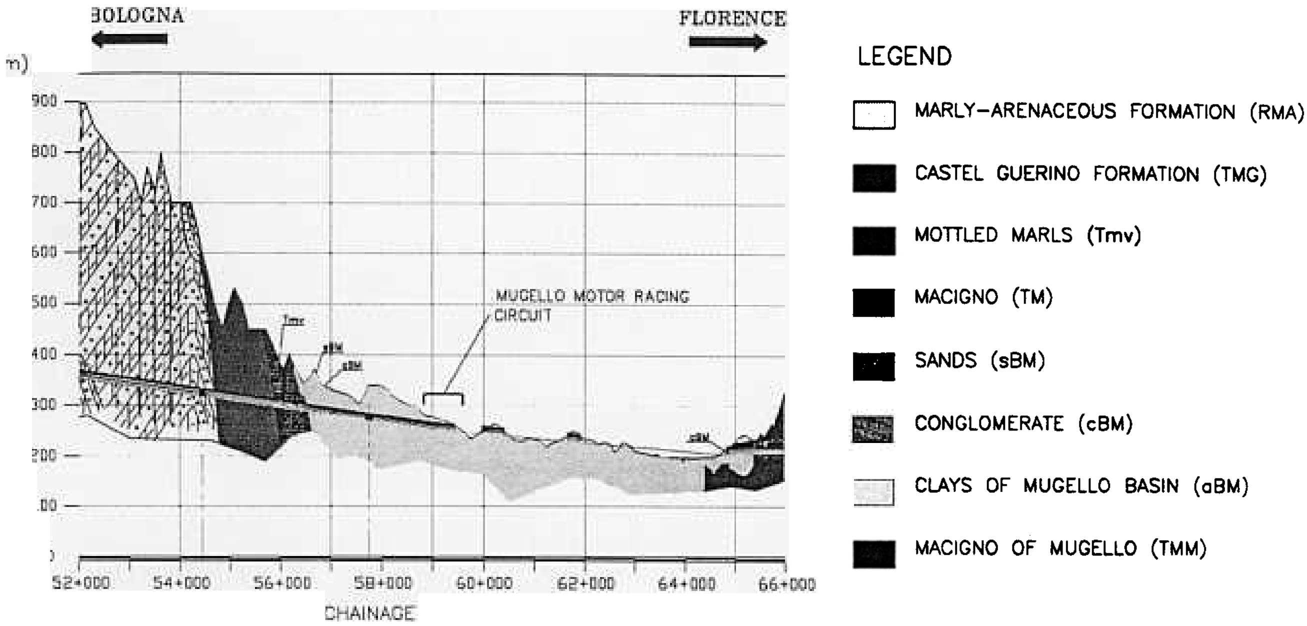

Figure 3 : Firenzuola Tunnel, Passing under the Mugello International Motor Racing Circuit

From a hydrogeological viewpoint, the Clays of Mugello Basin are basically an impermeable formation although it does contain levels and lentils of sand up to 3 metres thick which may hold confined water. A series of piezometer tubes installed along the route of the tunnel detected confined water with a piezometric line that tended to rise more or less following the interface between the overlying alluvial deposits and the clays beneath. At tunnel depth, the piezometric surface is approximately 40 m at the point of the greatest overburden.

