The Development of the Observational Method

Die Beobachtungsmethode einst und jetzt

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Abstract. A continuous observation during construction always has been an important element of geotechnical engineering for minimizing risks. The reasons are the uncertainties in the geological and geotechnical models, as well as the limited capability to sufficiently accurately describe the complex ground behaviour. In the early days design of geotechnical structures thus was mainly based on experience. As usual, experience was used to develop mathematical solutions to the problem. To account for the inherent scatter of parameters and uncertainties in the models, the assumptions made during design had and have to be verified or falsified during construction by observations. For safe and economical construction, the design has to be adjusted during construction to the actual conditions. The term "observational method" was first formally introduced by Peck and Terzaghi. The original ideas behind the method have not always been understood or followed.
The paper, after a brief historical review of the observational method shows the current status of the method is critically reviewed, and further developments discussed.

Kurzfassung. Die Schwierigkeit, den Baugrund ausreichend zu erkunden und dessen Interaktion mit dem Bauwerk zutreffend mathematisch zu modellieren erfordert die laufende Beobachtung während des Baues, um die Baumaßnahmen an die tatsächlichen Verhältnisse anzupassen und das Risiko vermindern zu können.
Mit vermehrter Erfahrung wurden auch Analysemodelle entwickelt. Zur Berücksichtigung der unvermeidlichen Streuung der Baugrundeigenschaften und der Unsicherheiten in den Modellen wurden und werden während des Baues Beobachtungen durchgeführt. Die Bezeichnung „Beobachtungsmethode" wurde formal von Peck und Terzaghi eingeführt. Die damals formulierten Grundsätze wurden nicht immer verstanden und befolgt.
Im Beitrag wird nach einem kurzen historischen Rückblick über Entstehung und Entwicklung der Methode der derzeitige Stand kritisch beleuchtet, und weitere Entwicklungen diskutiert.

Introduction

When designing a geotechnical structure, one has to deal with a number of uncertainties, the complex behaviour of ground, as well as the ground support interaction, and a large spread of properties. In addition simplifications in our models used for design add further uncertainties. With an excellent investigation programme, advanced testing and ground characterization methods, and the use of appropriate design tools, the uncertainties and the risk associated with the uncertainties can be reduced, but never completely eliminated. For safe and economical construction, an adjustment of the construction method to the in-situ conditions and behaviour is common practice. Investigation, testing, modelling, and monitoring techniques have been significantly improved over the last decades, making it easier to more realistically assess ground behaviour and ground support interaction. Still considerable uncertainties remain, requiring a consistent approach throughout the whole development and construction of a project.

Historical review

Besides empirical assessment of the ground behaviour, observation long has been the most important task in determining the stability of a structure and for choosing appropriate measures. In the past observation was restricted to visual inspection of the ground, failure mechanisms and ground loads on the supports. Due to the limited possibilities of exploration with higher overburden, it was quite common to construct a pilot tunnel. In this exploratory tunnel, observations on the behaviour served as an additional input for the choice of the construction method and determination of lining type and thickness. Bierbaumer (1) for example used the deformation of the cross beams as a measure for the rock load, which again served as an input for the determination of the support. More and more the need for quantitative determination of behaviours arose. An early measurement system for tunnel deformations was introduced by Rabcewicz (2). The position of the central post was determined by a surveying instrument, thus allowing to record absolute displacements of the marked measuring points. The information obtained on the behaviour of the pilot tunnel allowed a more precise design of the required final lining. Rabcewicz was convinced that observations eventually would form the basis for theoretical considerations. He also used the observations for the determination of the type of loading on supports, where he distinguished between loads caused by loosening, "real" ground pressure, caused by overstressing of the ground, and swelling pressure. Based on the type of ground and load, Rabcewicz recommended support types (2).
At those times it was quite common to base tunnel design on expected behaviour.

