Geotechnical Design of Underground Infrastructure—Outlining the Observational Approach

Florian Krenn

Abstract Tunneling for infrastructure has got a long tradition, and has become more and more important in the last years in India. The topographical features of India—the Himalayas as the best example—and the growth of urban spaces make tunneling an important component in many infrastructure projects, thus putting geotechnics for underground works into a key role. Geotechnics for tunneling needs therefore to be approached in a comprehensive manner, from investigation, ground description, and subsequent design to the implementation. The observational approach is in the opinion of the author the first choice for economical geotechnical works, with different depths of application depending on the project boundary conditions and risk appreciation.

Keywords Tunneling · Observational approach · NATM · Risk management

1 Introduction

The economic development of countries is highly dependent on their infrastructure. Even in the information age, the transport of goods and persons is an inevitable prerequisite to get goods and services to the place where they are needed. It can be coined as infrastructure being the link between demand and supply. Any landbound means of transport has an inherent linear sphere of influence, whereas the shipping and air traffic are in principle pointwise connections, leading to concentration of people and goods in one place. The distribution from such points of concentration (harbors, airports) requires usually landbound, i.e., linear, means of transport.

Since landbound means land use and dependence on the landform configuration, it becomes inevitable to put infrastructure below the ground (tunnels) or above the ground (bridges). The main difference between tunnels and bridges as "artificial" structures for infrastructure—and infrastructure includes apart from rail and road-

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ways also cables, water ducts, sewage ducts, air ducts, etc.—is that bridges by nature have limited points of contact to the ground, whereas tunnels are inside the ground and that means full interdependence with all existing structures and the ground in all respects, as well as influence onto the structures above the tunnel.

1.1 Geotechnical Design for Tunneling

Tunneling happens within the ground—be it through mountains or be it below the surface of a busy city. The main requirement for successful and economical tunneling is to understand the ground. The ground which a tunnel is developed through is load and building material at the same time. This stipulation has the consequence that the behavior (in the engineering sense) of the ground has to be described.

"Describing" the ground comprises the following activities

- Developing a Geological Model, through field and desk studies
- Geotechnical investigations with the objective to get the material properties for certain loading conditions (tests) and to confirm and refine the initial geological model
- Development of a Model to describe the behavior of the ground due to tunneling
- Assessment of the impact of support measures onto the ground behavior, with the objective of ensuring the stability of the opening, and of the behavior ground and support (system behavior)

The description of the ground behavior is part of a proper geotechnical design for tunnels; however, it is not the end of the process but the beginning.

1.2 Risk Management in Tunneling

In a linear infrastructure project of several hundreds of meters to tenths of kilometers describing every meter in detail is difficult, it is even in many tunnel projects hard to investigate the ground conditions throughout the length as overburden, accessibility, and other constraints make geotechnical investigations very costly or simply impossible.

In urban surroundings, it is also not possible to investigate everywhere, and in many places undocumented utilities, geometric deviations from original drawings, forgotten voids, and ancient structures are only encountered when the tunnel drive hits them.

So all the hazards associated with unforeseen ground conditions are there, from inadequate support, face instability, material inflow, excessive settlement to collapse. Comprehensive investigations and surveys reduce the risk substantially, also a geotechnical design which takes into account several possible forms of ground behavior, still a residual risk remains and the same has to be mitigated and brought under control.

Apart from the classical approach to risk management—identification of the risk and then developing mitigation measures the observational approach to tunneling allows a further reduction of risk.

1.3 The Observational Approach in Tunneling

The observational approach requires the following steps in addition to the steps outlined in Fig. 1:

- Putting down the expected ground conditions together with the proposed support and the expected system behavior ("Prediction")
- Development of a procedure to observe the prognosis and the behavior of the system ("Monitoring")
- Defining of actions and measures in case the monitoring highlights deviations from the Prediction
- Monitoring the impact of the measures

1.4 The New Austrian Tunneling Method (NATM)

The name "New Austrian Tunneling Method" was coined 1962 by Prof. Ladislaus van Rabcewicz; with his patent (1948) he prepared the grounds for the observational approach in tunneling, and since then it has been successfully applied in many projects and many countries, also in India. However, in some projects, NATM becomes a catchword, and the actual implementation contains only elements of NATM. This is highlighted in brief to stimulate the discussion on the actual implementation of NATM.

