Uncertainty and risk assessment of leakage in water tunnels – A case from Nepal Himalaya

Krishna K. Panthi & Bjørn Nilsen

Department of Geology and Mineral Resources Engineering,
Norwegian University of Science and Technology, Trondheim, Norway

SYNOPSIS: Safety and stability are the key issues in underground excavations. Making tunnels water tight plays an important role in this regards. Water leakage problems in unlined or shotcrete lined water tunnels are not new issues. In many occasions severe water inflow as well as leakage problems have been faced that not only reduced stability of the rock mass surrounding the tunnel, but also valuable water has been lost from it, causing safety risk as well as huge economic loss to the projects.

In the Himalaya, due to active tectonics in this region, the rock masses are highly fractured, folded, sheared and deeply weathered. Tunneling through numerous zones of weakness, fractures and faults is thus a matter of reality. Moreover, the majority of these zones are in general highly conductive, representing potential sources of ground water aquifer as well as possible sources of water leakage from the completed unlined or shotcrete lined water tunnels. Thus, the degree of uncertainty and risk associated with water leakage is extremely high.

Water leakage control in the tunnels plays a vital role not only in improving the rock mass quality, but also in increasing the safety as well as saving economic loss caused by large leakages. The real challenge is however accurate prediction and quantification of possible water leakage prior to tunnel excavation, so that cost consequences are incorporated well in advance. The main focus of this paper will be to discuss a new approach of uncertainty and risk analysis that leads to better understanding concerning quantification of possible water leakage from unlined or shotcrete lined tunnels. For this, factual data of the headrace tunnel of Khimti I Hydropower Project in Nepal Himalaya, where effective use of injection grouting was applied to control the leakage, has been exploited.

1. INTRODUCTION

The rock masses in the Himalaya are highly fractured and deeply weathered. As a result, considerable temporary rock support has to be installed during tunnel excavation, but the use of full concrete lining after completion of excavation is also a tradition in the Himalaya. Hence, tunneling through Himalayan rock mass are becoming expensive, time consuming and in some occasions economically unattractive for hydropower schemes. The only way to solve this problem is to include temporary rock support as a part of the permanent support and to use pre-injection grouting technique to control water leakage from the waterway tunnel. This concept was used in the recently constructed headrace tunnel of 60 MW Khimti I hydropower project by the Civil Construction Consortium (CCC, 2002). Khimti I hydropower project is a high head (gross head 680m) run-of-river (RoR) project that consists of an approximately 8km long headrace

tunnel, 1km penstock pressure shaft, an underground powerhouse cavern, a 1.5km long tailrace tunnel, a gravity weir and two bay surface settling basins.

One of most important aspects of the unlined / shotcrete lined water tunnel concept is control of water leakage while in operation at full hydrostatic pressure and limiting the leakage to an appropriate volume (in Nepal defined as maximum 1 to 1.5 liters per minute per meter tunnel). The real difficulty, however, is the prediction and quantification of possible water leakage prior to tunnel excavation (during planning).

In the following, a probabilistic approach for predicting water leakage will be proposed based on data from the headrace tunnel. Before using this approach, an attempt will be made to establish an empirical relationship between specific leakage (q) and input parameters of the rock quality index (Q). Data on measured specific leakage (q) through exploratory holes drilled ahead of excavation to

identify the need for pre-injection grouting (Panthi and Nilsen, 2005) and mapped input variables of the rock mass quality index (Q) in the headrace tunnel of the Khimti project are used for this purpose. Since the analysis will be based only on a single project of the Himalaya, it is acknowledged here that the uncertainties associated with this analysis will be considerable. Still, the approach is believed to have a considerable potential for this type of analysis.

