Tunnel monitoring system – A contribution for the preparation of guidelines

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1. INTRODUCTION

In conventional tunnelling, "geotechnical monitoring" is of fundamental importance as an instrument for verifying the appropriateness of the operations specified in the design and for calibrating the intensity and sequence of those operations during construction. It is also important for recording tunnel behaviour when it is in service, in order to check the condition of the tunnel over time, especially in relation to the rheological behaviour of the rock mass and possible changes in the hydrogeological conditions (fault zones, walled section, inflow, etc.).
The approach based on the "analysis of controlled deformation in rocks and soils", ADECO-RS [1, 2], considers two different stages, that of the "design" and that of the "construction" of a tunnel. In the first, the natural pre-existing equilibriums (*survey phase*) are taken as the basis for predicting the behaviour of the ground during excavation in terms of the deformation response (*diagnosis phase*), in order to decide the type of action to exert – confinement or preconfinement – to maintain deformation within acceptable limits for tunnel safety (*therapy phase*). During the second stage, the deformation phenomena are measured and interpreted (*monitoring phase*), firstly to verify the accuracy of the predictions made during the diagnosis and therapy phases and then to fine tune the design by adjusting the intensity, location and timing of stabilisation operations and the balance of these between the face and the perimeter of the excavation and to calibrate the speed and rate of tunnel advance (*operational phase*). This is all performed with a view to industrialising the tunnel construction process and to compliance with schedules and budgets (see Fig.1 flow chart).

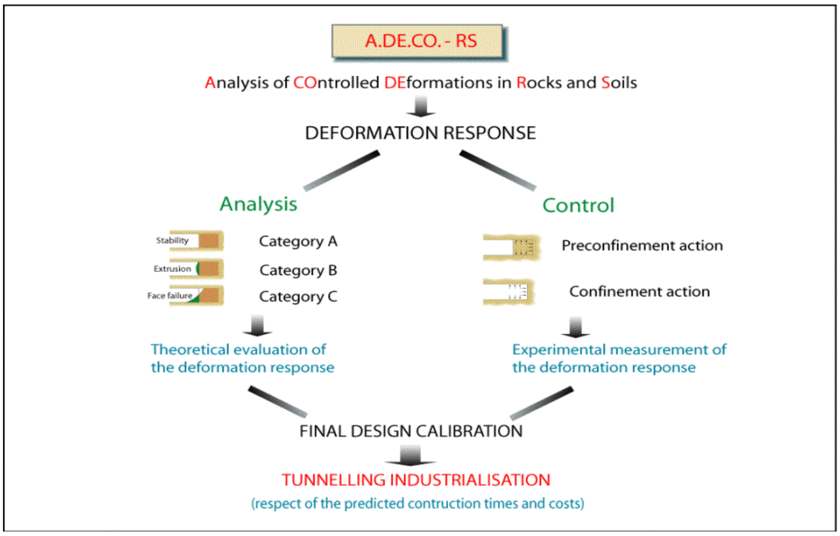

Figure 1 – ADECO-RS Approach

This paper clarifies the role of monitoring in the design and construction process and illustrates the criteria followed in the choice of instrumentation and in interpreting the data acquired, with particular reference to the analysis of the deformation behaviour of the face-core using "extrusion-meters". Some case studies taken from the construction of Apennine road and rail tunnels are examined.

2. DEFORMATION RESPONSE AND DESIGN APPROACH

The systematic observation of the stress-strain behaviour of a wide range of tunnels during construction has clearly shown that the deformation response is complex and involves not just the tunnel cavity, but also the volume of ground that lies ahead of the face, virtually cylindrical in shape, with dimensions quite similar to that of the diameter of the tunnel to be excavated. This region, called the “advance core”, is affected by a primary component of the deformation response: “extrusion”, which manifests on the surface of the face along the longitudinal axis of the tunnel (bellying or rotation of the face), and “preconvergence” of the cavity, i.e. the convergence of the theoretical profile of the tunnel ahead of the face (Fig. 2). These primary components depend on the relationship between the strength and deformation properties of the advance core and its original stress state [3, 4]. Research has found that:

- there is a close connection between extrusion of the advance core at the face and preconvergence and convergence of the cavity. Also, deformation in the cavity normally follows and is strictly dependent on deformation in the advance core, which is the true cause of the whole deformation process in all its components;
- it is possible to control advance core deformation (extrusion, preconvergence), and as a consequence also to control cavity deformation (convergence), by acting on the rigidity of the core with measures to protect and reinforce it (Fig. 3);
- the rigidity of the core plays a determining role in the stability of a tunnel both in the short and long term.