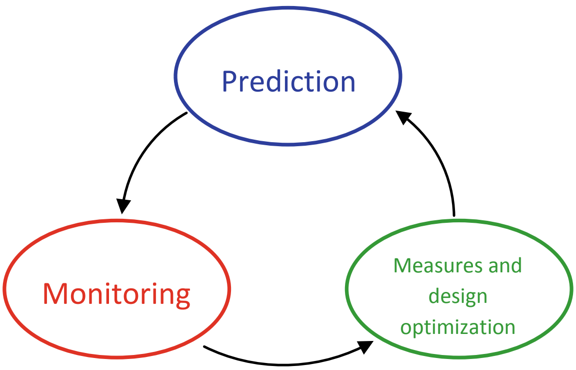


Fig. 1 Circular process of the observational approach

2 NATM—A Short Review on the Principles and the State of the Art

The "New Austrian Tunneling Method" or NATM has two peculiarities which are reflected in the name: on the one hand, it was developed mainly by Austrian engineers and miners, and this legacy is pointed out. On the other hand, the word "New"—to distinguish it from the so-called Austrian Tunneling Method, which was used up to the time the NATM came up.

Up to today, many engineers and tunneling experts worldwide have contributed to the progress of this approach to tunneling; however, the name remained NATM. NATM is employing the observational approach for tunneling and geotechnical monitoring is an integral part of NATM.

2.1 Historical Background

Prof. Rabcewicz filed a patent for a tunneling method which was based on a double concrete shell approach, where the inner (secondary) lining should be installed after the deformations have ceased. The (outer) primary lining should be installed quickly to avoid disintegration of the rock mass (loosening). The loosened rock mass is acting like a dead load onto the lining, a major shortcoming observed with the then traditional methods. Rabcewicz also proposed a waterproofing between primary and secondary lining. The point of time for installation of the inner lining should be determined based on monitoring results.

The combination of already existing materials like shotcrete (to prevent loosening of the ground) and rock bolts (now used in a systematic manner) made it possible to implement this tunneling method. The first application of a systematic support system consisting of rock bolts and shotcrete was successfully applied by Rabcewicz in 1956 in Venezuela. In 1962, Prof. Rabcewicz presented the new method during the Salzburg Colloquium and coined the name "New Austrian Tunneling Method." The breakthrough projects which were then executed were the Railway Tunnel in Schwaikheim (Germany, 1963–1965), the Massenbergtunnel in Leoben (Highway, Austria, 1964–1965). The international breakthrough of NATM came at the Tarbela project (Pakistan, 1968–1975), where the gate chambers were constructed according to NATM (Rabcewicz and Golser, 1974). The principles were successfully applied to shallow tunneling and tunneling with high overburden, and the method was adopted in other countries like Japan, India, Korea, etc. In India, the 11.2-km-long Pir Panjal (T80) railway tunnel, which is in operation since 2013, has been designed and constructed by applying NATM. The development of NATM has been dealt with in several publications (e.g. Schubert and Lauffer (2012), ITA-Austria (2012)).

2.2 Basic Principles of NATM

The following principles can be stated to be the basic principles of NATM:

- Prevent disintegration/detrimental loosening of the ground, thus keeping its strength
- Use the strength of the ground to take additional stresses resulting from the excavation
- Monitor the behavior of the system to observe stabilization process and allow for adjustments of construction measures to ground conditions

The following points need to be observed also:

- Rounded shapes to avoid stress concentrations
- Support shall ideally work as shell (support pressure to become normal forces in the lining)
- Only a closed cross section is a stiff cross section—ring closure must be obtained to activate the support pressure of the primary lining.

2.3 Further Developments and Current Status

The initial shortcomings of NATM were tackled by the tunneling community (mainly in Austria and neighboring states). Those shortcomings were the lack of accepted design rules, the missing specifications, the limited practice/training of miners, and the lack of appropriate contractual models. The quality assurance of the main support elements, rock bolts, and shotcrete had to be developed, and also the setup of the organization of a project had to be in line with the observational approach.

The issues of specifications, manpower training, and quality assurance in respect to shotcrete and rock bolts have been solved, also the contractual modalities in Austria have been brought in line, and the organizational setup was modified in a manner to take full advantage of the observational approach. Schubert (2008) outlines the development of the observational approach with emphasis on the geotechnical design.

The accepted design rules have been laid down in the "Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation" (current revision dates from 2010) which has been developed by the Austrian Society for Geomechanics.

Monitoring of the system support—ground is considered very important, and the improvement of the monitoring process by developing new monitoring and evaluation methods was actively supported by the Clients and the Contractors; since more than 20 years, the monitoring of absolute displacements by electronic total stations is the standard procedure.

3 Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation

The Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation (Austrian Society for Geomechanics 2010a, b) has been published to standardize *the ground characterization* and give a *coherent procedure for the determination of excavation and support during design and construction*.