2. PROJECT GEOLOGY

Geologically, the project lies in the crystalline Tamakoshi gneiss complex of the lesser Himalaya. Structurally, the area is bounded or surrounded by a major fault system of the Himalaya called "the Main Central Thrust (MCT)", see Figure 1. As indicated in the Figure, the rocks in the project area are mainly comprised by banded granite gneiss and augen mica gneiss. These gneisses have been subjected to frequent intercalation and shearing with chlorite and talcose mica schist. This intercalation is most frequent, with an interval of approximately 5-10 meters at the downstream end of the 7888m long headrace tunnel, whereas at the upstream stretch the interval is longer and banded gneiss and augen

gneiss are more fractured and open-jointed (Panthi and Nilsen, 2005). The foliation planes are generally striking Northeast – Southwest and dipping towards Northwest. Since the project area is bounded by the Main Central Thrust (MCT) the rock mass along the headrace tunnel is highly jointed, sheared, deeply weathered and deformed. The geology along the headrace tunnel is also influenced by several minor faults and weakness zones represented by very weak sheared schist and crushed zones, see Figure 2.

With respect to jointing three major joint sets with frequent random joints were observed along the tunnel alignment during excavation. The general strikes of the main foliation joints (J_f) were found varying from N15^o to 60°E. This is not very favorable relatively to the headrace tunnel alignment, which also is oriented in Northeast / Southwest direction. The foliation joints are mostly dipping towards Northwest with a varying dip angle of 50 to 60 degrees at the Southern part of the tunnel (adit 4 area), and this trend changes gradually making the dip angle more flat with almost 25 degrees at its Northern part (adit 1). The joint set number one (J_1) is oriented with almost the same strike direction as the foliation joints and is very close to parallel to the tunnel alignment but

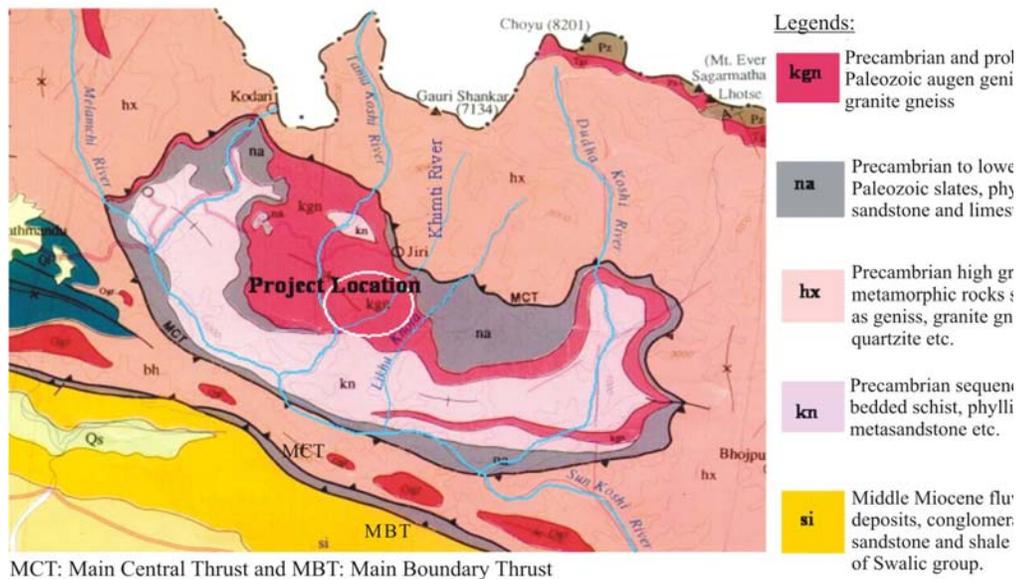MCT: Main Central Thrust and MBT: Main Boundary Thrust