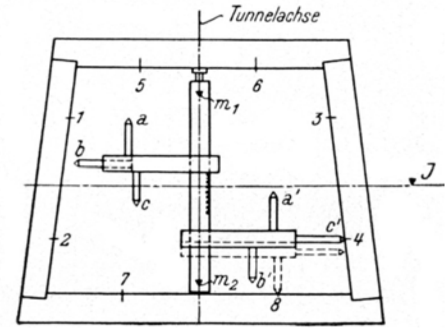

Figure 1 Device for measuring displacements of a pilot tunnel in the nineteen forties (from 2)
Bild 1. Vorrichtung zur Deformationsmessung im Pilotstollen um 1944 (aus 2)

The credits for developing the rather informal way of using observation for design of geotechnical structures into a method deserve Terzaghi and Peck (3,4). Peck (4) quotes a draft from Terzaghi for their book: *"In the engineering for such works as large foundations, tunnels, cuts, or earth dams, a vast amount of effort and labor goes into securing only roughly approximate values for the physical constants that appear in the equations. Many variables, such as the degree of continuity of important strata or the pressure conditions in the water contained in the soils, remain unknown. Therefore, the results of computations are not more than working hypotheses, subject to confirmation or modification during construction."*

Reviewing the method in 1969, Peck (4) writes: *"In brief the complete application of the method embodies the following ingredients.*

(a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
(b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.

(c) Establishment of the design based on the working hypothesis of behaviour anticipated under the most probable conditions.
(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
(e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
(f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
(g) Measurement of quantities to be observed and evaluation of actual conditions.
(h) Modification of design to suit actual conditions."

Peck also states that for a successful application of the observational method the setup of a project must be in a way that the design can be modified during construction. He also warns to adopt an approach of "wait and see" by stating: *"Potentially the most serious blunder in applying the observational method is the failure to select in advance appropriate courses of action for all foreseeable deviations of the real conditions, as disclosed by the observations, from the assumed in the design. If the engineer suddenly realizes that the observations show the job to be heading for trouble against he has no defense, he must reach crucial conditions under the pressures of the moment."*

With the evolution of modern tunnel construction methods, observation of the system behaviour soon became an important tool for the final determination of excavation and support methods. With the introduction of rock bolts and shotcrete, the loosening of the ground could now much better be controlled. As a consequence, also the traditional design methods considering dead loads on the linings had to be abandoned. Observations had to replace calculations to prove the stabilization process until more appropriate design methods were developed. It was hoped, that the systematic observation of the system behavior would eventually lead to design methods reflecting the experience gained with the new construction methods. In the nineteen sixties and seventies a wide range of measurement methods was developed, including convergence measurements, extensometers and stress cells. One of the pioneering companies in measurement and testing techniques was Interfels, founded in 1961 by L. Müller and colleagues. Test galleries have been built to observe their behaviour and form the basis for designs (5).
In particular the proponents of the NATM always have emphasized the importance of measurements to capture the complex properties of the ground and the ground support interaction (for example: 6, 7). On many projects the monitoring results are merely used to check whether the stabilization progress is as expected. Commonly displacements are plotted versus time and checked visually. "Normal" stabilization is assumed, when the displacement rate decreases with time. This hold true for a constant advance rate, but not for discontinuous advance. In such a case a judgment on the normality of the displacement development becomes rather difficult. The same applies for cases, where the effects of several excavation phases overlap. With the introduction of measurement of absolute displacements in the nineteen eighties, the ground support interaction could be captured much better than with the traditional relative displacement measurement methods.
Parallel to the improvement of surveying techniques, also the evaluations of the measured data and their graphical representation have been improved. The acquired data also allow a good assessment of the influence of the ground structure on the behaviour, and prediction of the ground quality ahead of the face (8).
Sulem et al. in the nineteen eighties have developed an empirical relationship, which very well describes the face advance and time dependent effects on the deformation development

(9, 10). This formulation has been extended by Barlow (11) and Sellner (12). Sellner developed software (GeoFit®), which allows the consideration of sequential excavation and different types of support.
With the development of numerical simulation methods from the nineteen seventies on, the hope increased that realistic tunnel designs would become possible. Quite some effort was and is still spent on developing codes and constitutive models. These efforts are practically limited by our insufficient ability to correctly and precisely determine the mechanical ground parameters and still widely unknown (or ignored) limits of simplification when using the different numerical approaches and constitutive models.
A rather unfortunate development for the industry was the widespread use of the so called classification systems, which reduce the information obtained during the investigation to a single number. No reference is made to potential failure modes, which should govern the design of excavation and support. Palmstrom and Stille (13) note: *"As already discussed, different types of analysis are appropriate for an intact rock, a blocky rock mass, or a crushed and heavily broken rock mass, as the behaviour of the excavation in each will be fundamentally different. Neither the Q system nor the RMR system gives any information on how the rock mass behaviour was considered in making their rock support recommendations. The classification systems available today were developed to cover the issue of structural resistance, which is only one of the design issues to be accounted for in the design. It is obvious that they do not take into consideration all the project related issues being required by most modern building codes, and they do not allow the user to quantify the degree of safety achieved by the design."*
The traditional Austrian way of classifying the ground according the behaviour during excavation (14) required ground characterization during design and predicting the behaviour of the ground support system. As this system implies a certain excavation and support method, project specific definitions and adjustments were required. In addition the classes were not too well defined, in particular the interaction with the construction measures made it difficult to determine classes in an unbiased way.