The objectives of the guideline are given as the *economic optimization of the construction considering the ground conditions as well as safety, long-term stability, and environmental requirements*.

The variability of the geological boundary conditions requires that a *consistent and specific procedure* be used during the design process.

The ground conditions and ground behavior determine the geotechnical design and need to be assessed in depth. This requires the application of a project and ground specific procedure, and a strategy allowing a *consistent and coherent design procedure* that is *traceable throughout the entire project*, and an *optimal adjustment of the construction to the actual ground conditions* encountered on site.

The guideline shall help to follow a systematic procedure. All concepts, considerations, and decisions shall be recorded in a way, that a review of the decision making process is possible.

The basic procedure outlined in this guideline covers 7 steps for the first phase (design):

1. Determination of Ground Types
2. Determination of Ground Behavior and Assignment to Ground Behavior Types
3. Selection of construction concept
4. Assessment of system behavior in the excavation area
5. Detailed determination of the excavation and support method and evaluation
6. Geotechnical report-framework plan
7. Determination of excavation classes (for the tender)

The stepwise procedure allows to identify hazards and aims at risk mitigation by tackling the cause of the hazard or appropriate measures to reduce the impact of any identified hazard.

The determination of the Ground Behavior Types defines the most common failure modes in tunneling and helps to identify the "main hazard" for a specific section according to the boundary conditions coming from the rock mass parameters, the hydrogeological conditions, and the stress conditions (overburden).

The work flow during the design phase is shown in Fig. 2.

The Phase 1 (Design) ends with issuance of the tender documents. Once the project has been awarded, the site organization is set up, and the Phase 2 (Construction) starts. This phase is broken down to 4 steps, namely

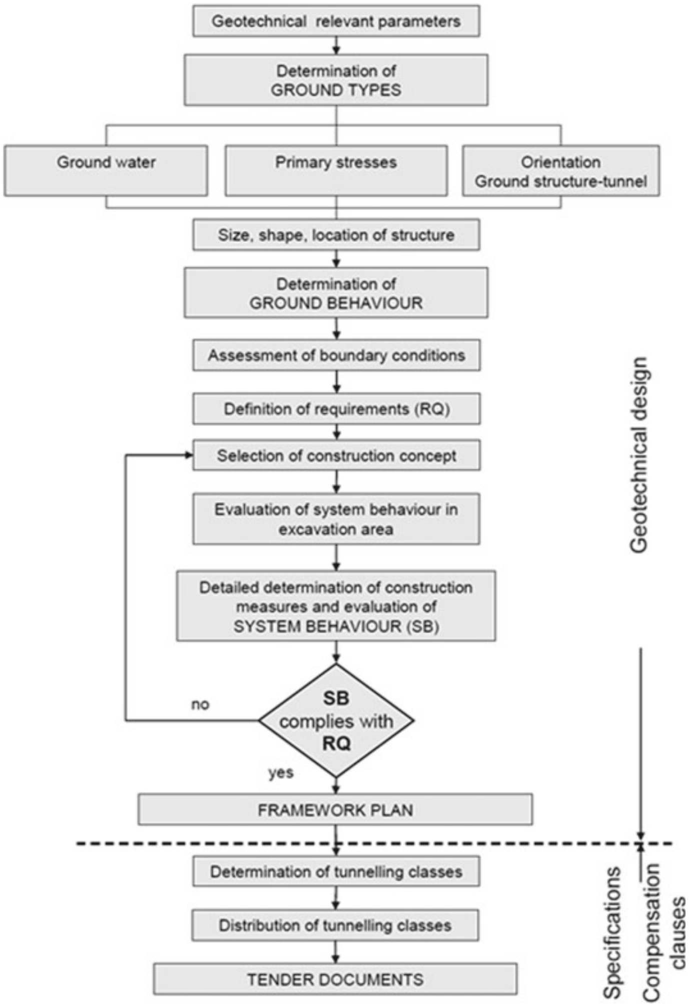


Fig. 2 Schematic procedure of the geomechanical design (Austrian Society for Geomechanics 2010a, b)

1. Determination of the encountered Ground Type and prediction of ground characteristics
2. Assessment of system behavior in excavation area
3. Determination of excavation and support measures and prediction of System
4. Verification of System Behavior

The associated work flow is shown in Fig. 3.

