Monitoring systems in squeezing rock conditions

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Summary

Based on actual experiences in this field, the paper summarises objectives, constraints and design criteria for monitoring systems for the control of underground excavations in squeezing rock conditions. The design of the monitoring system is a fundamental part of tunnel design, especially for deep tunnels in rock where large convergence is expected after excavation. In these cases the monitoring system must be designed to enable verification of design assumptions as well as measurement of actual loads in each structural component of the primary support system and lining for continuous assessment of safety and design. The paper illustrates schematically the application of the principles described.

1. Introduction

Experience gained to date in the construction of tunnels in squeezing rock conditions shows clearly that the design of an appropriate monitoring system is an essential part of the design of the tunnel. Considering the importance of this element and especially the interference and interactions between monitoring system and construction activities, the design of the two must be carried out as one, i.e. the design of the tunnel must include the design of the monitoring system just as it includes, for example, the design of the support system.

The main questions which arise in the design of the monitoring system for tunnels in squeezing rock conditions concern:

- the type of instrument which should be installed to monitor the behaviour of the excavated rock mass and the support system;
- the frequency of installation and readings;
- how to optimise the design of the system in terms of interference with other construction activities during installation and readings, direct costs of the system, resources for data management and interpretation.

2. Objectives and benefits

The objectives and general design criteria of monitoring system for tunnels in squeezing rock conditions are summarised in Figure 1 and discussed below.

Monitoring systems may be installed in tunnels with the following objectives:

- verification of design assumptions and check of structural safety during construction;
- verification of structural safety and serviceability in the medium and long term.

Satisfactory performance of the monitoring system with respect to these objectives results in the following benefits, amongst others:

- for a required level of safety, optimisation of support system as a function of actual rock mass behaviour and local variation thereof;
- increased reliability on medium and long term structural safety and serviceability with reduction of unplanned maintenance and corrective actions, especially after completion of construction.

3. General design criteria

To achieve these benefits monitoring systems must satisfy the following general design criteria:

1. Significant physical quantities should be monitored; within this context these are displacements and strains and, subordinately, pressure and loads;
2. the function of each instrument and measurement within the overall system must be clearly defined;
3. instruments would be installed as close as possible to the workface;
4. instruments are more conveniently grouped in instrumented sections rather than distributed along the tunnel;
5. systems for data acquisition, data management and data interpretation must be designed as an integral part of the monitoring system, using technology appropriate for the purpose. Geological and constructional data must be considered as part of the monitoring data.

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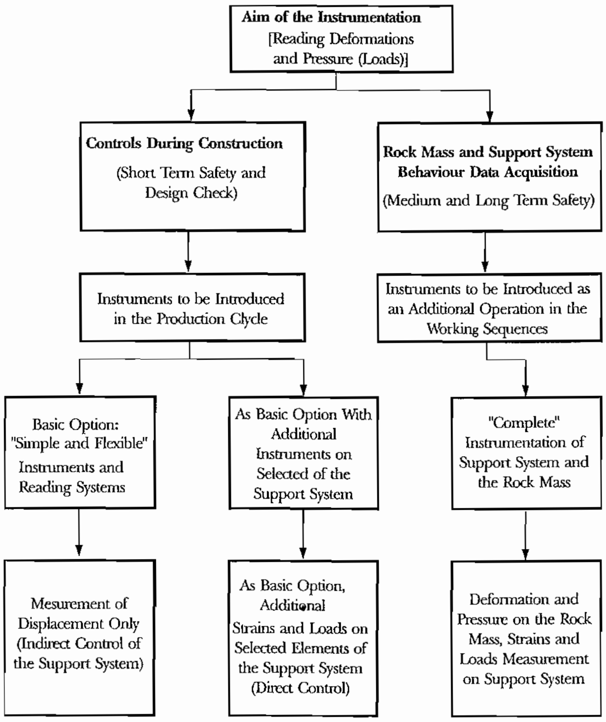

Fig. 1 – General design criteria for monitoring system in squeezing rock conditions.
Fig. 1 – Criteri generali di progetto del sistema di monitoraggio in condizioni di rocce spingenti.