The advance core can be seen as a “stabilisation instrument” and its analysis - in terms of action to be taken and the related prediction of deformation – is very important at the design stage, just as the monitoring and control of the deformation response of the core-face, and not just of the cavity, is very important at the construction stage.

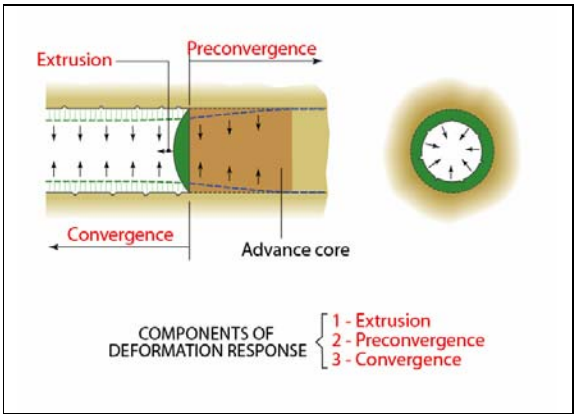

Figure 2 – Deformation response

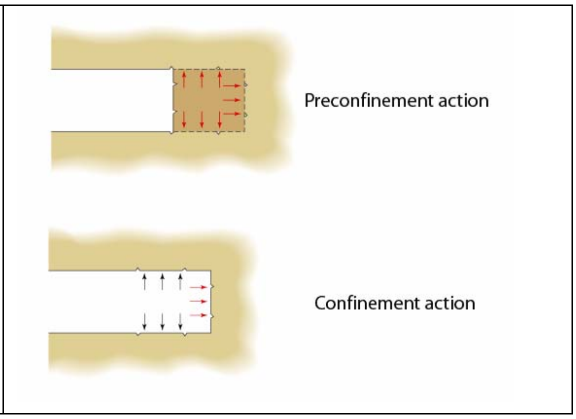

Figure 3 – Stabilisation action

The instruments used ahead of the face are those of “preconfinement”. They act to facilitate the formation of an artificial arch effect in advance (a protective function) or to improve the natural strength and deformation properties of the advance core (a reinforcement function). Typical examples of preconfinement are fibre glass structural elements inserted around the cavity and in the core, jet-grouting and full face mechanical pre-cutting. “Confinement”, on the other hand, acts inside the tunnel, back from the face, to prevent deformation phenomena from developing after the passage of the face and consists of a preliminary lining consisting of a shotcrete shell, steel ribs, radial bolts and the tunnel invert. The composition of these instruments, based on the category of the core-face (A “stable”, B “stable in the short term”, C “unstable”, [1]), determines the longitudinal and cross “section types”, which guarantee the feasibility of the excavation and the long and short term stability of the tunnel.
Owing to the variability of geological and geotechnical conditions, construction section type “variabilities” must be designed in order to unequivocally define the type, intensity and rates of the operations and the range of geological-geomechanical and stress-strain (extrusion and convergence) conditions within which a given section type can be employed. The monitoring system employs a set

of specific “guidelines” to govern the construction process and to calibrate operations so that they are appropriate for the local geomechanical conditions.A correlation between the deformation response and the operations used to control it, with the relative “variabilities”, is reported in Table 1 below.

Table 1 – Deformation response Vs Interventions

Deformation response	Interventions	Variabilities
Estrusion Preconvergence (Convergence)	Face and contour Preconfinement (FRP/JG structural elements …)	Intensity (N/m^2), Length (m), Overlapping (m)
	Drainages	Number, Length (m)
	Excavation step and shape	Lenghth (m)
Convergence	Cavity Confinement (shotcrete prelining, steel ribs, bolts …)	Thickness (m), Step (m), Length (m)
	Invert and crown casting	Face distance (m)

An example is given in Fig. 4 of the section type C2, employed for the excavation of the base tunnel of the A1 Milan-Naples motorway, between Sasso Marconi and Barberino di Mugello, in rock masses lying in the Scaly Clays formations, (160 sq. m. approx. of full-face excavation) [5]. Given the variability of the geomechanical conditions, with GSI values in the 30-40 range, and the related predicted deformation response, with extrusion values in the 40-80 mm range and diametrical convergence in the 100-140 mm range, the section type variabilities reported in Table 2 were considered and governed by means of an appropriate monitoring system.

