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Reliability aspects of rock tunnel design with the observational method

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A B S T R A C T

According to Eurocode 7, two accepted approaches for managing uncertainty in tunnel design are reliability-based methods and the observational method. Reliability-based methods account for uncertainty by acknowledging the random variation of the input parameters; the observational method does this by verifying the expected behavior from an initial design during the course of construction. However, in the framework of the observational method, as defined in Eurocode 7, no guidance is given on the selection of suitable parameters for observation and how they can be linked to the limits of acceptable behavior and, at a sufficiently early stage, the decision for implementing contingency actions. Furthermore, no guidance is given on how to verify that the structure fulfills society's required safety level. In this paper, we present a design procedure for shotcrete-supported rock tunnels that combines reliability-based methods with the observational method. The design procedure applies a deformation-based limit state function for the shotcrete support that is based on the convergence–confinement method. We suggest how the requirements in the observational method, as defined in Eurocode 7, may be satisfied for this application. In particular, we focus on the structural reliability aspects. The structural reliability of the preliminary design is assessed with Monte Carlo simulations by calculating the expected deformations of the tunnel. The appropriateness of the preliminary design is then verified by observing the actual deformations during the course of construction. The observed deformations are used to predict the future behavior of the tunnel and to update the assessed probability of unsatisfactory behavior. If the defined deformation-based alarm limit regarding the structural reliability is exceeded, predefined contingency actions are put into operation. The procedure is illustrated with a shotcrete-lined circular rock tunnel and practical aspects in satisfying the reliability requirements with the observational method are discussed.

1. Introduction

Design and construction of underground excavations in rock involve large uncertainties that can be accounted for using a number of different design methods. Such uncertainties should in countries within the European union be accounted for in accordance with Eurocode 7,[1] though it should be pointed out that the current version of Eurocode 7[1] does not explicitly cover rock tunnels. However, future revisions might and, if so, it is important that the proposed limit state verification methods are applicable. A common limit state verification method in Eurocode 7[1] is design by calculation in combination with an adjusted version of the partial factor method. However, as in all geotechnical engineering works, tunnel engineering implies working in conditions with large uncertainties that are mainly epistemic (i.e. uncertainties that are due to a lack of knowledge, as opposed to aleatory uncertainties, which are uncertainties due to the inherent variability). In addition, in some failure modes, the load is inseparable from the resistance; in others, the load–resistance relationship significantly varies depending on the geometry of the problem. Therefore, the Eurocode's version of the partial factor method is difficult to apply, as discussed by e.g. Bjureland et al.[2]

In addition to the partial factor method, another accepted set of methods in Eurocode 7[1] that accounts for uncertainties is reliability-based methods. In the code, no specific reliability-based design method is advocated; instead, the engineer is allowed to choose an appropriate method as long as the final structure fulfills the requirements of safety against failure.[3] The applicability of different reliability-based methods for design of tunnels has been discussed by a number of authors.[4–18] However, because of the large epistemic uncertainties present in design of tunnels, the behavior of the analyzed structural system should preferably be observed and compared with the initial assessment.[19] Therefore, another important design method accepted in Eurocode 7[1] is the observational method.

The observational method originates from work performed in the

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mid-20th century by Terzaghi and Peck[20]. It has since then been acknowledged as a valuable design methodology that is applicable to a variety of different geotechnical engineering problems; e.g. 13,14,21–34. Essentially, the observational method accounts for uncertainties through observing parameters critical to the decision of putting contingency actions into operation if the behavior of the structure is unsatisfactory. When applying the observational method in tunnel engineering, the actual behavior of the structure must be monitored. For tunnels, monitoring deformations is appreciative, primarily because deformation is an indirect measure of the stress state in the rock mass. It is also one of the most commonly observed parameters.[35] But instead of only reacting to observed deformations, it would be even more attractive to use observed deformations to predict the future behavior of the tunnel during construction. This will give the engineer time to implement the prepared contingency actions at a sufficiently early stage if exceedance of the defined limits is anticipated.