The most important point after the verification of the system behavior is the update of the design. As stated in the guideline, *Due to limited information*

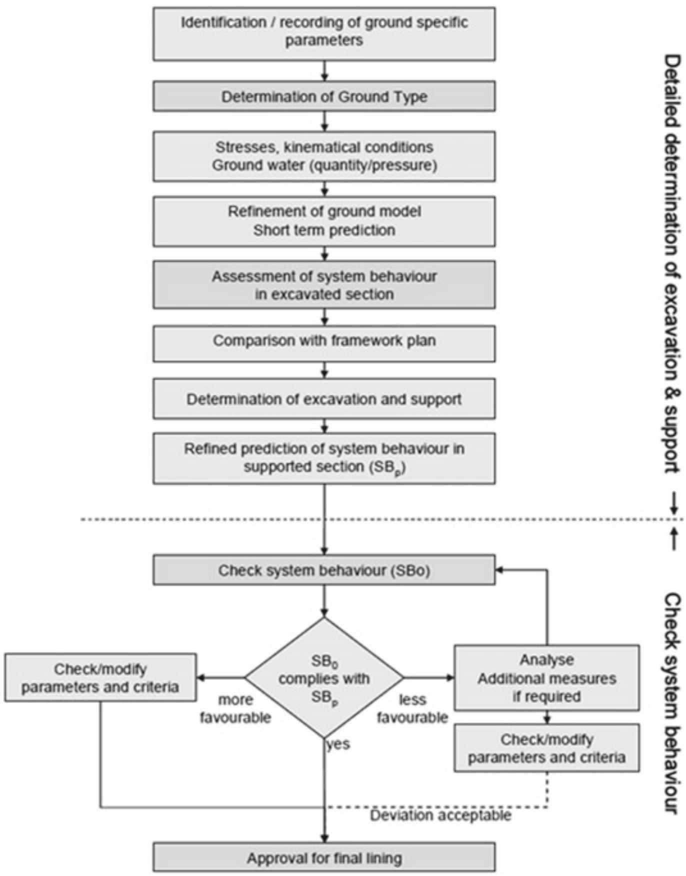


Fig. 3 Basic procedure of determination of construction measures and check of system behavior during construction (Austrian Society for Geomechanics 2010a, b)

available during design, the number of assumptions and simplified models has to be used to arrive at a design, which is the basis for the framework plan and the tender documents. To achieve the goal of a safe and economical construction, it is required to continuously update the geotechnical design with the increasing level of information.

This statement implies that the level of information is increasing during construction, and one means of getting information on the system behavior is regular geotechnical monitoring.

4 Monitoring and Risk Management

As outlined before, NATM has as central element the monitoring of the behavior of the system ground—support. Apart from being a tool for optimization the support system, the geotechnical monitoring is a valuable tool for risk management in tunneling.

The value of monitoring—not only the geotechnical monitoring of the system behavior—cannot be underestimated if and when the monitoring results are being analyzed, compared to the assumed conditions and behavior, and measures/actions are prepared.

Figure 4 shows the development of the level of risk in terms of point of time of recognition. The more promptly, precise, and systematic the monitoring cum analysis is done, the earlier deviations can be recognized and pro-actively mitigated/eliminated.

4.1 Geotechnical Monitoring in NATM

The application of NATM requires the development of a comprehensive geotechnical monitoring program, which is part of the daily operations and is one of the pillars of the geotechnical safety management.

The state of the art in (daily) monitoring is geodetic monitoring with precision bi-reflex targets and highly precise electronic total stations. Apart from the

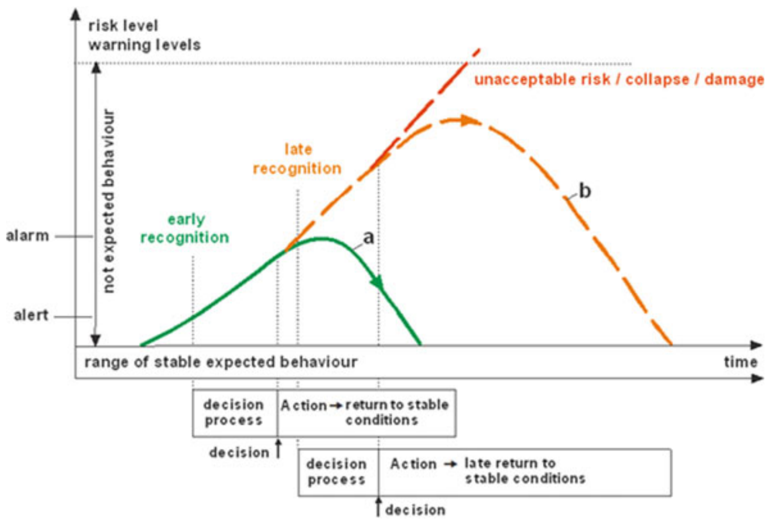


Fig. 4 Relation between risk level and point of recognition

displacement monitoring below and above ground, other instruments like extensometers, inclinometers, etc. are being monitored as per monitoring program, and the results are being reviewed daily.