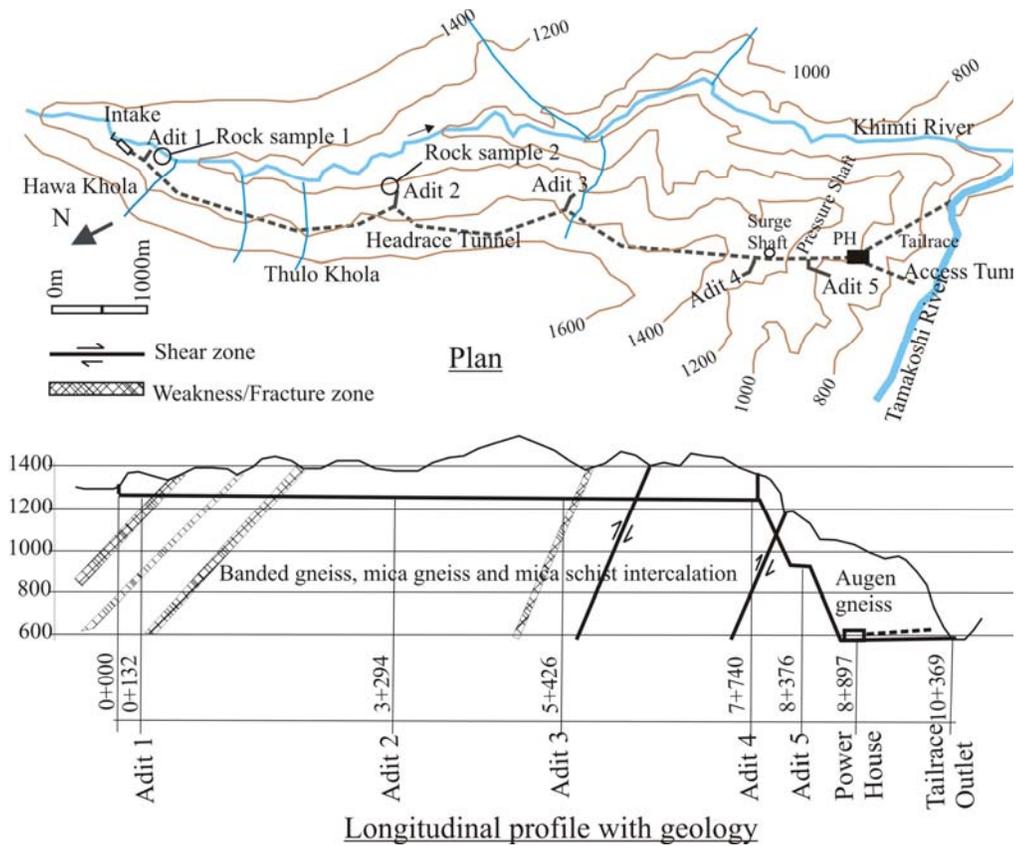Figure 1. Geological environment of the Khimti I hydropower project.

Figure 2. Project topography and profile with geological description of the waterway (Panthi, 2006).

dipping opposite to the foliation joints (dip angle 50 to 75 degrees towards Southeast). Joint set number two (J_2) is oriented in Northwest Southeast direction with very steep dip angle (70 to 85 degrees) towards Southwest.

With respect to joint filling and alteration, most of the discontinuities at the Southern section of the headrace tunnel (downstream from Adit 3) are filled with clay and bands of chlorite and talcose schist and have been characterized as impermeable with respect to water leakage. In contrast, the discontinuities present at the Northern section of the headrace tunnel are either open or filled with coarse grained permeable silt materials. The intercalation effect of mica schist is also present there, but at greater intervals. In this northern section several open joints with aperture up to 10 cm have been observed during tunneling. The degree of weathering along the tunnel alignment also varies

greatly and is classified as medium to highly weathered according to ISRM (1978). In some sections the degree of weathering was so deep that decomposed and highly sheared organic clay was found in the tunnel. Especially the tunnel section 500 meters downstream from Adit 2 (between chainage 3450 – 3900) was deeply weathered (CCC, 2002). The valley side slope in this stretch of the tunnel is flatter (about 25 degrees) and the rock cover is slightly more than 100 meters.

