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Uncertainty analysis for assessing rock mass quality and water inflow in hard rock subsea tunnels

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ABSTRACT: In many occasions considerable discrepancies have been found between predicted and actual rock mass conditions, resulting significant cost and time overrun. Finding innovative solutions for quantifying geological uncertainties and assessing risk are therefore keys for cost effective and optimum subsea tunneling. In this paper, an approach of uncertainty analysis has been presented for the discussion with examples of non subsea tunnels from the Himalaya and Frøya subsea tunnel of Norway. It is believed that similar uncertainty analysis approach might be relevant in analyzing uncertainties related to stability and water inflow in the subsea hard rock tunnels under planning.

1 Introduction

For economically viable tunnelling, it is crucial to have a method characterized by cost effectiveness and flexibility to adopt changing ground conditions, and by accuracy in the prediction of rock mass quality during planning. The planning and design phase decision in selecting tunnel alignment and predicting the rock mass quality and rock support requirement has direct influence on the overall cost of any tunnelling project (Figure 1).

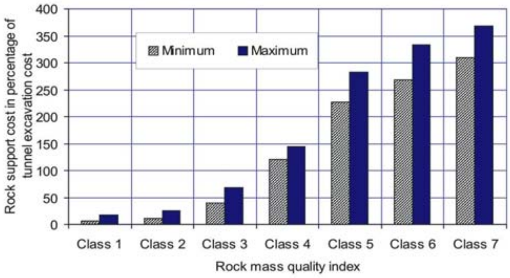

Figure 1. Approximate rock support cost for different rock mass classes (minimum and maximum for small and large section tunnels, respectively) (Panthi and Nilsen, 2007).

Figure 1 indicates that as soon as there is a decrease in rock mass quality (higher class), there is a dramatic increase in rock support cost. Therefore, the planning phase geological investigations are crucial for the overall control of the construction cost of all tunnelling projects. In this respect, identification, assessment and analysis of the engineering geological uncertainties always helps to minimiz the chances of variation (increase) in the cost of underground excavations.

The geological uncertainties are mainly related to the geological complexity of the project area and may be mainly represented by three engineering geological aspects of the rock mass. These are; a) rock mass quality, b) groundwater inflow through the rock mass, and (c) rock stresses. Among these three major engineering geological uncertainties the uncertainty (instability) posed by rock stress has relatively less significance in connection with the subsea tunnels. This is due to the fact that most of the subsea tunnels pass through relatively low rock cover giving no significant threat to the severe instability. On the other hand, other two uncertainties have considerable impact both on stability aspects and cost consequences of subsea tunnels.

The aim of this paper is to discuss the methodology of uncertainty analysis that may be used for the evaluation of rock mass quality and assessment of water leakage in subsea tunnels. It needs to be however emphasized that the methodology and concepts presented here was developed based on non subsea tunnel cases from the Himalaya.

2 Methodology for analysis

The basic methodology that is used for the probabilistic approach of uncertainty analysis for reliable prediction and quantification of the probable distribution of rock mass quality, potential rock squeezing and water leakage is given in Figure 2.

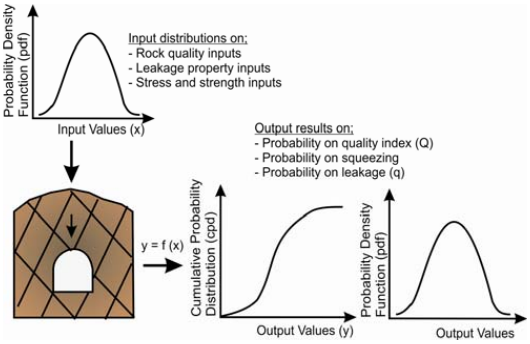

Figure 2. Model for uncertainty analysis (from Panthi, 2006).

While carrying out uncertainty analysis as indicated in Figure 2 it is important to characterize the most representative probability distribution of the input parameters. This is because, representative probability density functions of the input parameters is the only possible way to reliably and quantitatively predict the probability distribution of the output results. As a tool for the analysis the software program @Risk, an advanced statistical risk analysis software system introduced by Palisade Corporation in 1996 (updated periodically) may be used.