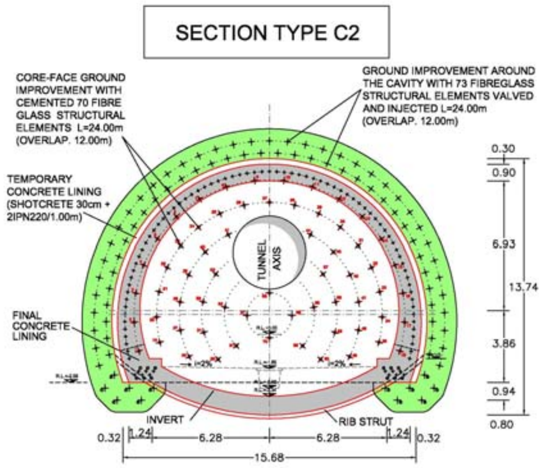

Figure 4 – Base Tunnel section type C2

Section Types	Intervention	Variabilities		
		Minimum	*Nominal*	*Maximum*
C2	Steel rib step	1.2 m	1.0 m	0.8 m
	N° VTR face	50	70	90
	VTR face overl.	10.0 m	12.0 m	14.0 m
	Excavation	14.0 m	12.0 m	10.0 m
	Invert-face (°)	< 2.0∅	< 1.5∅	< 0.5∅
	Crown-face	< 3.0∅	< 5.0∅	< 7.0∅

Table 2 – C2 section types variabilities

3. MONITORING SYSTEM

Monitoring systems are designed to systematically acquire information on the geological-geomechanical conditions of the face and the deformation response of the tunnel during excavation and when it is in service. The design must provide detailed specifications of monitoring stations: (i) the most appropriate instruments to detect the magnitude of the measurements to be monitored; (ii) how frequently they are installed as a function of local conditions; (iii) instructions on how to interpret readings so that they can be compared with design predictions.

3.1 Monitoring stations

The basic types of monitoring stations listed below are those generally used during tunnel construction. Monitoring stations must be installed very close to the face and the zero reading taken immediately if they are to provide useful and accurate information.

3.1.1 Geological-geomechanical survey of the face

These surveys give a graphical and numerical description of the geological, geostructural and geomechanical face conditions during excavation. Two different types of surveys are employed:

- “detailed surveys”: detailed descriptions of the structural, lithological and stratigraphic rock characteristics, with information on the degree and type of compactness, cementation, granulometry, alteration state, discontinuity characteristics (type, position, geometry, filling, JRC, JCS), and remarks on sources of water and on possible gravitational detachments during excavation. Geomechanical classifications are provided: RMR and GSI. Specimens may be taken for laboratory tests (classification, compression, triaxial, shear joint, extrusion tests, etc.) and *in situ* tests may be performed (metric pressure-dilatation, etc.);
- “snap-shot surveys”; these are employed to acquire qualitatively structural, lithological and stratigraphic rock characteristics only.

3.1.2 Estrusion measurement station

These measurements are used to provide a survey of the longitudinal displacements of measurement bases set inside an extensimetric rod, located along the tunnel alignment, ahead of the face, inside a sub-horizontal bore hole. The instruments constitute an incremental extensimeter, consisting of PVC pipes, fitted with annular anchors at intervals of 1 metre along them and set into the bore hole with slightly expansive grouting injections. The bore holes are usually greater than 30 m in length (2-3 times the tunnel diameter, with about 10 m of overlap). Once the grout injection has set, a zero reading must be taken before excavation starts.

3.1.3 Convergence measurement station

These measurements provide a plot of the 3D displacements for 5-7 points set on the preliminary lining (sometimes on the final lining), in the centre of the crown, in the spring line and the centre plane, fitted with optical targets and read using a precision topographic instrument. If differential deformation behaviour is observed between the shotcrete and the steel ribs, targets are also installed on the steel ribs using special supports. Cavity convergence is considered as being the average of the three diameter measurements. Multi-point extensimeters may also be used to measure convergence inside the ground outside the profile of the excavation.