3. ESTIMATING CORRELATION ON SPECIFIC LEAKAGE

The leakage through an unlined / shotcrete lined tunnel is mainly governed by hydrostatic head (h_{static}), degree of jointing and the discontinuity characteristics of the rock mass, see Figure 3 left.
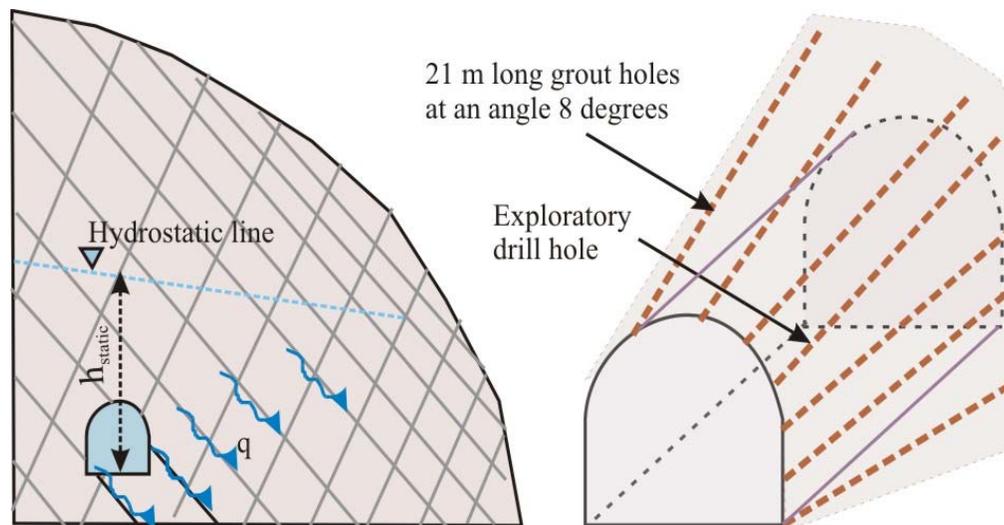
Figure 3. Principal illustration showing possible water leakage through an unlined / shotcrete lined tunnel (left), exploratory drill hole and grout/curtain for preventing water leakage (right) (Panthi, 2006).

During excavation at Khimti headrace tunnel, the specific leakage (q) was measured in an exploratory hole (approximately 18-21 meters long with an angle between 8 to 10 degrees relatively to the tunnel axis) drilled at the valley side of the tunnel as shown in Figure 3 right. The measured specific leakage in the drillhole may be considered as indicative for the specific leakage through the unlined / shotcrete lined tunnel during its operation at hydrostatic pressure.

For Khimti, the specific leakage (q) in the exploratory drillhole was expressed as:

$$q = \frac{V}{l \times t} \qquad \qquad \text{...(1)}$$

Where; q is the specific leakage in litres per minute per meter at an pressure 1.5 times hydrostatic head (1.5 represents factor of safety), V is the water volume in litres, l is the length of drillhole from the packer in meters (maximum 5 meters) and t is the time in minutes required to pump the water volume V.

Based on Equation above, if the measured specific leakage (q) was more than one, it was concluded that there was a need for pre-injection grouting.

After excavation of 2.5 kilometres of the Khimti headrace tunnel, it was realized that excessive leakage through the headrace tunnel might occur during operation. The main reason for such suspicion was the fact that the rock mass at the already excavated headrace tunnel sections was found to be highly fractured. Therefore, the principle explained above was introduced as a basis for pre-injection grouting for approximately 4.2 kilometres of the Khimti headrace tunnel, see Figure 4.

It has been analyzed for Khimti whether the measured specific leakage (q) used for identifying the need for pre-injection grouting is interlinked with rock mass quality parameters. In particular, correlations between specific leakage (q) and jointing characteristics described by the Q-system, which was used to map the rock mass condition at Khimti headrace tunnel, have been checked.

The mapped jointing characteristics of the rock mass, pumping pressure (P) to identify specific leakage, measured specific leakage (q) and specific pre-injection grout consumption (g_c) are summarized in Table 1. The Table shows statistical distributions of these parameters representing their minimum, maximum and mean values and their standard deviations.