However, the observational method, as defined in Eurocode 7,[1] is rarely used in practice.[26] One reason may be the practical difficulties in selecting parameters that are critical to the decision to act and observing their magnitude. This is because the link between observed parameters and limits of failure is, in many cases, not well defined.[36] In addition, a discrete observation of a specific parameter does not provide the engineer with information that can be used to predict the future behavior of the structure. Thereby, such observations make it difficult to assess at a sufficiently early stage whether the behavior will be within the defined limits of acceptable behavior, to allow for contingency action to be successfully undertaken. Furthermore, it is not explicitly stated within the framework of the observational method, as defined in Eurocode 7,[1] that verification of the structure's behavior is required and, if so, how this should be executed. However, sound engineering judgement suggests, similarly to other accepted design methodologies, that the engineer is required to verify that the structure fulfills the requirements on acceptable level of safety.

Addressing the practical applicability of the observational method, we have in this paper combined the observational method with a reliability-based design method into a design methodology for rock tunnels. The paper focuses on showing how the requirements of the observational method, as defined in Eurocode 7, can be fulfilled. Combination of the observational method with reliability-based design was previously discussed by Spross et al.[36], Spross[37], and Spross and Johansson[38]. The reliability-based calculations are utilized within the framework of the observational method to prepare an initial design and to verify that the tunnel fulfills the requirements of safety after additional information from measurements and observations has been considered. A measurable parameter is linked to the definition of unacceptable behavior and observation of this parameter is used to predict the future behavior of a tunnel section. The parameter is also used to assess the structural behavior and verify the tunnel reliability. The requirement of formulating contingency actions in parallel with the initial design is viewed as a more site-specific, practical concern that has therefore not been considered in this paper. However, examples of possible contingency actions are given in Section 4.2.

A brief outline of the proposed design concept was introduced in Bjureland et al.[39], which, however, did not discuss the strength of the rock support. In this paper, a shotcrete lining is introduced for rock support and used in the assessment of satisfactory performance of the tunnel.

This paper consists of three sections. In the first section, the suggested design methodology is presented. Thereafter, an illustrative calculation example is presented. In the last section, the results from the calculation example are analyzed and discussed along with a discussion on some challenges and opportunities of using Eurocode 7[1] in design of rock tunnels.

2. The observational method in Eurocode 7

In Eurocode 7[1], the requirements of the observational method are defined as follows.

(1) "When prediction of geotechnical behavior is difficult, it can be appropriate to apply the approach known as 'the observational method' in which the design is reviewed during construction.
(2) P The following requirements shall be met before construction is started:
   a) acceptable limits of behavior shall be established;
   b) the range of possible behavior shall be assessed and it shall be shown that there is an acceptable probability that the actual behavior will be within the acceptable limits;
   c) a plan of monitoring shall be devised, which will reveal whether the actual behavior lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully;
   d) the response time of instruments and the procedures for analyzing the results shall be sufficiently rapid in relation to the possible evolution of the system;
   e) a plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behavior outside acceptable limits.
(3) P During construction, the monitoring shall be carried out as planned.
(4) P The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put into operation if the limits of behavior are exceeded.
(5) P Monitoring equipment shall either be replaced or extended if it fails to supply reliable data of appropriate type or in sufficient quantity."

The principles marked with "P" must not be violated.

3. Reliability-based observational methodology for tunnel support

3.1. Managing uncertainty in the initial design

When applying the observational method, as defined in Eurocode 7,[1] an initial design must be prepared before construction is started. The requirement on the initial design is that the structure must avoid exceeding the predefined limits of unacceptable behavior with sufficiently high probability (principle 2-b). This obliges an assessment of the unacceptable, expected, and possible behavior of the structure.

3.1.1. Acceptable limits of behavior of tunnel support

Tunnels can be designed with a number of different methods, depending on the expected failure mechanism and tunnel geometry. To predict the expected development of deformations in a circular tunnel as the tunnel is excavated, the convergence–confinement method can be used as in Fig. 1 (see Section 4.1 for a more detailed presentation of the convergence–confinement method). For more complex tunnel geometries, numerical methods can be used, see e.g. 40,41, to derive the response curve of the rock mass using a successive relief of the supportive radial pressure, p_i, acting on the tunnel surface.

A common support measure to stabilize the tunnel is the application of a shotcrete lining. The shotcrete is applied to the tunnel periphery and improves the tunnel stability by reducing the deformations that otherwise would occur. In this paper, we have defined the limit of acceptable behavior (principle 2-a) of the shotcrete in terms of strain.