3.1.4 Principle measurement station

These stations are designed to give a complete map of the stress-strain state of the ground and of the lining and to collect data on hydrological conditions (water pressure and inflow) and the extension of the plasticised zone (plastic radius). In urban areas, or under shallow overburdens, surface settlement and ground movements are also monitored. Stations normally consist of: extensimeters, placed in the crown and at the centre line, to monitor ground deformation around the cavity; piezometers to monitor water pressure; load cells to monitor bolt and steel rib forces; convergence stations both for the preliminary lining and the final lining; strain gauges, in the preliminary lining and in the final lining, to monitor stress in the shotcrete and concrete.

3.2 Monitoring frequencies

The siting of monitoring stations along the tunnel alignment (quantities) must be carefully studied to achieve the best possible compromise between the need for adequate knowledge and the need to keep costs low and not to interfere with excavation work and tunnel use when in service. The predicted behaviour of the core-face is taken into account when deciding the frequency of the intervals at which stations are installed, as shown in Table 3. In “stable core-face” conditions (category A), in which the ground is stressed in the elastic range and the deformation response is immediate and very small, convergence measurement stations alone are sufficient, with few principle measurement stations. In “stable core-face in the short term” conditions, in which the ground is stressed in the elasto-plastic range and deformation phenomena is mostly deferred and not negligible in magnitude, extrusion, convergence and principle monitoring stations must be installed very frequently (extrusion and convergence stations are recommended when tunnel advance is halted for more than seven days, owing to the possible relaxation of the ground that may occur). Finally, in “unstable core-face” conditions, where deformation of the ground develops into the failure range if not properly controlled by preconfinement action, convergence, extrusion and principle monitoring stations must be installed extremely frequently. In situations of this type, it is very common to pass from conditions of stability to conditions of instability very suddenly, as a result of a very small increase in deformation, so the monitoring data are of fundamental importance.

Table 3 – Monitoring stations frequencies and readings

<table>
<tr><th rowspan="2">Monitoring stations</th><th colspan="2">A (stable core-face)</th><th colspan="2">B (stable core-face s.t.)</th><th colspan="2">C (unstable core-face)</th></tr>
<tr><td>Rate</td><td>Reading</td><td>Rate</td><td>Reading</td><td>Rate</td><td>Reading</td></tr>
<tr><td>Analytical geo survey</td><td>1/200m</td><td>-</td><td>1/150m</td><td>-</td><td>1/100m</td><td>-</td></tr>
<tr><td>Snap-shot survey</td><td>1/20-24m</td><td>-</td><td>1/10-12m</td><td>-</td><td>1/10-12m</td><td>-</td></tr>
<tr><td>Estrusion</td><td>-</td><td rowspan="3">1/day up to 10 m face distance, 1/wk up to stabilisation</td><td>1/24-48m</td><td rowspan="3">1/day up to 24 m face distance, 1/wk up to final lining casting (*)</td><td>1/20-24m</td><td rowspan="3">1/day up to 24 m face distance, 3/wk up to final lining casting (*)</td></tr>
<tr><td>Convergence</td><td>1/50-60 m</td><td>1/24-36m</td><td>1/10-12m</td></tr>
<tr><td>Principle measurement</td><td>1/400-500m</td><td>1/200-300m</td><td>1/100-200m</td></tr>
</table>

(*) estrusion: 1 reading before escvation, 1/day during excavation, 1 reading before and after ground intervention

Monitoring must be performed very carefully in certain contexts, such as in sections of tunnel affected by large tectonic dislocation, or under rock burst conditions, or when a strong hydraulic gradient might be encountered, or for tunnels under the water table, where the flow rate of drainage water and the water pressure on the final lining must be measured. In shallow tunnels, especially in urban areas, stations must be installed to measure deformation from the surface that develops at tunnel depth and to measure settlement at ground level so that effects on surface constructions, such as roads, buildings and utilities can be kept under control. In these cases the surface constructions themselves must be monitored using appropriate instruments (surface clinometers, differential settlement gauges, topographic levels, etc.). The information given in Table 3 gives a general idea of the frequency of the readings that should be taken by the instrumentation installed depending of course on the predicted behaviour of the face-core. The first data read will in any case enable the frequency of readings to be adjusted during construction.
Automatic devices are available for in-service monitoring of tunnels with remote measurement of most of the parameters needed to monitor the health of an underground construction (e.g. stresses on linings), so that the problem of maintenance and repair can be approached using scientific methods.