It has to be added that it is good practice to review the face mappings (geological documentation) together with the monitoring results.

4.2 Overall Monitoring

It has to be pointed out here that "Monitoring" is not limited to Geotechnical Monitoring as it is understood by tunnel practitioners (displacement monitoring). Monitoring or better *Observations* can—and shall—cover the whole range of information and assumptions taken during the design, as well as other *observable* incidents.

E.g., the face mapping in Conventional Tunneling is a documentation tool, and many times it is used as the sole input for the support choice when support classes are linked to index values like RMR or Q. However, the procedure to compare the encountered rock mass vis-à-vis the information available at the design stage would be the proper implementation of the observational approach. The next step is the review of the monitored displacements for a certain rock mass against the values predicted in the design.

Also the observation of certain phenomena, e.g., sudden increase water ingress at a TBM face can be coined monitoring and needs to be introduced into a comprehensive risk management if it is regarded as a hazard or can be linked to one.

4.3 Monitoring Issues

Monitoring is an activity which is time critical when used for the observational approach, as decisions are made based on the monitoring results. It cannot be overemphasized that monitoring data which are not taken frequently and processed immediately for further interpretation will not be the information the engineer needs; they will be mere documentation.

The diagram shown in Fig. 4 is already defining the requirements:

- The time between data capture and results presentation must be as short as possible, to identify deviations from the predicted behavior as soon as possible.
- Once a deviation is recognized, the decision process must start
- The earlier measures are started, the more efficient they are
- Needless to say, the more choice of measures is there, the more accurate a deviation can be tackled

This all leads to the conclusion that on the one hand the possible ground behaviors (failure modes) need to be assessed in the design phase, and on the other hand, all the possible contingency measures need to be planned and must be ready for implementation on site. A measure which is proposed in the design but cannot be executed due to lack of preparation is useless.

5 Design Issues

It can be observed that in the design of infrastructure tunnels, some issues are of recurring nature, leading more than once to uneconomical and inappropriate designs.

The area of focus is around the description of the ground and subsequently, based on this description, the excavation and support design.

5.1 Ground Description

Describing the ground in Engineering terms, that is defining the model which formulates the behavior of the ground under different loading conditions, its reaction to stress changes, its strength under changed stress conditions and finally arriving at a "classification," is a challenging task. It is no surprise that the way ground is described has taken an evolution from the rock mass classification proposed by Terzaghi (1946), the introduction of the standup time as important criterium by Lauffer (1958), and the introduction of the Ground Behavior Types in the Guideline for Conventional Excavation by the Austrian Society for Geomechanics (2010a, b).

5.1.1 Index Classifications

For rock mass, several classification systems have been developed. All these classification systems take several geological, geometric, and design/engineering parameters or parameter ranges as input and give one index number as output. The most common rating/index approaches for tunneling are the Rock Mass Rating (RMR) introduced by Bieniawski (1973, modified 1989) and the Tunneling Quality Index Q proposed by Barton et al. (1974). The Geological Strength Index (GSI) was introduced by Hoek (1994) and Marinos et al. (2005) and is focusing on the engineering geological description of the rock mass.

The objective of all classification systems is to divide the rock mass along the alignment or in the project area into regions, which are separately classified and given one range of index values.

5.1.2 Procedure as Per Austrian Guideline (2010)

The Austrian Guideline (2010) gives the designer a structured process which first defines the ground types (geological formations with similar properties) and then overlays the ground types with the relevant boundary conditions as:

- Ground water regimen
- Initial stress state
- Orientation of the structures

Many of the mentioned boundary conditions are also considered in the before mentioned index values. The addition which is made now is to introduce the size, shape, and position of the planned structure and assess the stability of this structure without any support. This leads to the definition of the Behavior Types as shown in Table 1.

It is obvious that more effort will go into such a classification system, and that the description of the anticipated behavior including the range of displacements to be encountered is highly valuable for the observational approach; also the careful consideration of the probability of occurrence of each behavior type in a specific project already leads to more appropriate planning of contingency measures.

5.2 Choice of Excavation and Support

The ground description forms the basis of design of the excavation and support measures. As already outlined in the prior section, one approach is the direct linking of the support measures to the RMR or Q derived earlier. The other approach is to design the support measures including additional measures (e.g., pipe roofing) based on the behavior type.