Present status

It is widely accepted that complete knowledge of the ground and its properties can never be obtained prior to construction. Consequently at least for complex ground conditions and tunnels with high overburden, observational methods are a must. The question now is: do we follow the basic idea of the observational method with the required sincerity?
Very seldom the principles of the observational approach, as formulated by Peck have been followed in tunnel design. The characterization of the ground yielded distinct "design parameters", which were and are used to make a deterministic design. Very rarely is the probable spread of parameters considered to asses the range of likely behaviours. For simple conditions, occasionally the Random Set Method is applied to consider the influence of the spread of parameters on the deformations of the system (15).
A very important task in each geotechnical design is the choice of appropriate design tools in relation to the ground conditions and expected behaviours. It appears that models are rather chosen on criteria of availability, than suitability to the problem. The following figure shall demonstrate the differences in results for very simple geological conditions when using different tools for the analysis. Rock mass with one joint set was chosen for the example, the strike of the joints is parallel to the tunnel axis, and dips with 60°. In the left model the joints were modelled discretely, while for the model in the center a ubiquitous joint model was used. At least qualitatively the two models show similar results. The model right considers continuous material; the joints have been "smeared" using common upscaling procedures. It6 can be easily seen that this model does not reflect the influence of the joints. Basing a design

on such a model would definitely lead to unrealistic results. One can easily imagine how the differences in the results would be for more complex geotechnical situations.

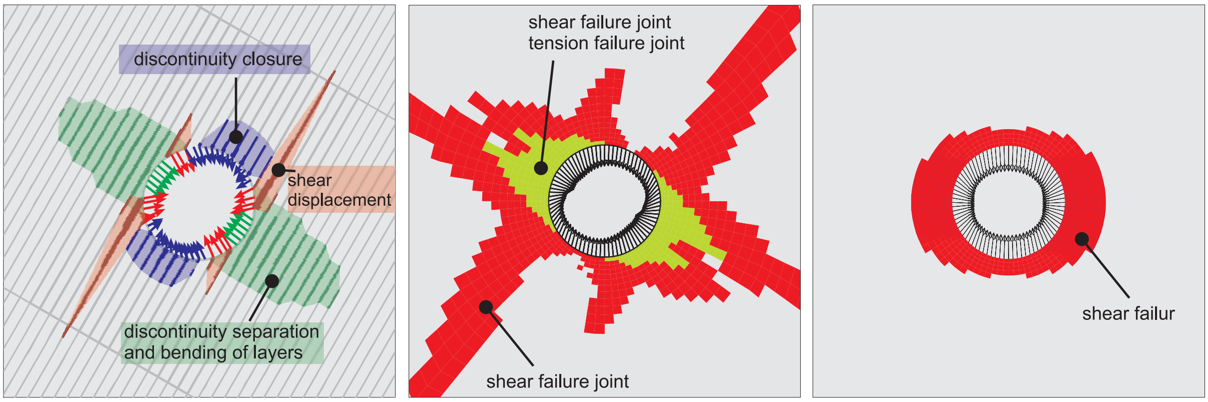

Figure 2. Comparison of numerical simulations of a tunnel in jointed rock mass with different models. Left distinct modelling of joints, center ubiquitous joint model, right continuum model
Bild 2. Simulation eines Tunnels in geklüftetem Gebirge. Links diskrete Modellierung der Trennflächen, Mitte Ubiquitous joint model, rechts Kontinuumsmodell

It can be observed that the original ideas of the observational approach to tunnelling experience a revival. For example, Eurocode 7 states that an observational approach and a review of the design during construction is appropriate, when the prediction of geotechnical behaviour is difficult (16). Following requirements are prescribed for the application of the observational approach:

- acceptable limits of behaviour 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 taken 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.
- During construction, the monitoring shall be carried out as planned.
- The result of monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put into operation if the limits of behaviour are exceeded.
- Monitoring equipment shall either be replaced or extended if it fails to supply reliable data of appropriate type or in sufficient quality.