3.3 Interpretation of data

It is fundamental for the measurements to be interpreted properly if monitoring is to be useful in the fine tuning of the construction process. Interpretation is often not easy for a whole series of reasons, but mainly because of the reliability of the instruments (device delicacy, wrong positioning or use, malfunctioning), a broad data scatter and external influences (running water, variations in temperature and humidity). It is preferable to use less sophisticated equipment, more appropriate to an underground environment and to install more than the minimum number considered necessary. It is important to consider all aspects that might influence data acquisition.
Core-face extrusion is normally plotted graphically to give the magnitude of the deformation as a function of time or face advance; the abscissa of the extrusion curve gives the magnitude of the extrusion and the angle of the tangent to the curve gives the “velocity”, while the curve itself describes its “acceleration”. The incremental curve, which is for the entire length of the drill hole (i.e. the extensimeter rod), and the curve for the individual sections into which the extensimeter is divided are plotted (Figure 5). Curves of the latter type are particularly useful for comparing events and trends that manifest in different bands of ground within the core-face, and more specifically for estimating the ”radius of influence of the face”, intended as the distance from the face at which changes in stress occur caused by tunnel advance. These data are very useful for calculating the length and overlap of the preconfinement operations. The magnitude of the incremental curve is used to verify the core-face conditions (category A, B or C) and to calibrate the intensity of the preconfinement operations, while the acceleration is an indicator of the onset of collapse: it therefore acts as an alarm bell to quickly place stabilisation structures or to remove personnel and equipment.
Convergence curves can be plotted as a function of time or of distance from the face and magnitude, velocity and acceleration can be derived from those curves, as in the case of extrusion. If measurements are taken inside the rock-mass (multi-point extensimeters), radial deformation as a function of the distance from the excavation profile can be plotted and - if the extensimeter is long enough - the plastic radius of the tunnel can be derived from them. A comparison of the magnitude of actual convergence with the design prediction for it can be used to verify pre-confinement and confinement operations and to calibrate them during excavation, especially the stiffness of the

preliminary lining (shotcrete thickness, steel rib intervals, radial bolt intervals and length). It's very important to monitor the "deformation gradient", because the deformation response must present a certain degree of deceleration: acceleration is normally at the maximum during and immediately after the passage of the face and during the excavation of the tunnel invert. Convergence must stabilise rapidly when this is cast. The deformation gradient is used to decide the distance from the face at which the final lining is cast (invert and crown). If substantial settlement is recorded the use of a steel rib invert strut is recommended.

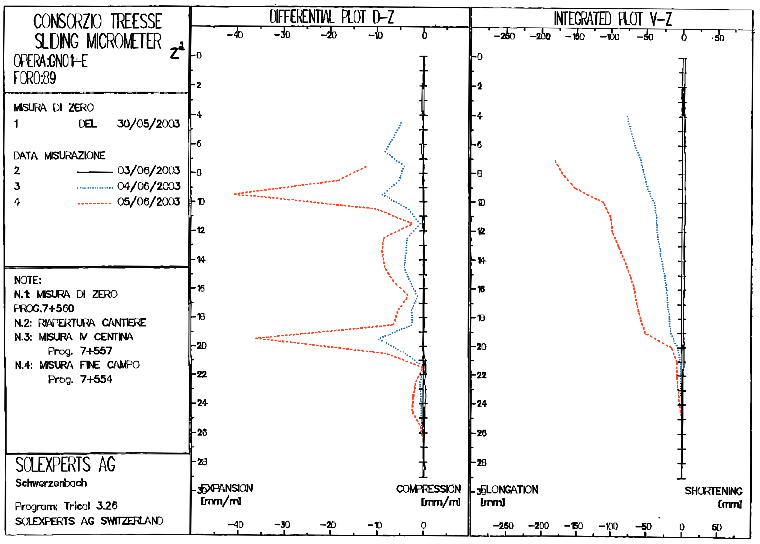

Figure 5 – Extrusion measurement

Data from strain gauge readings, the creep and the shrinkage components of strain in concrete and shotcrete, must be considered, to avoid overestimating the stress in the structure [6].