3 Assessing rock mass quality

It is generally accepted that quantifying the input parameters in most of the classification systems are subjective and much dependent on the personal judgment of the user (Nilsen et al., 2003).

Concerning the subsea tunnels it is even more complicated and uncertain since most of the project area is covered by water. Special investigation techniques need to be applied and interpretation of the investigation results becomes more challenging and uncertain than for most other projects. In addition, the locations of the fjords are often defined by major faults and weakness zones in the bed rocks (Nilsen and Palmstrøm, 2001). Therefore, the use of uncertainty analysis technique for evaluation of rock mass quality may prove to be more useful for subsea tunnels. In the following two tunnel segments, one from Khimti (segments L1) and one from Modi (segment L2) headrace tunnels (Figure 3), have been demonstrated as examples of the uncertainty analysis for rock mass quality evaluation. The Q-system of rock mass classification, which was used to quantify the quality of rock mass in these tunnels, is considered a basis for the uncertainty analysis.

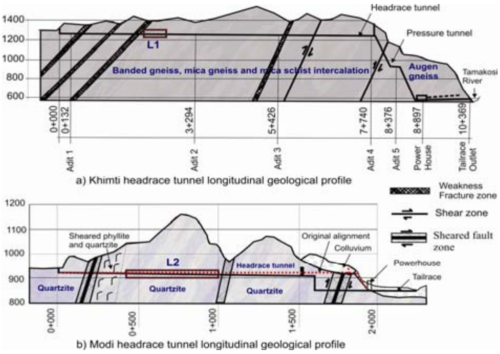

Figure 3. Longitudinal geological profile of Khimti and Modi headrace tunnels (7.9 km and 1.5 km long, respectively). L1 and L2 are headrace tunnel segments used for uncertainty analysis.

The rock quality index (Q) is a function of six variable input parameters and is described by the following equation (Barton, Lien and Lunde; 1974):

$$Q = f(x) = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \qquad (1)$$

In the equation; RQD is the rock quality designation that represents degree of jointing and its rating varies from 10 to 100, Jn is the joint set number that varies from 20 to 0.5, Jr is the joint roughness number that varies from 0.5 to 4, Ja is the joint alteration number that varies from 20 to 0.75, Jw is the joint water reduction factor that varies from 0.05 to 1 and SRF is the stress reduction factor that varies from 400 to 1. Details concerning characterization of these parameters are discussed in Barton (2002) and in many other papers.

In terms of probabilistic approach for uncertainty analysis, the rock mass quality index (Q) should be considered as an uncertainty that is dependable on these six variable input parameters and all these six variables are considered to be independent to each other. The main principle of uncertainty analysis based on Q-value is thus to characterize the uncertainties that exist while estimating these six variable input parameters. The characterization of these uncertain input variables is done by assigning probability density functions (pdf) to each of them. Logical judgment, mapped input variables in the tunnel during excavation and the best fit tool of the @Risk program are used to define the probability density function (pdf) for each input variable.

Segment L1 of Khimti headrace tunnel represents a segment where poor to fair quality rock mass was actually encountered. This is a tunnel segment located upstream of Adit 2 (Figure 3a). During planning the rock mass in this tunnel segment was predicted to be of fair to good quality. In the tunnel, the rock mass was found to consist mainly of fresh to moderately weathered and jointed micagneiss in intercalation with thin bands (less than 1 meter) of weak, highly weathered and deformed talcose micaschist.

Segment L2 of Modi headrace tunnel also represent a segment where fair to good quality rock mass was encountered as predicted during planning. The rock mass mainly consists of very hard, abrasive, fresh to slightly weathered and highly jointed quartzite (Figure 3b). The discontinuity surfaces in the tunnel were observed to be altered and filled with silt and clay, but the overall quality of rock mass in the tunnel was found to be of fair to good quality.