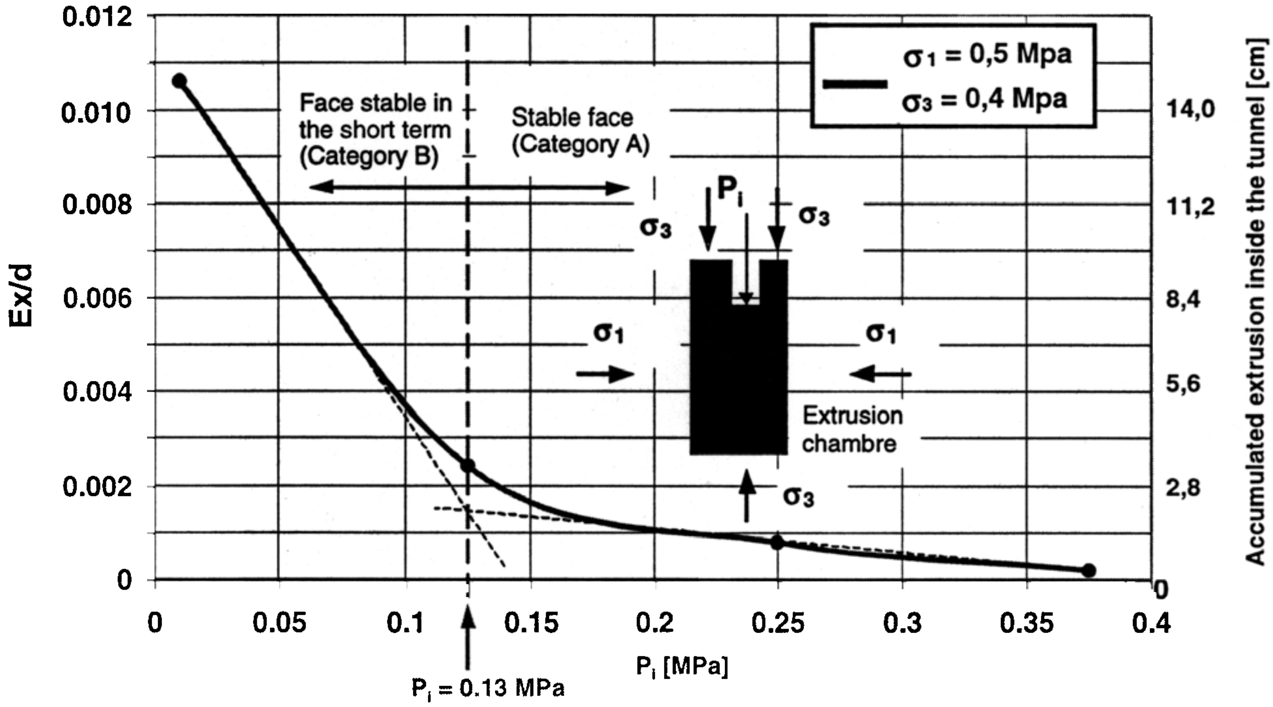

Figure 4 : Prediction of the behaviour category using triaxial extrusion tests

Diagnosis Phase

In this phase analysis of the deformation response of the ground to excavation in the absence of intervention to stabilise the tunnel found core-face behaviour stable in the short term (behaviour category B) (Figure 4). This condition, as is known, occurs when the stress state in the ground at the face and around the cavity during tunnel advance is sufficient to overcome the capacity of the medium to resist it in the elastic range. Deformation therefore develops in the elastic-plastic range and as a consequence an 'arch effect' is not created close to the cavity but at a distance from it depending on the size of the band of ground that is subject to plastification.

In this situation the stability of the face is strongly affected by the speed of tunnel advance and given the shallow overburden, deformation in the core manifesting as extrusion would give rise to unacceptable subsidence if not adequately contained (Lunardi, 2000).

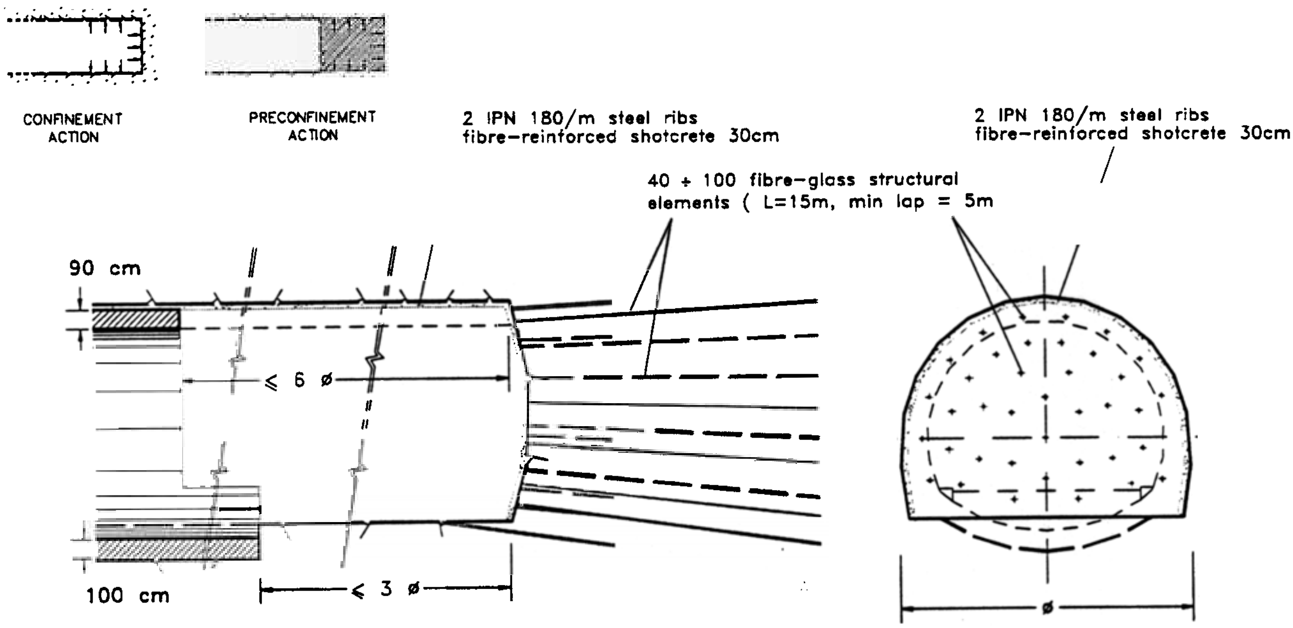

Figure 5 : Section Type B2

Therapy Phase

In this phase the design problem to be solved was how to develop design and construction stratagems which would ensure that surface subsidence caused by excavation and possible damage to the road surface of the race track would be adequately contained especially considering the reduced overburden (from 20 m to 60 m), the particular geomorphology of the area and the geological and geotechnical features of the alluvial deposits of the Mugello Basin. With regard to the race track, the design also had to take account of the calendar of racing events of various types and the absolutely imperative requirement for the race track to be in perfect condition ready for approval inspection well before the World Motorcycle Championship (April-May 2000).

All the various requirements were taken into account and the resulting construction design specified the following type of advance (Figure 5), which would then have to be calibrated on the basis of monitoring measurements during construction:

1. full face advance after first stiffening the core by placing 40 - 100 fibre glass structural elements: L ≥ 15 m, overlap ≥ 5 m and cementing them using controlled shrinkage mixes or expanding cement;
2. preliminary lining composed of 2IPN 180 steel ribs at intervals of 1.00 - 1.40 m and a 30 cm layer of fibre reinforced shotcrete;
3. a tunnel invert, 100 cm thick, cast at the same time as the kickers at a maximum distance of 3 Ø from the face;
4. a final concrete lining, 90 cm thick in the roof, cast at a maximum distance of 6 Ø from the face.

As for total difference in extrusion (ε_x) the following maximum limits were set: 0.5 % for the alert threshold and 0.9 % for the alarm threshold.