In an attempt to find a correlation between specific leakage (q), hydrostatic head (h_{static}) and discontinuity characteristics of the rock mass, a regression analysis was performed by using
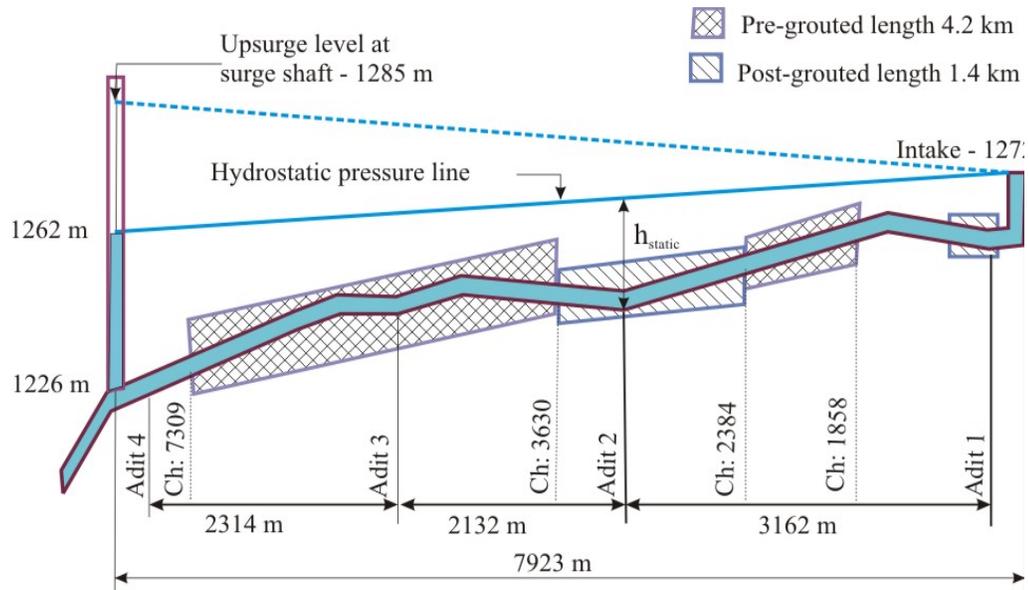
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Figure 4. Khimti headrace tunnel profile showing hydrostatic pressure (h_{static}) line during operation and areas with pre-injection and post-injection grouting (Panthi, 2006). The Figure is not in true scale.

Table 1. Measured values of specific leakage (q), pumping pressure (P), hydrostatic head at operation (h_{static}) and jointing characteristics along the pre-grouted section of Khimti headrace tunnel (Panthi, 2006).

Descriptions	Statistical distributions			
	Minimum	Maximum	Mean	Standard deviation
Discontinuity conditions:				
Rock quality designation (RQD)	10	85	40	25
Joint set number (J_n)	6	20	12	6
Joint roughness number (J_r)	0.5	3	1.5	0.7
Joint alteration number (J_a)	3	15	8	4.2
True hydrostatic head (h_{static}) in meters	19	39	29	6
Pumping pressure in bars (P)	2.9	5.8	4.4	1
Specific leakage (q) in litres per minute per metre	0	16	3.9	4.4
Specific grout consumption (g_c) in kg / m. tunnel	0	815	164	205

Note: Water pumping pressure through exploratory holes represents 1.5 times h_{static}.

different combinations of input variables of the Q-system. Figure 5 shows the results of regression analysis for different combinations of parameters.

A first attempt was made based on measured specific leakage, hydrostatic head and measured Q-values, see Figure 5a. As can be seen, no acceptable correlation was found. The second attempt was made by omitting J_w and SRF in the Q-value, assuming that these two input variables have very little influence on water leakage, see Figure 5b.