The message of the Eurocode is quite clear: the observational method must not be mistaken with a “design as you go” approach, but needs careful preparation to be successful. However, no definition of behaviour is provided and no details are given on how to arrive at behaviours. It can be assumed that the term behaviour refers to the combined behaviour of the ground and the support.

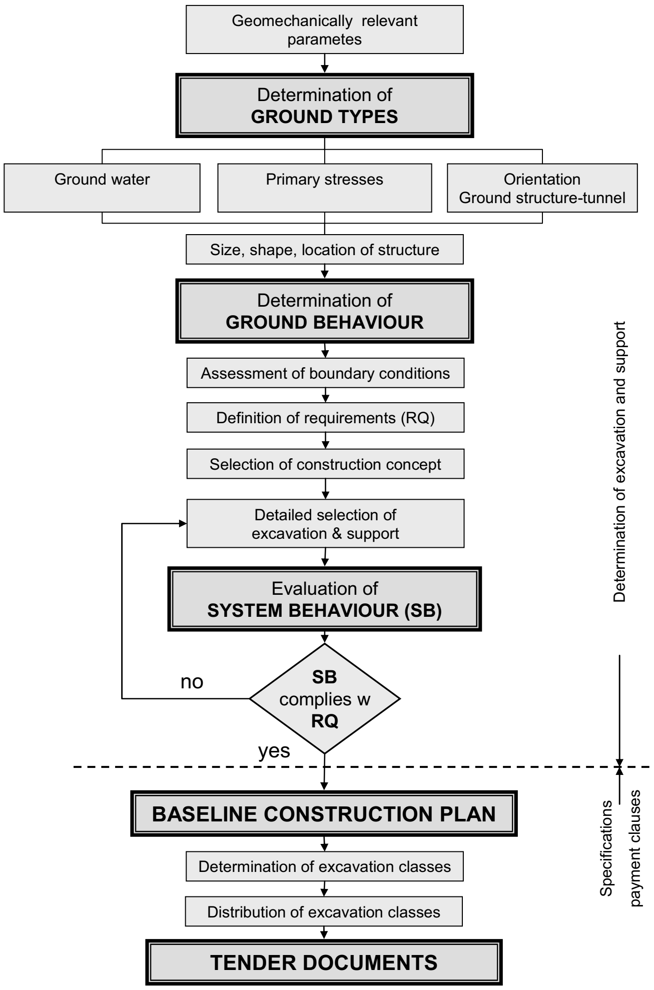

Figure 3. Flow chart of the geotechnical design according to the Austrian guideline (17)
Bild 3. Flussdiagramm des Planungsablaufes nach österreichischer Planungsrichtlinie (17)

More precise definitions are given in a guideline of the Austrian Society of Geomechanics (17). Ground behaviour in this guideline is defined as the reaction of the ground to the excavation in full profile, without consideration of supports or divisions of the face. The focus in this step is put on identification of potential failure modes. Only after the ground behaviour has been assessed, a construction concept is chosen and the system behaviour evaluated (Figure 3). The system behaviour is checked against the project specific requirements, and if necessary the construction measures modified until agreement is reached. Detailed description of the system behaviour is required, which during construction can be compared to the observed behaviour. A continuous updating of the geological and ground models is integral part of the procedure.
A similar approach is proposed by Stille and Palmstrom (18), who also stress the importance of assessing the ground behaviour as a basis for the selection of excavation and support methods (Figure 4).