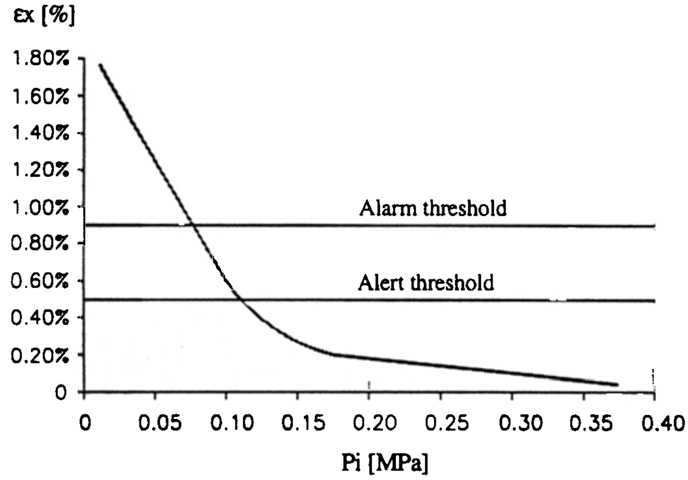

Figure 6 : Setting of the alert and alarm thresholds by using the triaxial extrusion tests (reconstructed by means of an axial-symmetric model)

Monitoring Programme

Considering the complexity of the situation, as the race track was approached in June 1999, a real time monitoring programme was set up as stipulated in the design specifications and also for the purpose of ensuring the safety necessary for the racing circuit to be able to keep to its calendar of events.

The deformation response of the ground to excavation was monitored accurately both from inside the cavity and from the surface. Inside the tunnel it was analysed by systematic measurement of extrusion at the face (using both a sliding micrometer and topographical survey type measurements) and of cavity convergence and it was studied from the surface using real time topographical measurements of subsidence induced by the passage of the face. The sliding micrometer was described in detail elsewhere (Kovári and Amstad, 1993).

Figure 7 : The 'Borgo San Lorenzo' curve

The external monitoring system which was designed and created by the design team (Rocksoil S.p.A. of Milan) together with the Treesse Consortium, was structured so that a series of optical targets could be automatically hit at hourly intervals from a specially constructed 'light house' located near the zone where the tunnel passes under the race circuit. The targets were positioned in a 10 x 5 m grid pattern on the ground over the centre line of the approaching tunnel before and after the point where the route crosses the race track near the 'Borgo San Lorenzo' curve (Figures 7, 8 and 9). The data obtained was transmitted in real time to a control centre where it was immediately processed and transmitted to the design team on the construction site.