4. DATA MANAGEMENT

Once acquired, data must be filtered and organised by a "monitoring manager" and made available in real time to the principle personnel concerned (design engineer, construction manager, construction supervisor, client) with the construction of a data bank that is constantly updated with the use of GIS or similar IT systems. The processed data output will consist of "type sheets" containing all the information needed for correct interpretation of the measurements (name, position and type of instrument, date of the reading, zero reading, system and unit of measurement employed, graphs for viewing data trends, etc.). It is important to be able to correlate data readings with operations in the tunnel. A daily log of work performed must therefore also be compiled indicating the position of the face, the preliminary lining, the casting of final linings (tunnel invert and crown) and the tunnel section type employed. It is recommended that the monitoring manager prepares a periodic report summarising the activities performed, with indications of any differences from design predictions.

The procedure for managing the construction process in the light of data readings is as follows (account is taken of the "variabilities" for the section type provided for in the design and adjusted by the "guidelines"). Excavation must commence using the main section type specified for the section of tunnel in question and with the operations specified by the design, i.e. employing the average values for the range specified in the guidelines. At the same time monitoring as specified in the monitoring programme commences and measurements are acquired on the geological-geomechanical context and the deformation response. Once the geomechanical and deformation conditions are known, they can be compared with design predictions and the following decisions can be made:

a) confirmation of the tunnel section type specified according to the intensity of the intervention and sequence of operational stages given in the design (average values);
b) confirmation of the tunnel section type and variation of the intensity of the intervention or the sequence of the operational stages in order to adapt them to fit the geomechanical conditions encountered during construction more precisely (section type variabilities);

c) selection of a different tunnel section type from those specified in the design, if the geological and geomechanical conditions encountered diverge from those forecast for that section of tunnel (use of section types along the tunnel alignment);
d) report the need to design a new tunnel section type with different technical characteristics in cases where completely unforeseen lithological and geomechanical conditions are encountered or unexpected deformation behaviour is encountered.

The decisions made in the light of the data acquired and of a comparison with design predictions are taken by the design engineer, the construction manager or the construction supervisor, depending on the contents of the contract with which the client awarded the construction work. With the contracts generally employed in Italy, decisions of the type described in points a) and b) are taken directly by the construction manager and checked by the construction supervisor. Tunnel excavation is only occasionally followed continuously by the design engineers with the appointment of a resident "geomechanical engineer", in order to systematically assist with decision-making for tunnel advance procedures. This occurs under geologically difficult conditions or for major projects. The intervention of the design engineers is, however, required for the conditions defined in points c) and d), since they are unexpected conditions not contemplated by design predictions. Finally any increases in construction times and costs will require the involvement of the client.

5. CASE STUDIES

Some case studies taken from the construction of Apennine road and rail tunnels are examined and discussed to show how an examination of monitoring data and graph summaries to interpret them can guide methods of tunnel advance. Figure 6 relates to the section of excavation for the Base road tunnel shown in Fig. 4 and gives the changes in geomechanical conditions (RMR and GSI) and deformation behaviour (in terms of convergence and settlement) for a section of tunnel close to the passage through the Scaly Clays formation and the *Arenarie del Cervarola* formation. The geomechanical characteristics of the latter are much better than those for the Scaly Clays (a sharp increase in readings for GSI from 30-35 to 55-65 can be observed, with a minimum value of approximately 20 at the point of contact between the two formations).