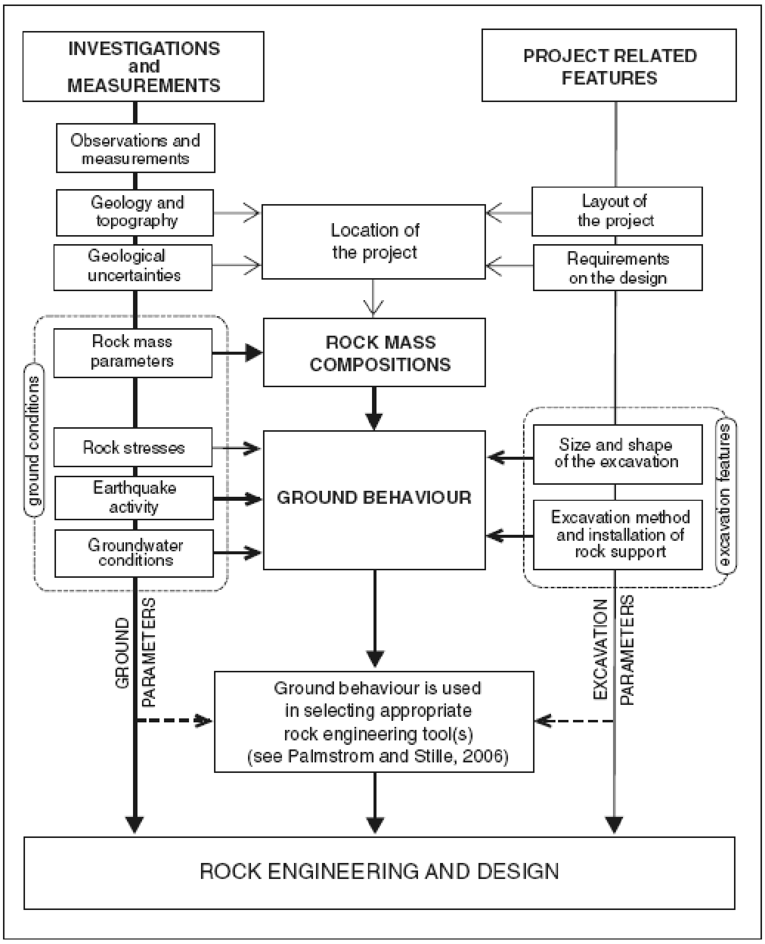

Figure 4. Principle design process as described by Stille and Palmstrom (18)
Bild 4. Grundsätzlicher Planungsablauf nach Stille und Palmstrom (18)

Following the procedures described above basically the stage is set for a successful application of an observational approach. The ground conditions and their spread has been evaluated, the expected behaviours in relation to ground conditions, influencing factors and construction method analysed. A responsible approach also includes the assessment of the reliability of the applied design with respect to expected variations in ground conditions. Monitoring and data evaluation methods dramatically have improved over the last decades. Not only can monitoring results be collected and processed quickly and efficiently, but the results can be made available also to experts around the world practically in real time. Up to date software can provide information on the utilization of the shotcrete by using the measured displacements and advanced material models (19). The use of trends of displacement vector orientations for the prediction of ground quality ahead of the face has become standard on many sites. To optimally use the acquired data, an automation of the evaluation process is currently under development (20). The idea is to use site data and results of simulations to establish an expert system, which will support the engineers on site in "reading" the results. In addition, valuable time can be saved in case of unfavourable developments of the system.

Required actions

As it is quite clear that we will never be in the position to accurately describe and model the ground and the ground structure interaction, the observational approach will be required also in future. Quite some progress has been made in the investigation, testing, modelling, and

monitoring methods. However there is still a wide field for improvement to obtain the goals of safe, economical, and sustainable structures.
The main fields of required improvements can be listed as follows:

- Improvements in the ground characterization process. Overly simplified approaches need to be replaced by more realistic technical descriptions of the ground properties
- Further development of modelling methods to realistically capture ground and system behaviours
- Develop rules for the selection of appropriate design tools. Too often wrong tools are used, simply because the user is familiar with one tool only, and clear rules are missing.
- Description of ground and system behaviours, as well as specification of acceptable limits
- Intensify the use of probabilistic methods for the consideration of natural spread of the parameters and uncertainties in the models, and checking of reliability of the design
- Establishment of realistic and meaningful safety management plans
- Use of the potential of modern monitoring and data evaluation methods
- Better use of experience gained during construction for improving the models and enhancing the understanding of geotechnical problems

Conclusion

Under the pressure of new standards (e.g. Eurocode, etc.) and the insurance industry, the design and construction processes have to be improved. There is a strong need for research in the field of ground characterisation, and for further developing analysis tools to describe the complexity of the ground conditions better. An increase of the reliability of the design and the correctness of the decisions during construction will only be possible if the models are calibrated with observations.
It seems that the awareness is again increasing that geological and ground models contain uncertainties, which require an adjustment of the design during construction. It also seems that the era of oversimplification of the ground characteristics and the models used for design is coming to an end. Gradually it is recognized that “shortcuts” in the design process for the selection of tunnel supports lead to a lack of understanding of the mechanical processes, making it extremely difficult to take appropriate contingency measures on site.
The tools required for a successful application of the observational approach, both for design and for construction basically are available.
To be successful, it is required to abandon the nearly “religious” preference for certain design and tunnelling methods. Rather the community should seek ways to combine available methods and tools and further develop them.

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