4. Scheme of instrumentation

Based on these general criteria it is considered advisable to arrange instruments in two different types of instrumented sections depending on function. As shown in Fig. 1, it is recommended to distinguish between the following types:

1. sections for control of construction;
2. sections for acquiring data on the behaviour of rock mass and support system in the medium and long term.

To ensure that the control of construction provided by the monitoring system is valid, sections must be installed and monitored frequently, typically every 20÷25 m. Readings should be taken every 2÷3 m of excavation at least, which means up to twice per day, depending on advance rate, up to 1.5÷2 diameters from the face. Accordingly, installation and monitoring should be an integral part of the production cycle, just as any other construction activities. This implies that simple and "flexible" instruments and reading system be used to minimise impact on production. In practice, only displacements are measured, with an indirect control of the support system.

On the contrary many of the instruments appropriate for acquiring data on the behaviour of the rock mass and support system require, by necessity, complex installation and data acquisition system. This, together with higher costs of the system and resource requirements for data management and interpretation, implies that such instrumented section can be used much less frequently (say every 200÷300 m). However provided conditions within the tunnel are relatively uniform such lower frequency can be sufficient for the purpose of providing data on medium and long term behaviour. Installation of this type of section falls outside the normal production cycle and must be considered as a separate operation. Measurements may include displacements and pressure in the rock mass and displacements, strain pressure and loads in the support system.

Under special circumstances, it may be necessary, as part of the control of construction to implement direct measurement of strains and/or pressure/loads in the support system in addition to the measurement of displacements as normally carried out. For example, this may be necessary where a reduction in the support system is implemented following interpretation of monitoring data.

5. Data interpretation

As a general criterion, data management and interpretation must be an integral part of the management of the project, both during construction and maintenance, in the same way as the physical installation and readings of instrumentation must be designed as an integral part of the tunnel.

During construction, data from instruments must be analysed very rapidly, by means of predefined interpretation procedures which must include guidelines on appropriate design changes depending on the results obtained ("simplified" procedures). Since this has an implication in terms of work safety, it is particularly important that appropriate resources are available to ensure that interpretation and, if appropriate, design changes, progress at the same rate as construction.

Data from instrumented sections designed for monitoring the behaviour of the rock mass and the support system require more detailed interpretation to take account of the complex interaction between the various elements of the system. In practice it is impossible to predetermine the interpretation procedure, other than in general terms. However, data from these sections enables the "simplified" interpretation procedures for control of construction to be validated.

6. System design in practice

6.1. Generality

A monitoring system for 80 m^2 tunnels in squeezing rock conditions (uniaxial compressive strength of the rocks in a range of $\sigma_c \approx 6 \div 10$ MPa; deformability modulus in a range of $E \approx 1000 \div 2000$ MPa) designed in accordance with the above principles is described below. The support system (steel ribs, rock bolts and shotcrete) was adjusted during construction following interpretation of the monitoring data.

6.2. Control of construction

To control rock mass displacement during excavation, simple instrumented sections consisting of 5 convergence nails cemented minimum 0.5 m in the rock were installed, typically every 20 m, maximum $1.0 \div 1.5$ m from the face. Similar nails were welded to steel ribs to monitor their displacements and therefore any relative movement between rock and supports.

Convergence readings were carried out using high precision topographical instruments and fixed optical targets on the nails. The frequency of readings depended on the advance rate; typically every $2.5 \div 3.5$ m up to a distance of the instrumented section from the face of $15 \div 20$ m. Thereafter, this frequency decreased to one reading a week.

Where direct measurements of the behaviour of the support system was required for construction control, additional instrumentation was installed on selected sections as follows:

- 3 pairs of vibrating wire strain gauges on steel ribs;
- electrical pressure cells at each of 3 joints in steel ribs.