As can be seen, the correlation has slightly improved, but is not satisfactory. The third attempt was made by reversing RQD and J_n, considering that the degree of jointing represented by J_n should increase leakage and high RQD on the other hand should reduce leakage. As shown in Figure 5c, the correlation improved considerably. The final attempt was made by omitting RQD, which gave a fairly good result with a correlation factor of 85 percent, see Figure 5d.
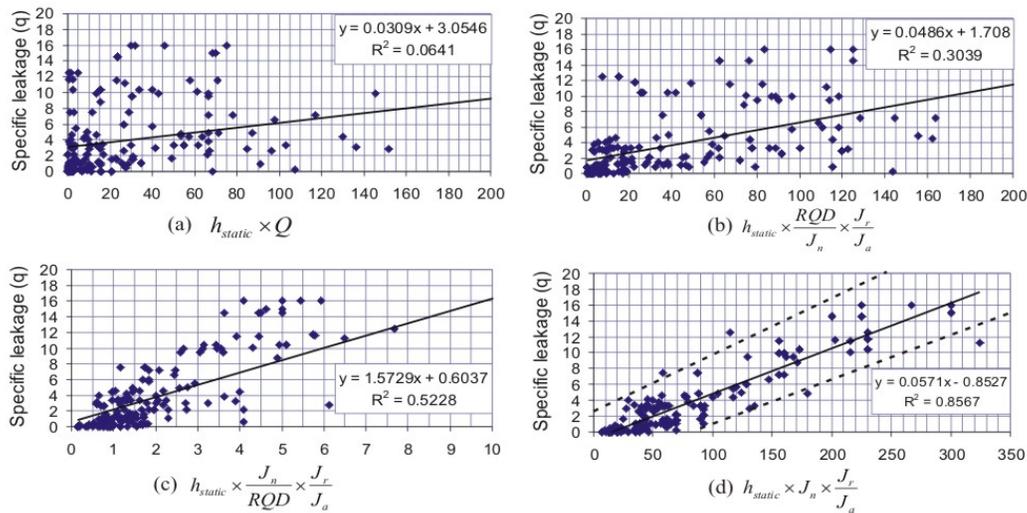
Figure 5. Correlations between specific leakage (q), hydrostatic height (h_{static}) and input variables of Q-system based on Khimti tunnel log and injection grouting records (Panthi, 2006).

This result is rather surprising since in theory, the *RQD* value that describes relative block size of rock mass, should have considerable effect on water leakage. A possible reason for the surprisingly small effect by *RQD* on leakage may be the fact that *RQD* covers only a small part of the range of block size possible in the rock mass. For instance, in a tunnel located in highly jointed rock mass, if the spacing between most of the joints is just above 10 centimetres, the *RQD* value may be as high as 90. On the other hand, if the spacing between joints is slightly less than 10 centimetres, the *RQD* value may be as low as 10.

In the correlation represented by 5d, there are four parameters that influence on the leakage; hydrostatic height (h_{static}), degree of jointing (J_n), joint roughness (J_r) and joint alteration (J_a). Three of these parameters are directly proportional to the leakage and therefore tend to increase leakage. Joint alteration is inversely proportional, and tends to reduce the leakage. This seems quite logical, because the higher the hydrostatic pressure and the more jointed the rock mass, the higher will be the possibility for large leakage, and the more altered and clay filled the joints are, the more impermeable the rock mass will be.

According to 5d, the specific leakage in the tunnel (q_t) may roughly be estimated by the equation 2:

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

Where; f_a is a joint permeability factor with unit litre per minute per sq. m. This factor is related to the permeability condition of joint sets and expresses connectivity between joint sets, joint spacing, aperture and infilling conditions. The factor f_a may vary from 0.05 to 0.12 (represents lower and upper line, respectively) depending upon the condition of discontinuity infilling. Lower values represent impermeable joints and higher values represent more open joints or joints filled with permeable material.

It needs to be emphasized here that the results shown in Figure 5 are based only on data for Khimti headrace tunnel. In this tunnel, the rock mass is highly fractured and has more than two prominent joints sets plus random joints, see J_n value in Table 1. Unless similar conditions are present, the uncertainty connected to the proposed correlation will be considerable.

4. WATER LEAKAGE ESTIMATION

A probabilistic approach is used to estimate leakage based on Equation 2. The uncertainty analysis is carried out by using @Risk statistical analysis software. The post-injection grouted section of

Khimti headrace tunnel between chainage 2384 and 3630 (near adit 2) is used for this purpose, see 4. Through this tunnel section considerable volume of water leaked out during test water filling of the headrace tunnel. Approximately 200 litres of water per second leaked from adit 2 approximately 50 to 60 meters from the junction. Since no water leakage was observed around the concrete plug area, it was assumed that the leaking water was flowing in open joints. To control this leakage, an extensive post-injection grouting was performed in the un-grouted section upstream and downstream of adit 2 (CCC, 2002 and Panthi and Nilsen, 2005a), see Figure 4.

In terms of probabilistic approach, the specific 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.

As Table 1 indicates, this section of headrace tunnel passes through highly fractured rock mass with an average J_n value of 12. The headrace tunnel mainly passes through mica gneiss, banded gneiss and sheared mica schist intercalations. The discontinuities in the mica gneiss and banded gneiss are either open or filled with permeable silt material, while the occasional bands of sheared schist are rather impermeable in character. The unfavorable orientation of joint sets and the open character of joints are believed to be the main causes for the large leakage in this section of the headrace tunnel.