The @Risk uncertainty analysis model was run after defining and assigning the probability density functions (pdf) for each input variable of the quality index Q for both L1 and L2 segments of headrace tunnels (Figure 3). The simulation settings of the @Risk model were specified to single number of simulation and maximum iterations of 5000. The Latin Hypercube simulation technique that selects single value at random from each interval was selected. The outcomes for pseudo-randomly distributed quality index Q based on simulation by @Risk are shown in Figure 4 and Figure 5.

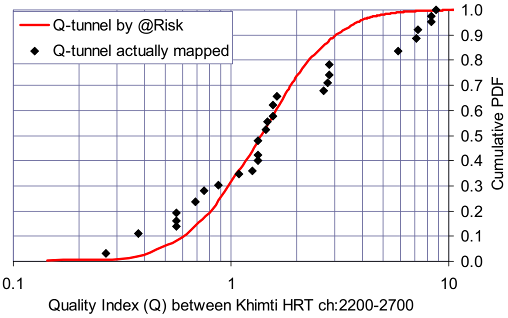

Figure 4. Distribution of quality index Q at segment L1 of the Khimti headrace tunnel (based on Panthi, 2006).

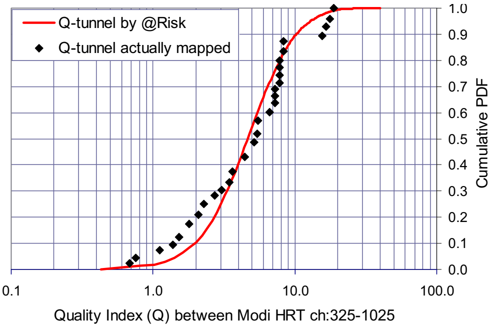

Figure 5. Distribution of quality index Q at segment L2 of the Modi headrace tunnel (based on Panthi, 2006).

Figure 4 and 5 show cumulative distributions of Q-values for Q-tunnel calculated by @Risk for both segments of the headrace tunnels. The cumulative curve for actually mapped Q-values in both segment of the tunnels are also presented. These curves are plotted based on summarizing sections of tunnel with a given Q-value and dividing by the selected tunnel length (in this case 500 and 700 meters, respectively). The frequency values are added with increasing value of Q to convert into cumulative form.

The cumulative probability distribution as calculated from actual data by @Risk and the distribution of actually mapped values of Q are found to be in fairly good agreement for both headrace tunnel segments (Figure 4 and Figure 5). This indicates that the assigned probability density functions of input variables are fairly representative of the real ground conditions.

From the analysis presented in Figure 4 and Figure 5 it can be concluded that it is possible to carry out uncertainty analysis using quality index (Q). The real challenge however is the quantification of ratings for the input parameters of Q in areas where the rock mass is not exposed at surface, which is generally the case for subsea tunnels. In subsea tunnels, the most difficult tasks are the identification of weathering depth, the evaluation of the extent of weathering and alteration, the estimation of degree of jointing and identification of dykes representating weak rocks within stronger rocks.

The engineering geological investigations such as directional core drilling and geophysical investigations are the popular investigation methods used for assessing the quality of rock mass in subsea tunnels during planning. During such investigations focus should be made in predicting the possible statistical ranges of each input variable used for characterizing the quality of rock mass and use such data base of statistical variation for the uncertainty analysis similar to as have been illustrated above.

4 Uncertainty analysis for leakage

The logical assumption, apparently, would be to expect most of the water inflow in a subsea tunnel to come from major faults or weakness zones. This is, however, not exactly the case due to the fact that such zones generally have very low permeability due to a high content of fine clay. In addition, in many cases the major weakness or fault zones are located under the central part of the fjord or strait having low permeability moraine clay cover on top of the bedrock (Nilsen and Palmstrøm, 2001). The trend is that the major leakage in subsea tunnels is encountered often in the transition zones between central core of the major weakness zones and un-jointed adjacent bedrock.

Due to complicated topographical conditions, mostly covered by sea water, investigation on the exact location and extent of water leakage in subsea tunnels during planning is a real challenge.