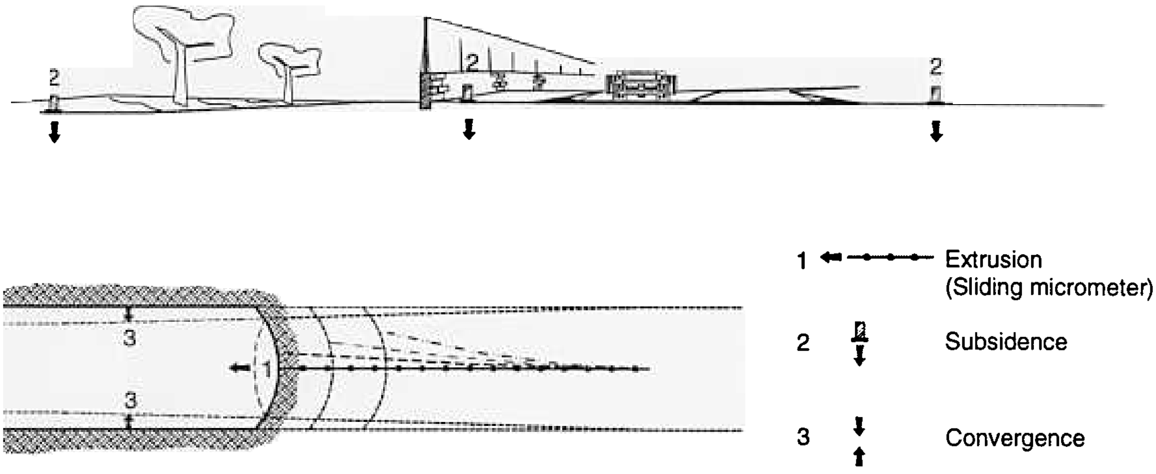

Figure 8 : Types of measurements performed

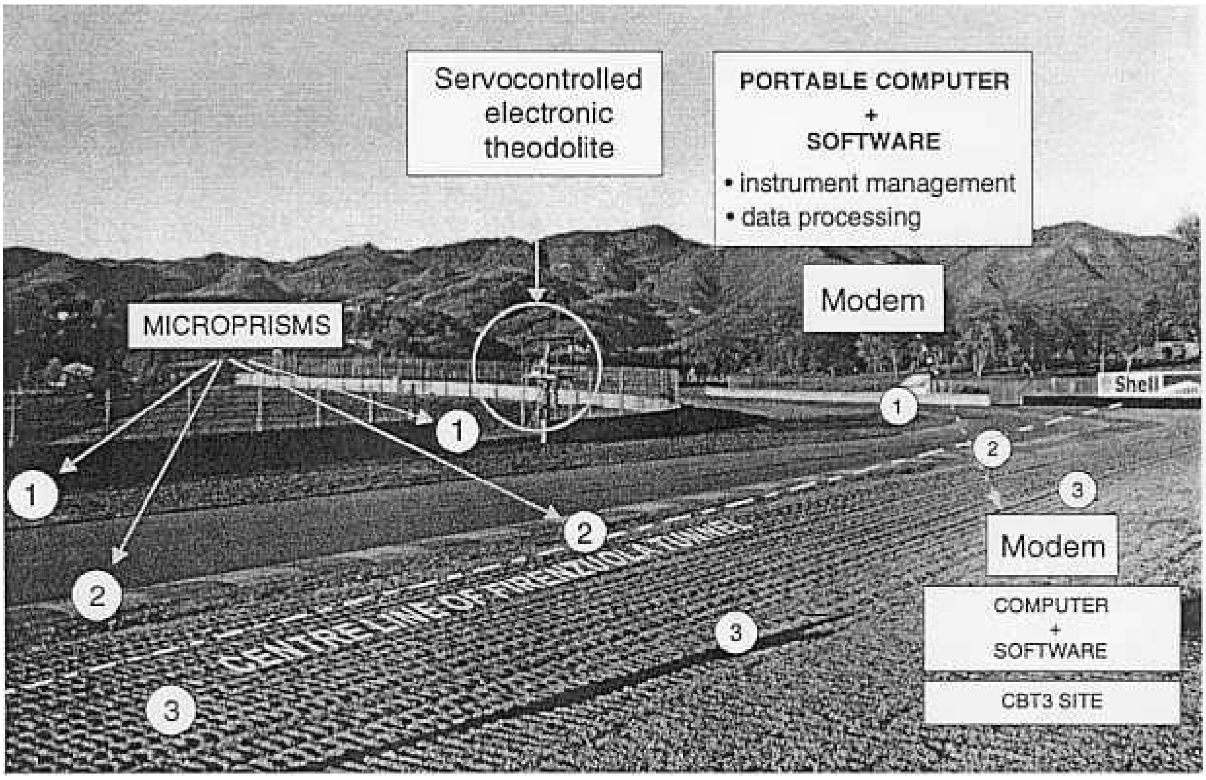

Figure 9 : Topographic surface monitoring

Calibration of the Design on the Basis of Monitoring Data

The monitoring system showed that subsidence began around 60 m before the arrival of the face and then increased to values significantly higher than those predicted for the tunnel section type adopted. Subsidence of 14 cm was recorded at chainage km 58+690 which increased to 22 cm after the passage of the face (Figure 10). When the development of subsidence is plotted on a graph as a function of the distance from the face, it can be clearly seen that 60% of total subsidence occurs before the arrival of the face. A further 30% occurs in the 20 m following the passage of the face (before the tunnel invert is cast) and the remaining 10% in the next 40 m.

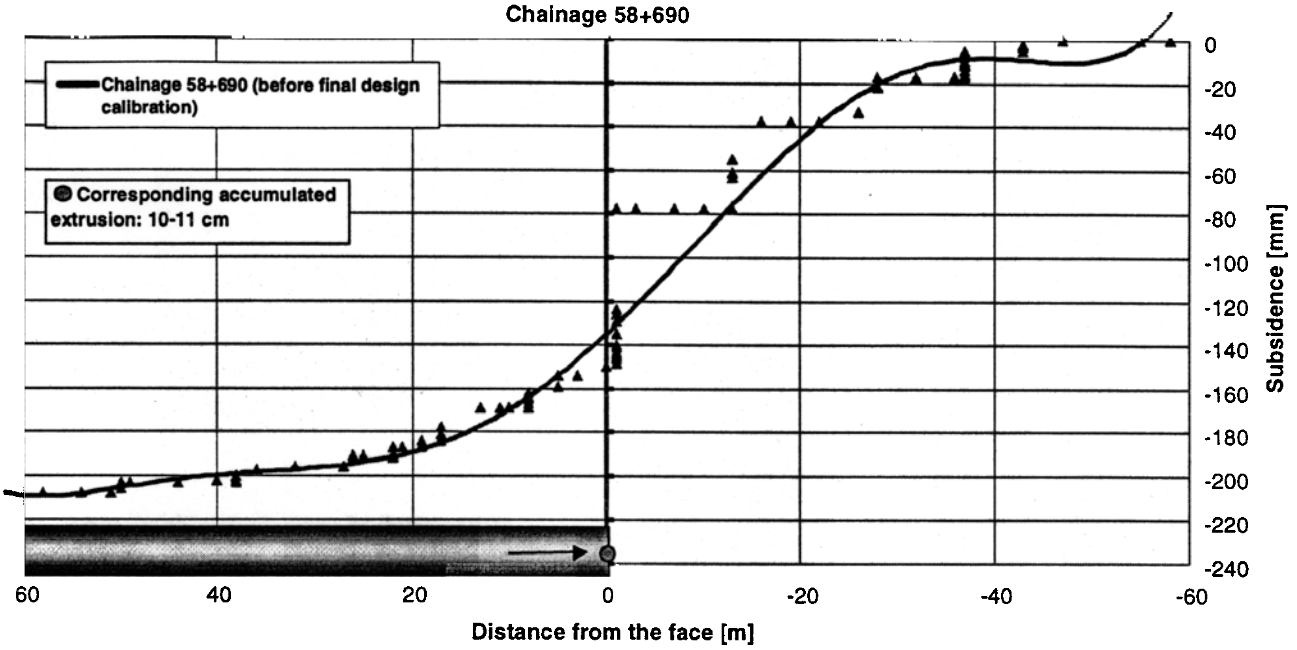

Figure 10 : Longitudinal subsidence as a function of distance from the face

At the same time accumulated extrusion measurements of around 10 cm were recorded inside the tunnel together with average radial convergence of around 10-12 cm. Differential accumulated extrusion was well above the alarm threshold that had been set (Figure 11). This difference between predicted and actual values was mainly due to differences between the real geotechnical situation and the situation forecast by the geological survey campaign on which the predictions were based.

The problem that then had to be tackled was how to calibrate the intensity and distribution of the stabilisation intervention between the face and the cavity to produce an optimum design from the viewpoint of subsidence (damage to the race track), cost and time (advance past the race circuit by the end of February 2000).