The statistical ranges of discontinuity characteristics calculated from geological tunnel logs, actual hydrostatic head at operation and specific leakage calculated according to Equation 2 are given in Table 2.

Definition of representative probability density function (pdf) plays a key role for uncertainty analysis based on @Risk. Probability density functions of variable input parameters of the Q-value are discussed in Panthi (2006). A triangular probability density function (pdf) is used for J_n, with most likely value 12 and minimum and maximum values 6 and 20, respectively. In blocky rock mass condition, J_r and J_a are assumed to cluster towards their mean, giving normal distributions. A triangular distribution is assumed for h_{static}, since the hydrostatic head changes linearly as shown in Figure 4. The factor f_a is assumed to have a mean value of 0.085 based on the fact that joint sets other than bands of intercalated schists within foliation joints are most permeable. Since the distribution pattern of f_a is not clearly known, it has been considered logical to use normal distribution.

The @Risk uncertainty analysis model was run after assigning probability density functions (pdf) for each input variable of Equation 2 as shown in Table 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 (Panthi, 2006). The outcomes for the pseudo-randomly distributed specific leakage (q) achieved after simulation based on @Risk are shown in Figure 6 (see also Table 2).

Table 2. Ranges of discontinuity characteristics, hydrostatic head, and specific leakage calculated based on Equation 2 by @Risk for Chainage 2384 – 3630 of Khimti headrace tunnel (Panthi, 2006).

Descriptions	Statistical distributions				@Risk values
	Minimum	Maximum	Mean / most likely	St. dev.	
Discontinuity characteristics:					
Joint set number (J_n)	6	20	12	-	12.67
Joint roughness number (J_r)	0.5	3	2	0.5	2.00
Joint alteration number (J_a)*	15	2	4	2	4.22
Hydrostatic head (h_{static}) in meters	19	30	25	-	25.00
Permeability factor (f_a) in l / min / sq. m.	0.05	0.12	0.085	0.03	0.085
Specific leakage (q_t) in l / min. / m tunnel	0.2	108	12.75		12.76

Note: *Maximum number of J_a represents its minimum with respect to specific leakage and vice versa.

The Figure 6 indicates an average specific leakage (q_t) of about 16 litres per minute per meter tunnel. This gives an overall leakage of approximately 350 litres per second through this section of the headrace tunnel. More importantly, the right hand diagram indicates specific leakage between 5 and 42 litres per minute per meter tunnel for a tunnel length of approximately 1120 meters (90 percent). The further illustrates that approximately 40 percent of the tunnel length (approximately 500 meters) has a specific leakage over 15 litres per minute per meter tunnel.

To find the total leakage for the 1246 meter tunnel section, the average specific leakage (qt) for each segment of tunnel (segment length defined by respective relative frequency of that segment multiplied by total tunnel length, in this case 1246 meters) is converted to total leakage for that segment. The calculated total leakage for each segment is than converted to cumulative leakage. The calculated cumulative leakage is shown in Figure 7.

As indicated in Figure 7, approximately 40 percent of the tunnel (cumulative curve above sixty percent) has estimated leakage of 225 litres per
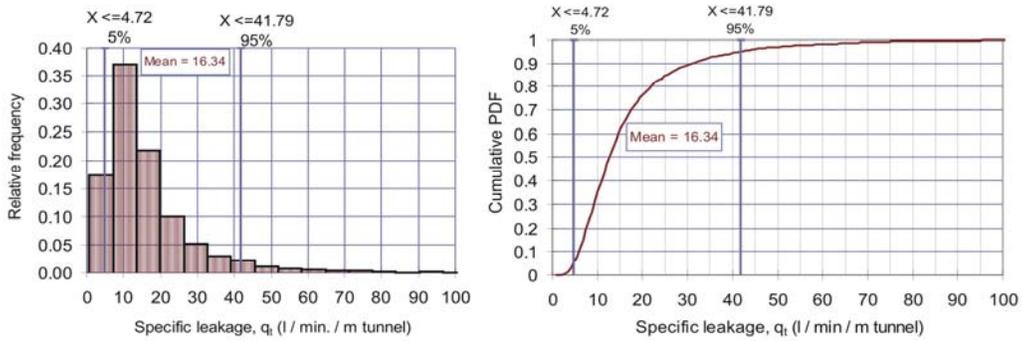