Based on the data records of water leakage measurement in the probe holes carried in determining the need of pre-injection grouting from pressurized unlined/shotcrete lined Khimti headrace tunnel (Figure 3a) Panthi (2006) has suggested a relationship between specific leakage, hydrostatic head and some Q-value parameters as given by Equation 2.

$$q_t = f_a \times h_{static} \times \frac{J_n \times J_r}{J_a} \qquad (2)$$

Where; f_a is a joint permeability factor with unit liter per minute per square meter. This factor is related to the permeability condition of joint sets and expresses connectivity between joint sets. The factor f_a may vary from 0.05 to 0.12 depending upon the connectivity of the joint sets and their condition infilling. Lower values represent impermeable joints and higher values represent more open joints or joints filled with permeable material.

In the following the Equation 2 will be used for carrying out uncertainty analysis in estimating water leakage between stations (chainage) 4521 to 4665 of Frøya subsea tunnel of Norway (Figure 6) where considerable leakage occurred during tunnelling. According to Holmøy (2008) highest registered water leakage recorded was 2,144 liters per minute per one pre-injection grouting round (21 meter tunnel length) through injection grouting holes at station 4535, which gives approximately 102 liters per minute per meter tunnel leakage.

4.1 Geology and input variables

In terms of probabilistic approach, the specific tunnel leakage (q_t) defined by Equation 2 is considered as a factor which depends mainly on five variable input parameters; i.e. joint permeability factor (f_a), hydrostatic height (h_{static}), degree of jointing (J_n), joint roughness (J_r) and joint alteration (J_a). This means that the main principle of uncertainty analysis based on Equation 2 will be to characterize the uncertainties regarding these variable input parameters.

Statistical data of discontinuities as calculated from geological tunnel logs, actual hydrostatic head and specific leakage as calculated according to Equation 2 for Frøya tunnel are given in Table 1.

Table 1. Ranges of discontinuity characteristics, hydrostatic head and specific leakage as calculated based on Equation 2 by @Risk for Chainage 4521 – 4665 of Frøya tunnel.

Descriptions	Distinctive values				@Risk values
	Min.	Max.	Mean / most likely	St. dev	
Joint set number (J_n)	4	12	9	-	9
Joint roughness (J_r)	1.5	3	2	0.5	2.00
Joint alteration (J_a)	6	2	4	2	4.22
Static head (h_{static}) in m.	130	150	140	8	140.00
Permeability factor (f_a) in l min/sq. m.	0.05	0.1	0.075	0.02	0.078
Specific leakage (q_t) in l/min./m.t	9.75	270.00	47.25		46.84

As Table 1 indicates, this section of the Frøya tunnel passes through jointed rock mass with an average J_n value of 9. According to Holmøy (2008) and the geological tunnel log the rock mass at this tunnel section consists mainly of granitic gneiss and occasional occurrence of migmatite and limestone dykes. The quality of rock mass varied considerably along the tunnel and sudden changes in the quality was registered. The joints in this tunnel segment, which is a transition zone of the major weakness zone (Figure 6), were rough, irregular and planner with an aperture ranging between 0–50mm. The joints were occasionally clay filled that ranged also between 0-50mm. The Q-value ranged between 0.8-5.9. In contracts, in the weakness zones clay thickness often ranged from 100 to 200 mm thick.