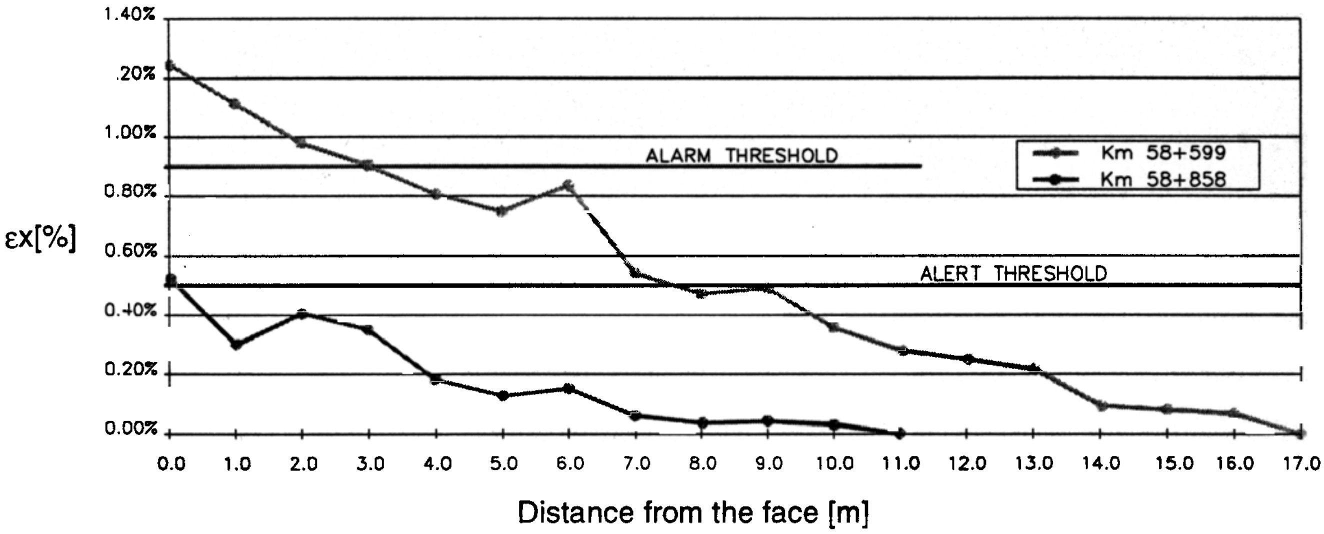

Figure 1 Employment of the differential total extrusion principle to assess excavation safety

The following steps were taken to solve the problem (Figure 12):

1. reconstruction of the real situation by means of mathematical modelling using all the data furnished by the monitoring system (extrusion, convergence and surface subsidence) and a back-analysis procedure in order to determine strength and deformation parameters and the mathematical procedures most suitable to represent the reality;

2. use of the weighted mathematical models from the previous step to calibrate preconfinement and confinement intervention aimed at maintaining extrusion and subsidence within set maximum limits.

Various finite differences mathematical models, 12 axialsymmetric and 32 plane, were set up to recreate the real situation using FLAC software ver. 3.40 and a strain softening failure criterion which simulated the real stress-strain behaviour of the ground quite faithfully. The new geotechnical parameters found with this method are summarised in Table 1.

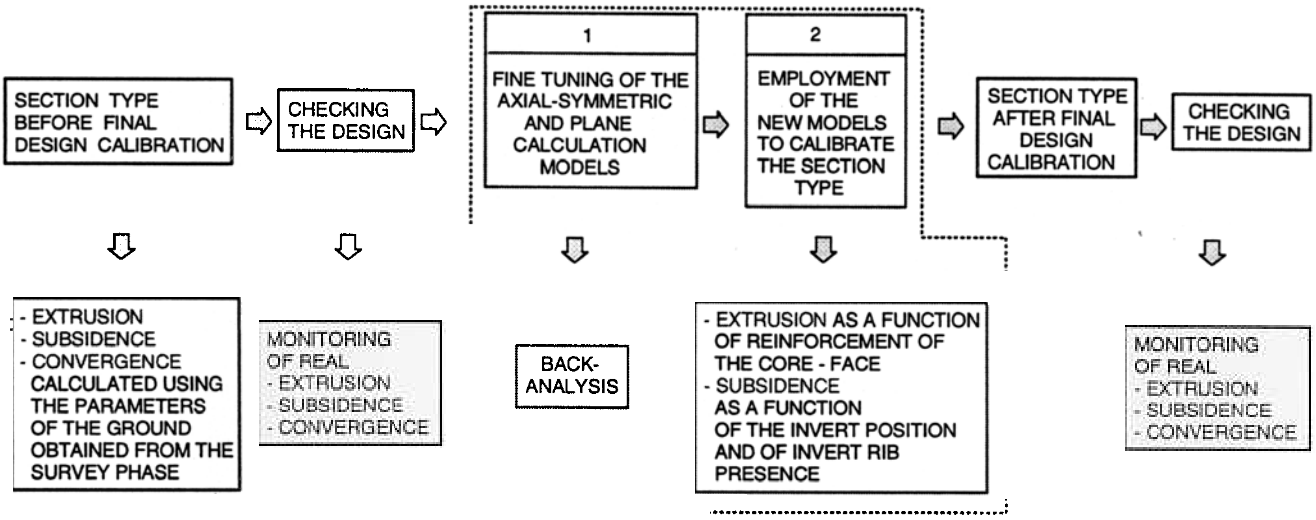

Figure 12 : Main stations of the final design calibration

Table Clays of Mugello basin

Geomechanical parameters:

Parameter	After the survey phase	After the back-analysis
Unit weight	19,9 - 20 kN/m^3	19,9 - 20 kN/m^3
Peak effective cohesion	0,02 - 0,03 MPa	**0,015 MPa**
Residual effective cohesion	0	0
Peak effective angle of friction	24° - 28°	**22°**
Residual effective angle of friction	15° - 18°	**15°**
Modulus of elasticity	$E(z) = 11{,}5 + 3{,}02 \cdot z$ [MPa]	**$E(z) = 11{,}5 + 0{,}5 \cdot z$ [MPa]**
Over Consolidation Ratio (OCR)	2 - 5	2 - 5

Once the models had been weighted so that they reproduced, by calculation, the same data furnished by the monitoring system (Figure 13), they were used:

1. to reconstruct the course of the deconfinement curve as a function of distance from the face for a given cross section of tunnel; knowledge of this curve is essential for reliable analysis using plane models;
2. to study the effect of possible preconfinement and confinement of the cavity.