Table 1 Categories of behavior types (OeGG 2010a, b)

Basic categories of behavior types (BT)	
1	Stable
2	Potential of discontinuity controlled block fall
3	Shallow failure
4	Voluminous stress induced failure
5	Rock burst
6	Buckling
7	Crown failure
8	Raveling ground
9	Flowing ground
10	Swelling ground
11	Ground with frequently changing deformation characteristics

5.2.1 Excavation and Support Design with Index Values

For the most commonly used classification systems, RMR and Q, correlations/guidelines have been developed to derive the appropriate support system as per index value. The definition of support classes for a project would flow out from the anticipated ranges of index values. Here it has to be mentioned that in these rock mass classification schemes different combinations of geological input parameters may result in the same value, and this might be misleading.

The Q system requires, apart from the Q-value derived from RQD and joint data, the so-called Equivalent Dimension which is the span or height of the structure over the excavation support ratio (ESR). The values for ESR are suggested by Barton et al. (1974), so the span remains as variable factor.

For the RMR system, Bieniawski (1989) gave guidelines for excavation and support of 10-m span horseshoe shaped rock tunnels, as per RMR value.

In both cases, a system as complex as excavation and support of a tunnel is based on one index value, which may not be appropriate at all. The Q system allows to consider the influence of the span, but there is no consideration of the shape of the structure, whereas the RMR system has predefined the shape and the span of the structure for its support guideline.

None of the index values—RMR or Q—allow/propose an estimate of the anticipated deformations/displacements, which is a shortcoming when the design needs to be verified by means of Geotechnical Monitoring.

5.2.2 Excavation and Support Design According to the Austrian Guideline (2010)

The analysis of excavation and support is based upon the behavior types defined earlier. This implies that the order of magnitude of deformations (unsupported structure) has been analyzed before, as well as the proposed cross section—shape and size (span). The support design is done with the objective to reach the requirements for the structure—support and ground. The requirements are depending on the project and may range from maintaining a defined factor of safety for the support to restricting the deformations to maintain the strength of the ground (e.g. in shallow tunneling).

The interaction between the ground and the support system is being analyzed, and the results are reviewed against the requirements. Once the requirements are met for a specific behavior type, an excavation and support class can be formalized. Apart from the geological boundary conditions also the anticipated range of displacements is part of the design and is a key parameter for the observation/monitoring during design.

5.3 Design of Contingencies

The application of an observational approach calls for a plan of contingency actions if the monitoring reveals behavior outside the acceptable limits.

One inherent contingency is that in case the ground changes, the excavation and support scheme may change. This is true for any design based upon classification systems (RMR, Q) as well as the design as per the Austrian Guideline (2010). Once the index range/behavior type has been covered in the initial excavation and support design, it can be implemented when needed.

The design of further contingencies requires to leave the framework of a classification system and directly model the anticipated risk/failure mode. The particular design risk is that originally the ground has been described in terms of a value only, which is not reflecting the actual situation in totality and might lead to wrong design assumptions for special support situations. This needs to be overcome by employing a comprehensive design approach for contingencies and employ more refined models than (single) index value rock mass classification schemes.

6 Implementation and Update of the Design

Once the design is being implemented, the validation and feedback process is started for an observational approach. Here we can identify the major difference between any design which is relying on a rock mass classification system only and the observational approach: within the chosen rock mass classification scheme, the face mapping is taken and the respective RMR or Q-value is being assessed. Based upon the calculated value, the support measures will be defined and implemented. In the observational approach, the similar procedure is applied, but in addition the geotechnical monitoring results are also taken into account on a daily basis. This way also mid-term and long-term stability issues can be identified and tackled, before the support develops overloading phenomena or even local failures occur.

Since the displacement measurements are connected to the geological conditions, the design assumptions are verified constantly and in case of systematic deviations the design assumptions can be reworked.

6.1 Monitoring Program

One of the key elements of the observational approach is the implementation of a comprehensive monitoring program. As discussed earlier, the time between taking the reading and getting the results must be as short as possible. In case of tunneling and the optical displacement monitoring employed there as standard procedure, this means that the time to take the readings should be as short as possible (electronic data acquisition is a must), and the time to process the data to get the information must be kept as short as possible through automated data transfer and processing through appropriate software.

The state of the art is to have electronic total stations which connect directly to a geotechnical monitoring software which automatically stores the data, processes the same, and produces immediately diagrams for further use by the geotechnical/tunneling engineer.

In order to be able to interpret the data correctly, the construction activities around the monitoring sections needs to be plotted also.

7 General Implementation Issues

It has to be stated that with the most sophisticated design tools, and most advances construction materials, the Quality Assurance and Quality Control still remains paramount. It becomes even more important as with a more accurate modeling inherent factors of safety are reducing and a deviation from the design assumptions may prove fatal. At the same time, the observational approach helps to identify shortcomings in the models used for the design and improve the models to guarantee the required factors of safety.