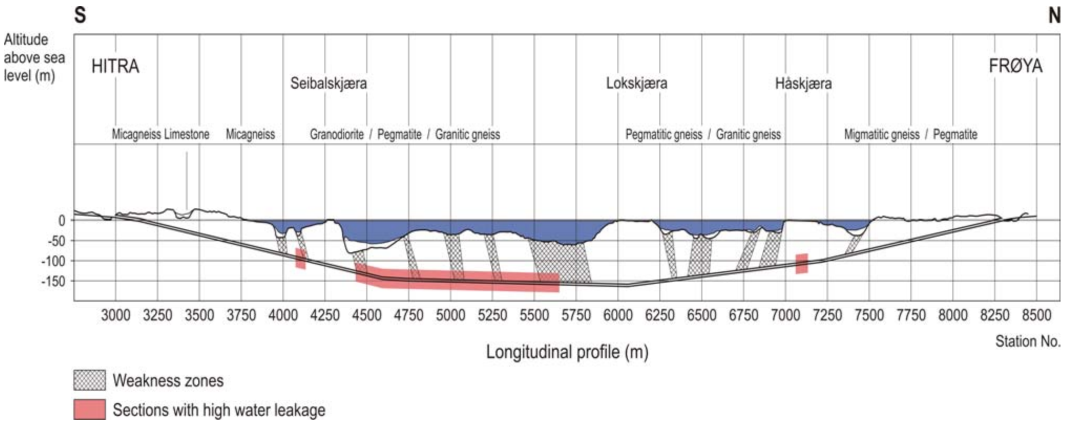

Figure 6. Longitudinal profile of the Frøya subsea tunnel (from Holmøy, 2008).

Estimating reliable ranges of factor f_a and other input variables of equation 2 is vital for successful water leakage analysis. The other inputs apart from f_a have been calculated based on the actual records. The fact that this tunnel segment is located adjacent to the deepest part of the fjord and there is thin moraine clay deposit above the bed rock (Figure 5). On the other hand, the joints in the tunnel were interconnected and have fairly permeable character (with less clay infilling). Hence, the factor f_a is assumed to have a mean value of 0.075 with its minimum 0.05 and maximum 0.1.

4.2 Simulation results and interpretation

The @Risk probabilistic analysis model was run after assigning probability density functions (pdf) for each input variable of Equation 2. The simulation settings of the @Risk model were specified to single number of simulation and maximum iterations of 5000. The Latin Hypercube simulation technique that selects single value at random from each interval was selected. The outcomes for the pseudo-randomly distributed specific tunnel leakage (q_t) achieved after simulation based on @Risk are shown in Figure 7 (see also Table 1).

The figure indicates an average specific leakage (q_t) of about 46.8 liters per minute per meter tunnel. This gives an overall leakage of approximately 6740 liters per minute through 144m long tunnel section. The figure further illustrates that the probability of exceeding the specific leakage by more than 120 liters per minute per meter tunnel is only five percent and may be considered as outlier. As discussed above the maximum leakage recorded at this tunnel section was 102 liters per minute per meter tunnel at the pre-injection round drilled from station 4535.

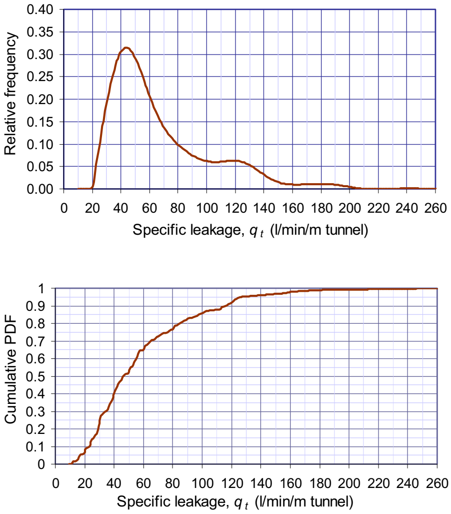

Figure 7. Relative (top) and cumulative (bottom) distribution of specific leakage (q_t) between chainage 4521 - 4665 of the Frøya tunnel.

The method illustrated above gives fairly promising result in assessing the leakage through subsea tunnels. Therefore, the methodology is considered to be helpful in evaluating the extent of leakage that may occur in the tunnel. However, the real challenge is the quantification of the input variable needed for such analysis. The data and geological information collected from directional drilling and geophysical investigations may be utilized to estimate such statistical ranges of input variables. Based on such data an uncertainly analysis may be carried out to estimate the extent of leakage, which could be of great help to reduce the overall risk.

5 Conclusion

The overall conclusion is that the probabilistic approach of uncertainty analysis for evaluating rock mass quality and for assessing potential water inflow may prove to be useful also for subsea tunnels. It needs, however, to be emphasized that the uncertainty issues should be prioritized based on the characteristics and geological formation of respective locations of subsea tunnels and available data information. A mathematical relationship giving quantitative description of an uncertainty in concern is of prerequisite for the analysis.

Acknowledgement

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