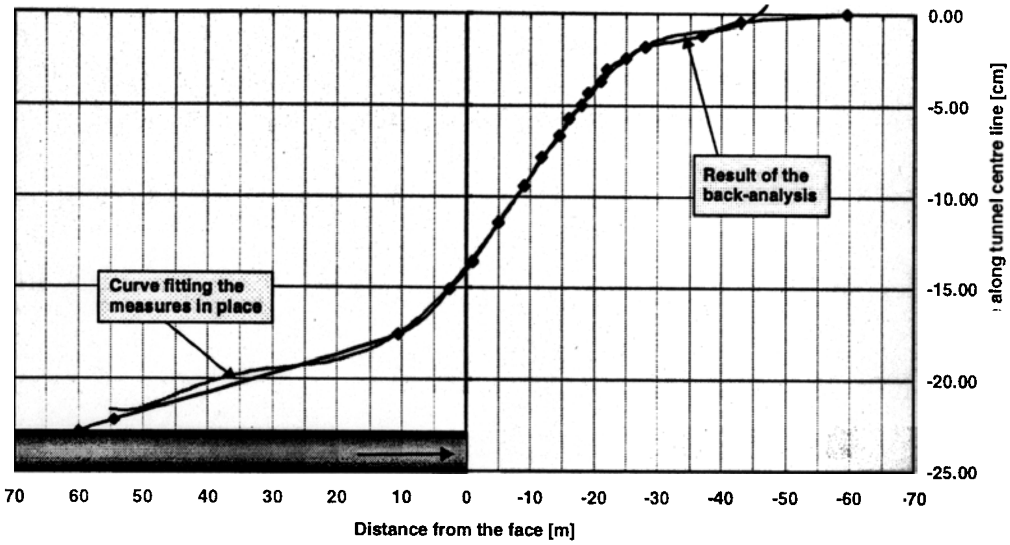

Figure 13 : Reconstruction of the real situation by using an axial-symmetric model

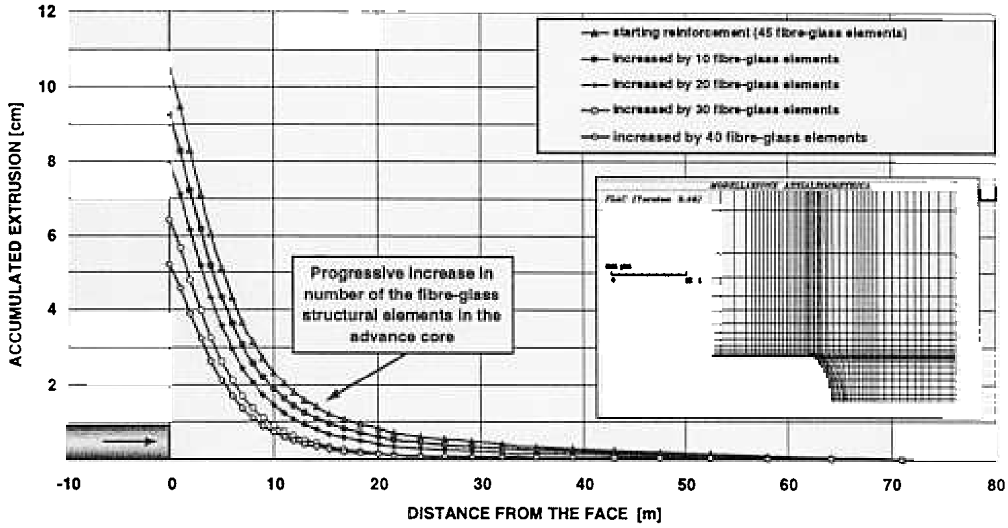

Figure 14 : Optimisation of the advance core reinforcement using axial-symmetric models

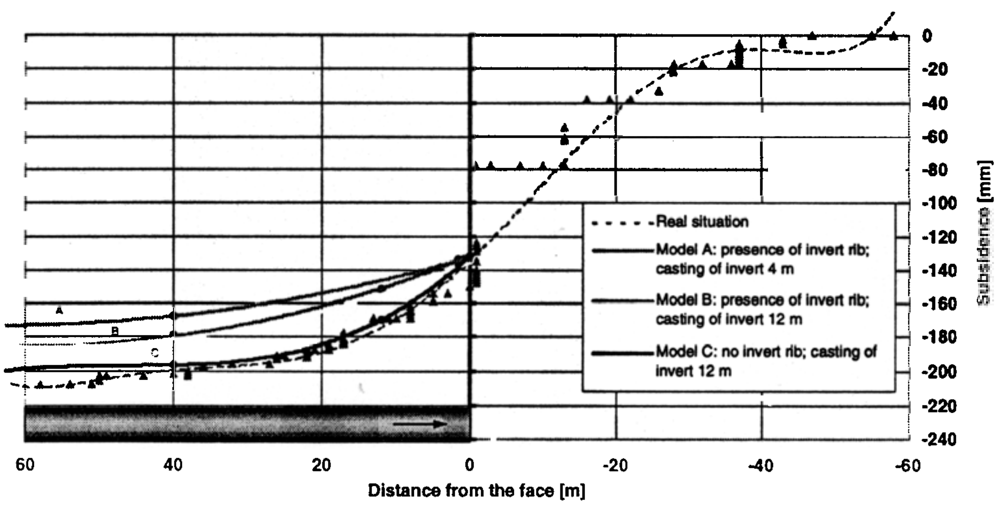

Figure 15 : Optimisation of the intervention in the advance core and in the cavity

Axial-symmetric modelling was used to calculate the optimum number of ground improvements required to both guarantee face stability and accumulated extrusion of not more than 5 cm as specified in the construction design (Figure 14).