8 Case Study

In order to show the advantages of the observational approach one case study will be given. It is an underground cavern project which was executed between 1998 and 2004.

8.1 Project Outline

The CERN LHC (Large Hadron Collider) project comprised apart from a complete exchange of the accelerator to supra conducting magnets the construction of new caverns for the ATLAS and CMS experiments. GIBB-SGI-GC JV was awarded the contract for the civil engineering consultancy services for the new Large Hadron Collider LHC, Package 02 in CERN, comprising the caverns and facilities for the CMS experiment.

The caverns UXC 55, with a height of 33 m and a width of 27 m, and USC 55 (height of 16 m and a width of 19 m) are the main underground structures which were excavated in the overconsolidated ground (see Fig. 5).

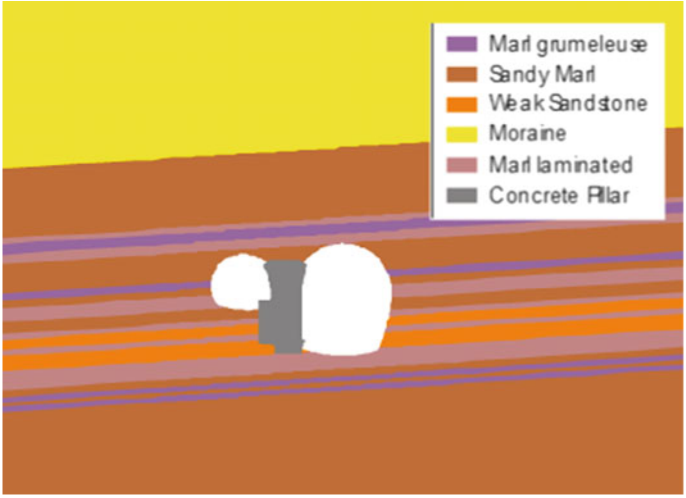


Fig. 5 Geological model—UXC55 and USC55 caverns

8.2 Construction Stages and Monitoring

The construction of the caverns happens in the following stages:

1. Excavation of the pillar between the two caverns
2. Backfilling of the pillar with concrete
3. Excavation of the caverns
4. Inner lining/water proofing and concrete works

During the excavation of the pillar in 2000 and 2001, the ground showed time-dependent behavior which was clearly monitored during a stop of excavation works due to a strike.

The monitoring data shown in Fig. 6 triggered a design review process in June 2001, as this behavior was not anticipated in the design.

8.3 Design Review and Model Calibration

The design review process started with runs to simulate the pillar excavation—as there were geotechnical monitoring data available. These back calculations were used to choose the material model employed and to establish the parameters by calibration against the monitored displacements. This task was concluded, and two parameter sets were chosen for the further design—the most probable behavior ("black line") and the worst probable behavior ("red line") as shown in Fig. 7.

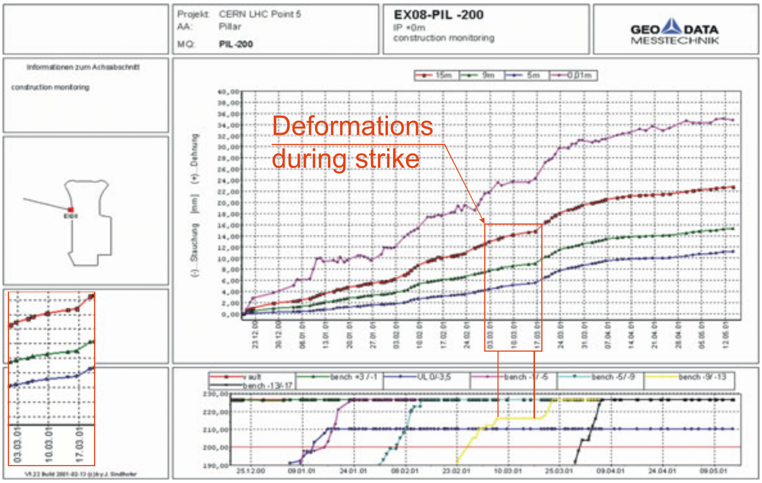


Fig. 6 Monitoring data—pillar excavation

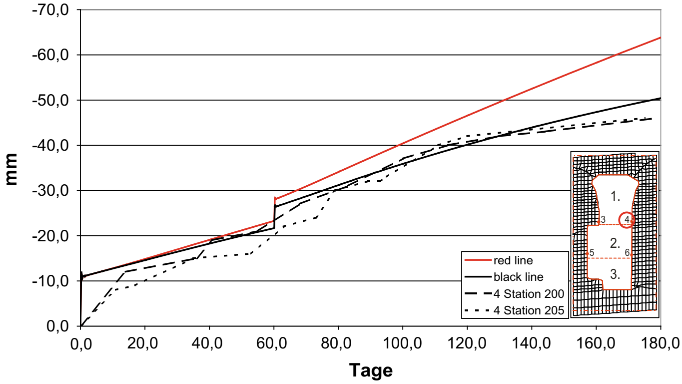


Fig. 7 Calibration results from pillar excavation

On the basis of the two parameter sets, the primary support was reviewed and subsequently re-designed. The initial support design was done for the most probable case, with clearly defined procedure of support increase in case the monitored behavior turning toward the "red line" prediction.