Readings were taken daily using a portable data logger.

6.3. Rock mass and support system behaviour

Rock mass behaviour around the tunnel section was monitored using the following instruments (Figure 2):

- 5 convergence nails as above (Fig. 2: "A");
- 4 electrical multipoint extensometer (Fig. 2 "B");
- 4 electrical instrumented tangential pressure cells in 0.3 m deep slot in rock (Fig. 2 "C");
- 2 vibrating wire piezometer at different depths (Fig. 2 "D").

Behaviour of the support system was monitored using the following instruments (Fig. 3):

- 5 pairs of vibrating wire strain gauges on steel ribs (Fig. 3 "A");
- 3 pairs of vibrating wire strain gauges within the shotcrete lining (Fig. 3 "B");
- 3 pairs of vibrating wire strain gauges within the concrete invert arch (Fig. 3 "B");
- 3 electrical pressure cells in joints in the steel ribs (tangential pressure cells) (Fig. 3 "C");
- 3 electrical radial pressure cells between ribs and excavated rock (Fig. 3 "D");
- 2 loads cells below steel ribs (Fig. 3 "E");
- 3 hollow bolts specially instrumented with miniature multipoint extensometer (Fig. 3 "F").

These two sections were installed together, typically every 250-300 m, maximum 3.0 m from the face.

Considering the large number of instruments, automatic data acquisition system were used, whereby readings could be carried out frequently without interference with production.

Behaviour of rock ahead of the tunnel face was monitored using the following instruments:

- 9 reference nails cemented minimum 0.5 m in the rock
- one 15 m long incremental extensometer.

This section was installed typically every 300 m. Readings were taken daily during pauses in advance; reading of incremental extensometer were taken every 1.2 m of excavation thereafter.

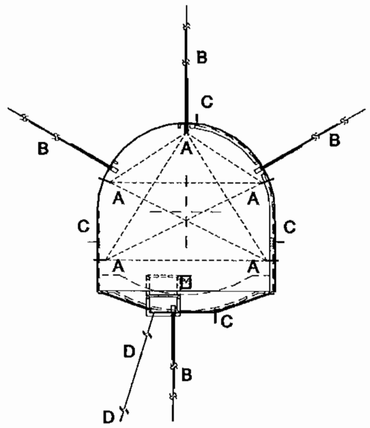

Fig. 2 – Scheme of the monitoring system for rock mass.
Fig. 2 – Schema di monitoraggio dell'ammasso roccioso.

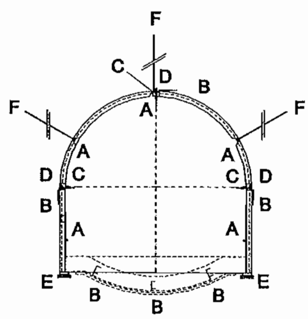

Fig. 3 – Scheme of monitoring for support system.
Fig. 3 – Schema di monitoraggio del sistema di sostegno.

6.4. *Typical results and scheme of interpretation*

The monitoring system described above permitted to control during and after construction the response of the excavated rock mass and of the support system.

Figure 4 shows typical convergence measurements. These results were interpreted daily and compared with the convergence in each representative section, as expected on the basis of preliminary numerical analysis. The comparison, which was done very rapidly by means of a predefined design procedure, led to changes to the support system during excavation.

Typical results obtained from measuring strain gauges on steel ribs instruments are shown in Figure 5, as an example of results obtained from instruments installed to monitor the behaviour of the support system.

These results were mainly used for back analyses, by using numerical methods, to verify the adopted constitutive law of the rock mass, to determine the stability conditions of the tunnel face, etc.

6.5. *Interference with excavation process*

Two types of interference with the excavation process were distinguished:
- interference due to installation
- interference due to readings.