Figure 6. Distribution of specific leakage (q_t) between chainage 2384-3630, covering 1246 metre of the headrace tunnel from Adit 2 (Panthi, 2006).
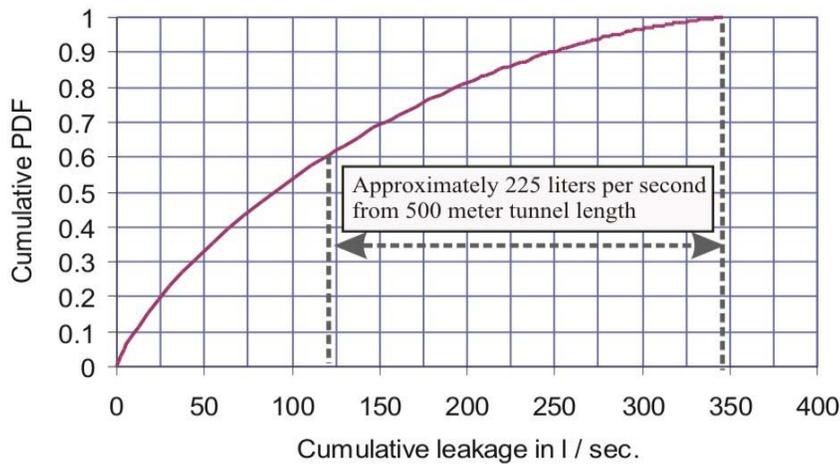

Figure 7. Calculated cumulative leakage for 1246 metre of the headrace tunnel near Adit 2 (Panthi, 2006).

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second (350 – 125). This 40 percent tunnel length covers approximately 500 meter tunnel length. In fact, this result is fairly close to what was observed during test water filling of the headrace tunnel. As mentioned earlier and also discussed by Panthi and Nilsen (2005a), 200 litres per second of water leaked from adit 2. To control this leakage an extensive post-injection grouting was carried out. During post-injection grouting special attention was given to the headrace tunnel section 300 meters upstream and 200 meters downstream adit 2.

5.   CONCLUSIONS

Based on the results presented above it can be concluded that the results of uncertainty analysis using Equation 2 and discontinuity characteristics that were mapped during excavation (see Table 2) gave fairly good estimate of the water leakage for the Khimti headrace tunnel. This means that if reliable discontinuity data are available, it may be possible to carry out uncertainty analysis for estimating leakage from a planned unlined or shotcrete lined tunnel in similar geological conditions. Further it can be concluded that the probabilistic approach of uncertainty analysis for assessing potential leakage through unlined / shotcrete lined tunnel has a great potential in the future.

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BIOGRAPHICAL DETAILS OF THE AUTHOR

Dr. Krishna Kanta Panthi completed MSc in Tunnel Engineering from Moscow Automobile and Road Construction Institute, Russian Federation in 1992. He completed second MSc in Hydropower Development from Norwegian University of Science and Technology (NTNU), Norway in 1998. He obtained Dr.Ing. in Rock Engineering from NTNU in 2006.

His professional career started from 1985 after the completion Diploma Engineering in Nepal. He mostly devoted his professional life in tunnelling and hydropower engineering and worked in leading positions in projects such as 144 MW Kaligandaki – A Hydropower Project (7 km tunnelling), 60 MW Khimti I Hydropower Project (12 km tunnelling), 14 MW Modi Khola Hydropower Project (3 km tunnelling), 12 MW Jhimruk Hydropower Project (2.5 MW tunnelling). He gave consulting service for 800 MW Parbati II Project and Rothan Tunnel Project in Himachal, India, where stress induced instability are being the major concerns. From June 2008 he has been Associate Professor of Rock Engineering at the Department of Geology and Mineral Resources Engineering of NTNU, Norway.