Plane modelling, on the other hand was used to study the effects obtained in terms of the deformation response of the ground, from controlling extrusion of the core-face with different methods of closing confinement in the tunnel back from the face (Figure 15):

Model A) absence of a tunnel invert rib, casting of the invert in steps of 12 m, casting of the crown at 40 m from the face;

Model B) presence of a tunnel invert rib, casting of the invert in steps of 4 m, casting of the crown at 40 m from the face;

Model C) Absence of a tunnel invert rib, casting of the invert in steps of 4 m, casting of the crown at 40 m from the face.

On the basis of the results of the mathematical modelling based on monitoring data it was decided to calibrate the construction design as follows (Figure 16):

- the use of 93 fibre glass structural elements 24 m in length with a minimum overlap of 12 m for ground improvement of the advance core;
- a tunnel invert rib;
- tunnel invert cast in steps of 12 m;
- expanding cement mixes for cementing the fibre glass structural elements in the advance core.

Operational Phase

Tunnel advance under the race circuit was performed on the basis of the decisions taken at the construction phase (Figures 17 and 18) and the design was fine tuned on the basis of monitoring data. The design predictions were faithfully verified both with regard to deformation and advance rates.

The critical zone under the 'Borgo San Lorenzo' curve of the race track was successfully tunnelled with constant advance at an average of 2 metres/day of finished tunnel.

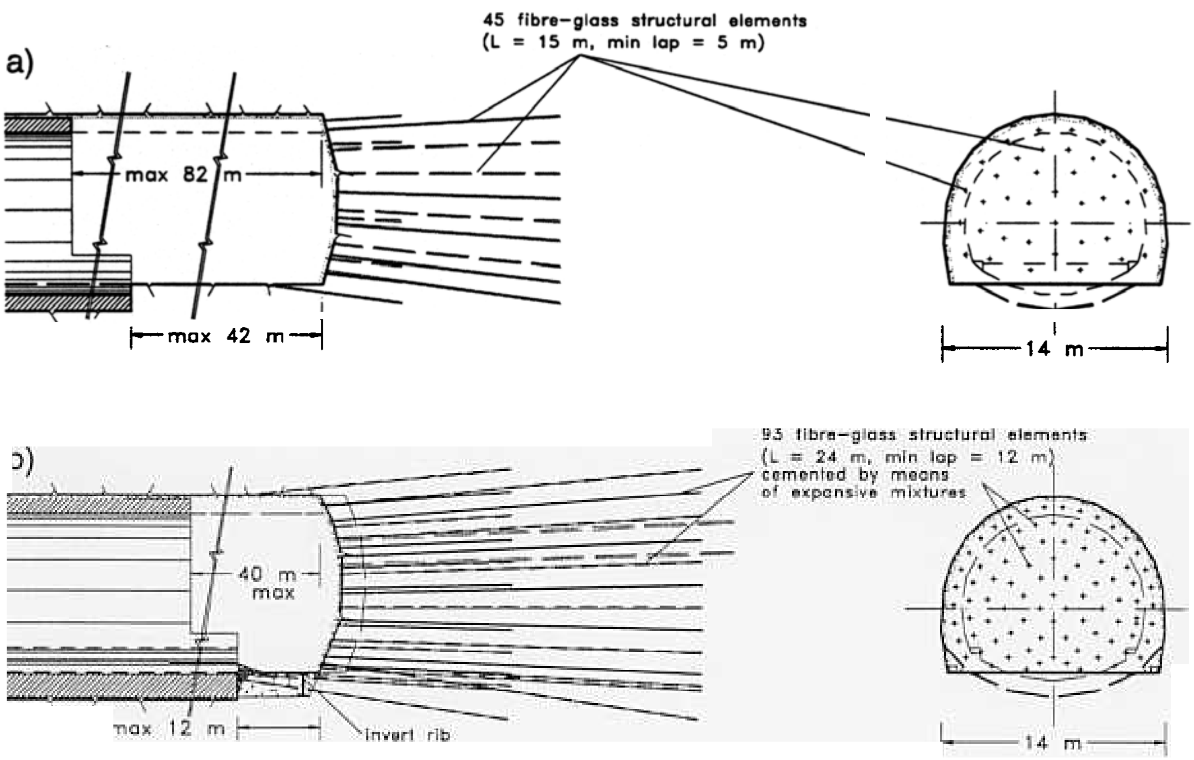

Figure 16 Passing under the Mugello International Motor Racing Cirquit
a) Section type B2 before final design calibration
b) Section type B2M after final design calibration

Monitoring Phase

The figures that follow summarise the course of the monitoring data recorded, after calibrating the design, while tunnelling under the race track. It is interesting to see how the progressive decrease in accumulated extrusion was followed by a corresponding decrease in both tunnel convergence and vertical settlement of the lining itself (Figure 19). Similarly, differential accumulated extrusion rapidly fell below the alert threshold (Figure 11). Figure 20 shows how subsidence values along the centre line of the tunnel were consequently also significantly reduced during the passage under the track: maximum subsidence measured was around 13 cm, within the desired margins. This value, which in itself may be considered high, could easily have been further reduced by appropriately stiffening the advance core (dotted line in the graph in Figure 20). This, however, could not have been done before the racing season started. The solution adopted not only guaranteed stability and safety during excavation but also turned out to be the best in terms of execution times and costs.