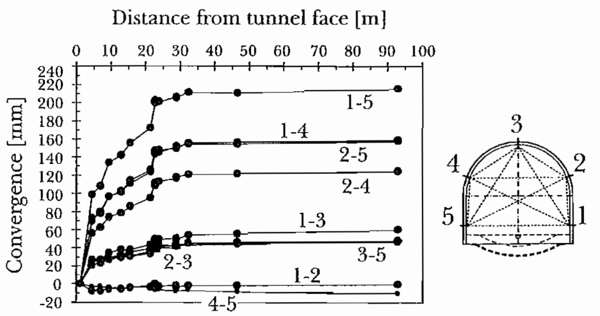

Fig. 4 – Typical convergence results.
Fig. 4 – Risultati tipici di monitoraggio delle convergenze.

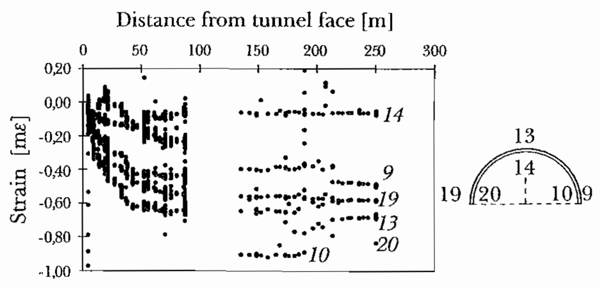

Fig. 5 – Typical strains measured on steel ribs.
Fig. 5 – Risultati tipici di misura delle deformazioni sulle centine.

For the instrumented sections for control of construction, installation interference was limited to between less than one hour and a couple of hours in the case that convergence nails were installed also on the steel ribs. Considering the high frequency suggested for this type of section, it appeared reasonable to introduce the installation in the weekly cycle. As far as the interference due to readings is concerned, each set took between half and one and a half hour, depending on the number of nails and the precision requested.

Installation of the instrumented sections for acquiring data on the behaviour of rock mass and support system required up to 4÷5 days, including all cabling. The suggested frequency of these instrumented sections required that installation was introduced as an additional operation every 3÷4 months. Readings did not interfere with the excavation process, thanks to full automation.

Installation of the incremental extensometer to monitor the reaction of the rock mass ahead the tunnel face required almost one day. Readings, which were manual, required almost one hour each 1.2 m advance. This gives the main interference with the excavation process for the working time of the instrument.

It must be pointed out that the above interference should be compared with the resulting benefits (optimisation of support system, construction safety, control of medium and long term safety level, etc.).

7. Conclusions

The main conclusions can be summarised as follows:
- the design of tunnels in squeezing rock conditions must include the design of the monitoring system as an integral part;
- systematic monitoring for control of construction must be "simple" and flexible; it must have high frequency and must be considered from the earliest planning stages as part of the production cycle;
- the interpretation procedure for systematic monitoring must be simple, predefined and directly relevant to confirming safety levels and support system design;
- confirmation of structural safety in medium and long term requires a complete understanding of the behaviour of rock mass and support system in time, which can only be achieved with a resilient data acquisition and data management system;
- data management and interpretation must be an integral part of the management of the project.

Sistemi di monitoraggio in galleria in presenza di condizioni spingenti

Sommario

La nota descrive obiettivi, condizionamenti e criteri di progettazione di sistemi di monitoraggio di gallerie in condizioni spingenti, sulla base di esperienze dirette. Il progetto del sistema di monitoraggio è una componente fondamentale del progetto della galleria, in particolare per gallerie profonde in ammassi rocciosi caratterizzati da grandi convergenze in corso di scavo. In questi casi il sistema di monitoraggio deve essere individuato in modo da consentire la verifica delle ipotesi progettuali e la determinazione dei carichi agenti sulle componenti stutturali del rivestimento di prima fase e del rivestimento finale, allo scopo di valutare in continuo le condizioni di sicurezza e l'adeguatezza del progetto. La nota illustra schematicamente l'applicazione dei principi descritti.