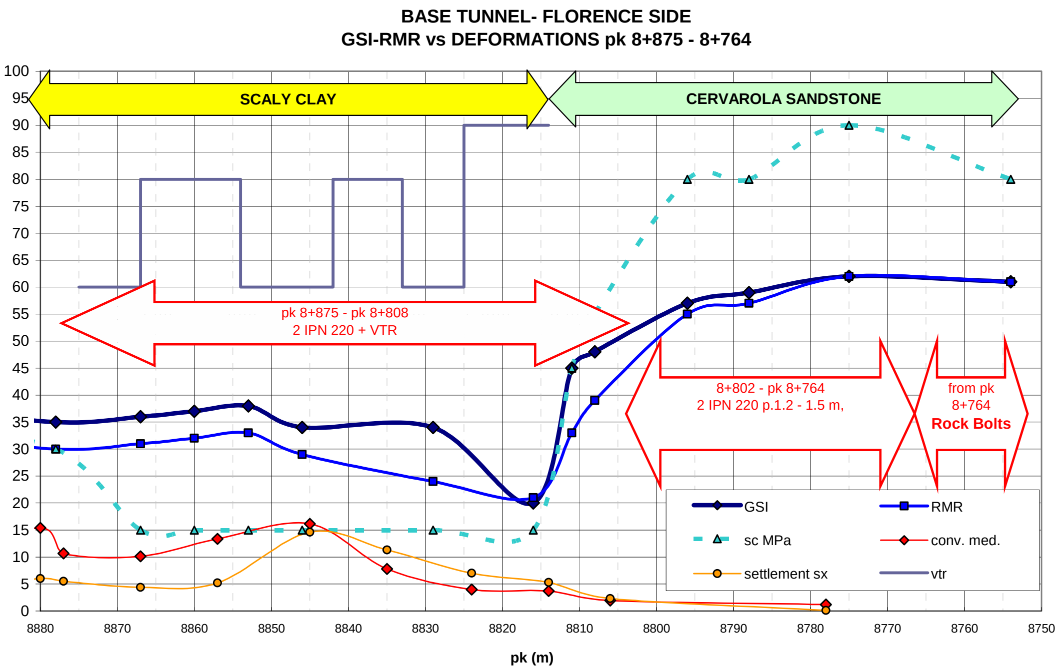

Figure 6 – Base Tunnel – GSI-Deformation response Vs Pre-confinement actions

The application of the C2 tunnel section type was adjusted by varying the intensity of the ground reinforcement at the face in order to maintain diameter convergence below 10 cm. This was performed by increasing the number of fibre glass structural elements inserted in the face from 60 to 80-90 whenever the deformation response consisted of convergence values in the 15-20 cm range. Once excavation reached the sandstones, tunnel advance proceeded with cavity confinement action only, initially with 2IPN220 steel ribs at 1.20 m. intervals and then, when GSI values of greater than 60 were reached, with radial rock bolts [5]. Figure 7 shows changes in the deformation response in terms of extrusion and convergence as a function of the overburden (i.e. the geostatic stress conditions) for the Pianoro tunnel on the high speed Bologna-Florence railway line [7] in the *Complesso Caotico* formation. Values for cumulative extrusion varying between 15 cm and 5 cm can be observed for overburdens varying between 100-120 m. and 30 m. In this case too the number of fibre glass structural elements in the face was varied between 40 and 100-120, in order to maintain the deformation response within design limits (extrusion/convergence < 10 cm).

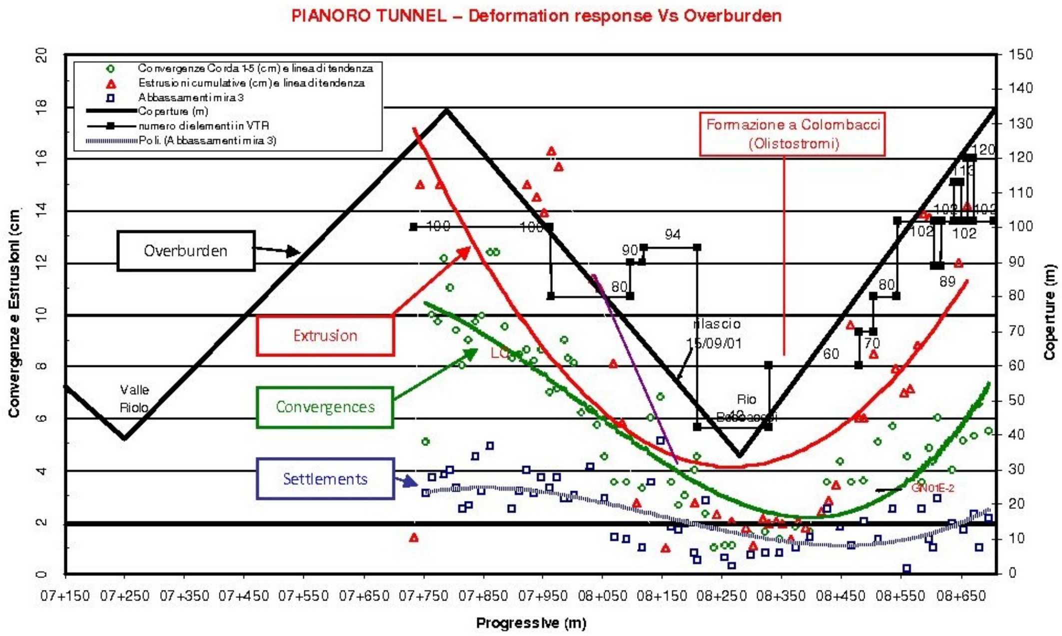

Figure7 – Pianoro Tunnel – Deformation response Vs Overburden

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