Figure 17 : The full-face excavation

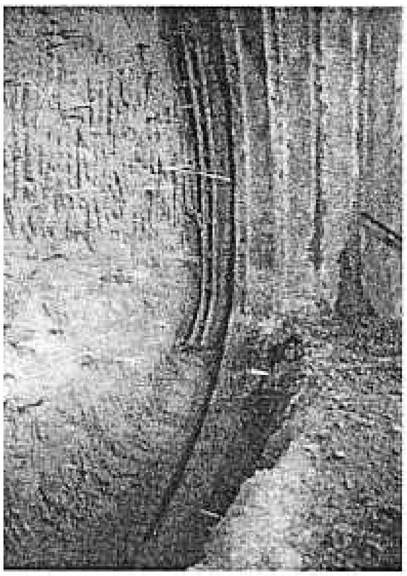

Figure 18 : Details in the cross-section

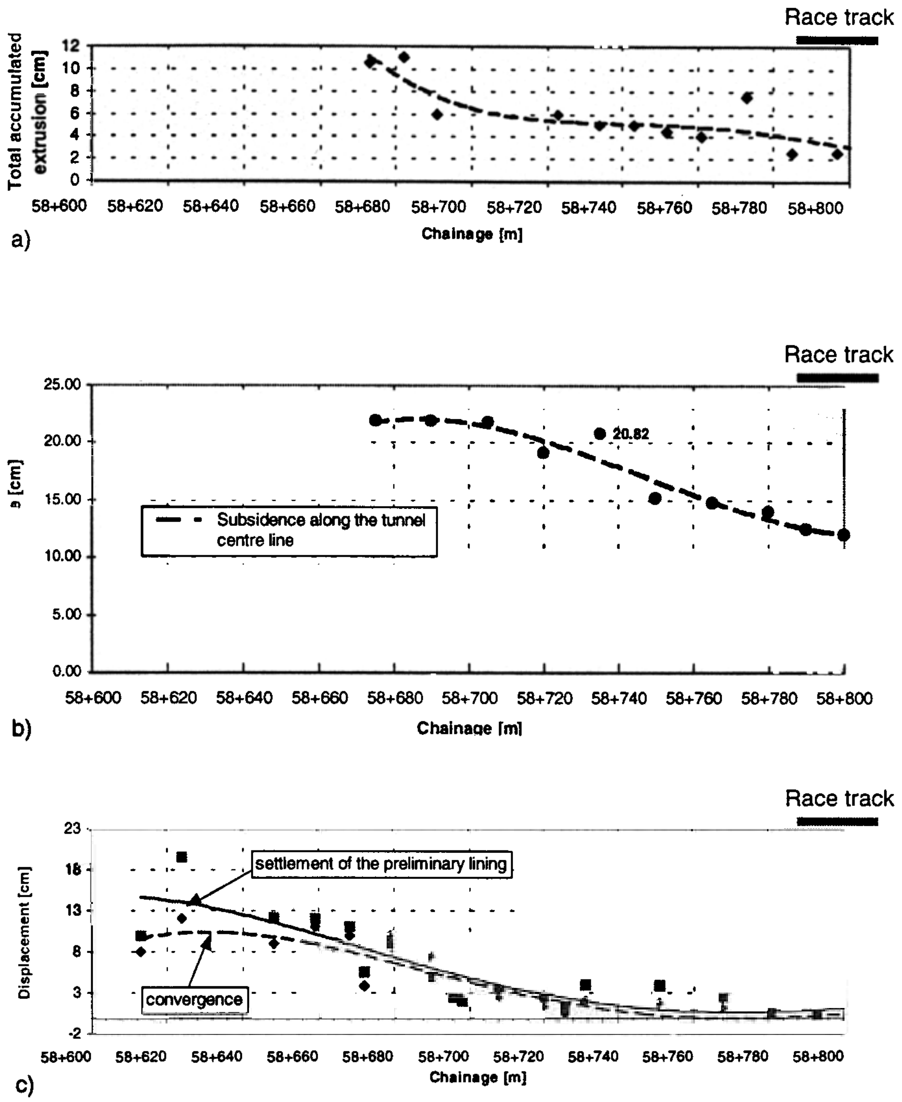

Figure 19 : Passing under the Mugello International Motor Racing Circuit
a) Progressive reduction of accumulated extrusion after final design calibration
b) Reduction of subsidence along the tunnel centre line after final design
c) Progressive reduction of the convergence and of preliminary lining settlements after final design calibration

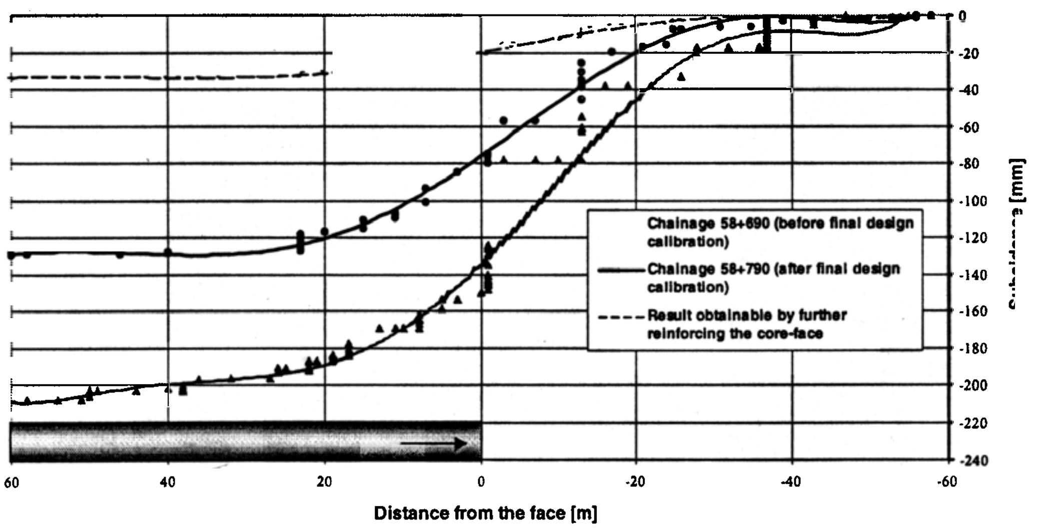

Figure 20 : Effect of final design calibration on subsidence values

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