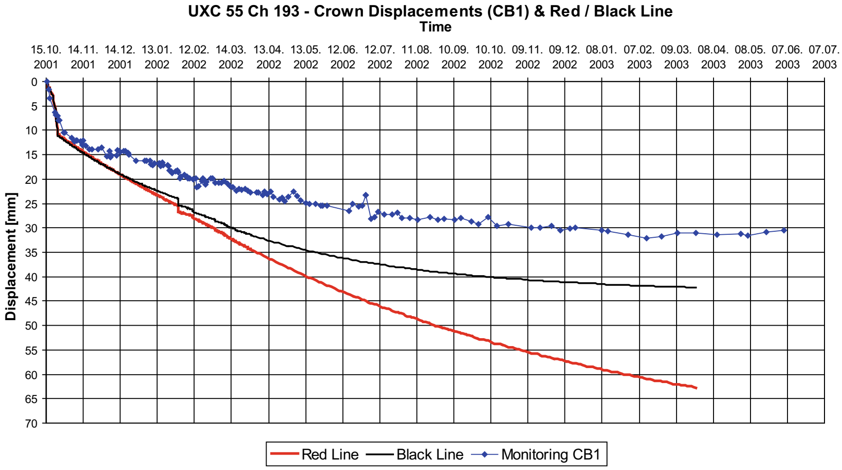
At the same time, the structural team prepared its estimates for the inner lining which under the given loading can fulfill the specifications and requirements, with the provision to take the most appropriate design after having reviewed the monitoring data after the excavation has been completed.

8.4 Monitoring Results—Cavern Excavations

The monitoring during construction showed that the most probable parameter set was the most appropriate choice as shown in Fig. 8.

The structural design of the inner lining was then continued and concluded, as were the other construction works.

The last CMS detector piece was lowered into the UXC55 cavern in 2008, and the LHC project was inaugurated on 10 October 2008.



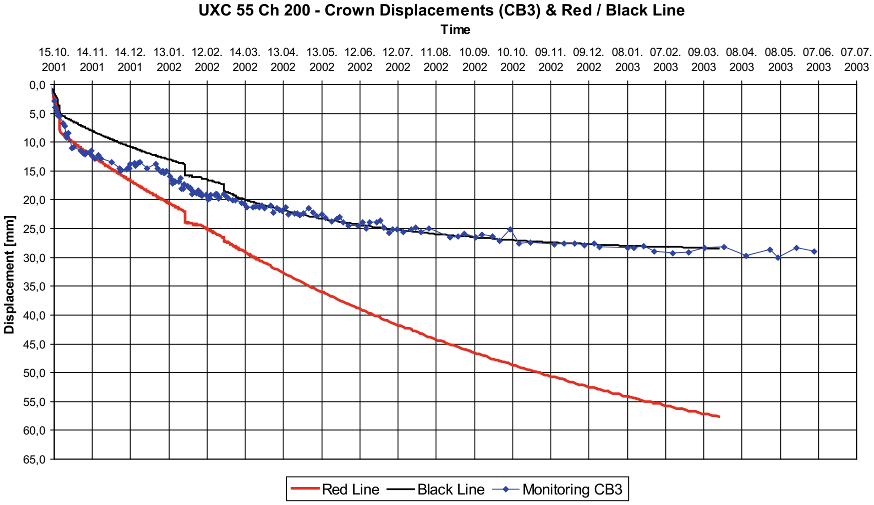


Fig. 8 Monitoring data and predictions for selected cavern displacement points

9 Conclusions

A brief overview over the observational approach and the New Austrian Tunneling Method (NATM) with specific emphasis on the Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation (2010) was given. Some shortcomings which may arise in the application of Rock Classification schemes, namely RMR and Q, were highlighted and in parallel the procedure with an observational approach outlined.

Finally a case study of a cavern project is given, showing the advantages of the observational approach.

This paper shall stimulate the discussion and encourage the implementation of the observational approach, and the author is grateful to have been invited to give his views on the subject.

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