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Leakage potential through a shotcrete lined high-pressure headrace tunnel - An analysis on a case from Nepal

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ABSTRACT: The use of unlined / shotcrete lined pressure tunnels and shafts are very cost effective solutions for the hydropower project and therefore are being implemented worldwide. However, the ground conditions at the area of concern should be favorable regarding both minimum principal stress magnitude and rock mass strength, which should be higher than the hydrostatic head acting on the tunnel periphery. In addition, the rock mass should be relatively unjointed or joints in the rock mass should be tight enough. The most vulnerable issue in the design of unlined high-pressure headrace tunnel is to insure the potential leakage out of the tunnel during operation is within acceptable limit. This manuscript assesses the potential leakage extent from a shotcrete lined high-pressure headrace tunnel of the Upper Tamakoshi Hydroelectric Project (UTHP) in Nepal. Most of the headrace tunnel at UTHP is supported suing sprayed concrete (shotcrete) in combination of rock bolting in the walls and the crown and concrete lining in the invert. The downstream stretch (at surge shaft area) of few hundred meters headrace tunnel will be supported with full concrete lining. The approximately 8 km long headrace tunnel will face a maximum hydro-static pressure head of up to 120 m during power plant operation. The preliminary results of the leakage assessment using approach suggested by Panthi (2006) indicates that the average specific leakage from the headrace tunnel will be around 2.7 l/min/m tunnel. The evaluation concludes that the outer reach of the headrace tunnel after chainage 7300 m is extremely vulnerable for excessive water leakage to occur during operation. The joint set dipping towards the valley side slope of Gongar Khola seem very critical for potential water leakage, suggesting remedial measure before water filling in the tunnel.

1 INTRODUCTION

The fluid flow characteristic in most of the rock mass is mainly governed by permeability of the joints and discontinuities. In an unlined or shotcrete lined pressure tunnel, water gives pressure (Pw) to the rock mass equivalent to a hydrostatic head (H). The interaction between the water pressure and joints in the rock mass will therefore govern potential of fluid flow capacity, which is termed as hydraulic conductivity. Basnet & Panthi (2018) used the Norwegian confinement criteria to study the applicability of shotcrete lined tunnel at Upper Tamakoshi Project. The Norwegian confinement criteria showed that the whole headrace tunnel alignment is safe against hydraulic jacking with factor of safety exceeding 3.5. The stress state analysis on the other hand showed some critical locations where the factor of safety is less than minimum required factor of safety of 1.3. The low level of factor of safety was mainly confined at areas where weakness zones are located and also on the downstream stretch of the headrace tunnel. The detail rock engineering assessment concluded that the geological features such as small scale crushed zones, shear bands and some joints in unfavorable direction from where water leakage is likely to occur during operation of the project. Therefore, it is realized that the stress state analysis carried out for the UTHP was not sufficient to address the behavior of these geological features when exposed to high hydro static water pressure. It is therefore felt necessary to carry out study on the potential leakage from the headrace tunnel during operation phase when the headrace tunnel will have to sustain maximum up to 120 m water column. Panthi (2006) suggested a semi-empirical approach to assess potential leakage from water tunnels, which is used in this article to assess extent of leakage out from the headrace tunnel of UTHP project.

2 PANTHI 2006 APPROACH

According to Panthi (2006), among the most important aspects of the unlined or shotcrete lined water tunnel concept are control of water leakage while in operation at full hydrostatic pressure and limiting the leakage to an acceptable limit. The leakage limit for unlined or shotcrete lined water tunnel maybe defined maximum up to 1.5 liters per minute per meter tunnel. However, the main difficulty in leakage assessment is the quantification of possible water leakage prior to and during tunnel excavation. To address this difficulty, Panthi (2006) exploited comprehensive data records of certain Q-value (Barton et al., 1974) parameters and systematic water leakage test carried out ahead of headrace tunnel excavation of Khimti I hydropower project in Nepal. A semi-empirical relationship between specific tunnel leakage (q_t), some parameters of the rock quality index (Q) was established, which is expressed by Equation 1.

$$q_t = f_a \times H \times \frac{J_n \times J_r}{J_a} \tag{1}$$

Where, f_a is a joint permeability factor with unit l/min/m^2. This factor is related to the permeability condition of joints in the rock mass and varies from 0.001 to 0.25. H is the static water head, J_n, J_r and J_a are some Q-value parameters represented by joint set number, joint roughness number and joint alteration number, respectively. All input parameters in Equation 1 increase the leakage potential excluding Joint alteration number (J_a), which tends to decrease the leakage upon its increase in numerical value.

Panthi (2010) further suggested that the joint permeability factor (f_a) can be quantified using Equation 2, which is related to joint spacing (J_s), joint persistence (J_p) and the shortest perpendicular distance (D) from the rock slope topography to valley side tunnel roof (Fig. 1).

$$f_a = \frac{J_p}{D \times J_s} \tag{2}$$

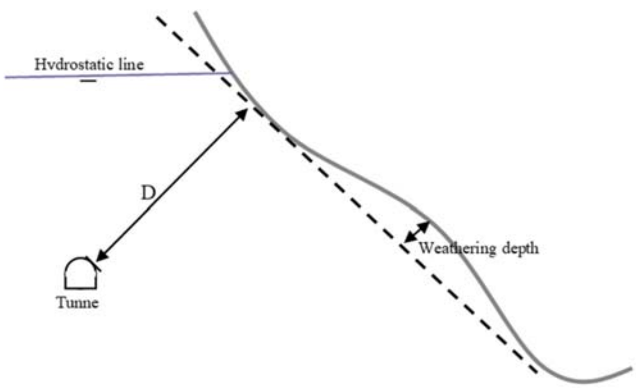

Figure 1. Typical topographic arrangement explaining D (Panthi, 2010).

Panthi (2006) emphasizes that the permeability condition in the rock mass mainly depends on the degree of jointing and condition in the different joint sets represented by joint aperture and infilling conditions. In addition, the hydrostatic water pressure that exists in the rock mass domain, spacing of the must unfavorable joint set, joint persistence and the distance from tunnel to the topographic surface will govern the extent of leakage from the water tunnels. In the following, the approach suggested by Panthi (2006 and 2010) described by Equations 1 and 2 will be used to estimate the potential water leakage from the headrace tunnel of Upper Tamakoshi Hydroelectric Project in Nepal.

3 BRIEF ON THE CASE PROJECT

The Upper Tamakoshi Hydroelectric Project (UTHP) is located at about 90 km northeast from Kathmandu, Nepal (Fig. 2a). The project has an installed capacity of 456 MW and exploits the design discharge of 66 m3/sec and 822 m gross hydrostatic water head. The project consists of low head diversion dam, settling basins, high pressure headrace tunnel, vertical penstock shafts, underground powerhouse, tailrace and access tunnels (Fig. 3b and Fig. 3c). From pre-feasibility study in 2001 to until 2014, there have been several design changes in locating pressurized headrace tunnel alignment of the UTHP. The latest alignment of the headrace tunnel is shown in Figures 3b (plan) and 3c (profile).

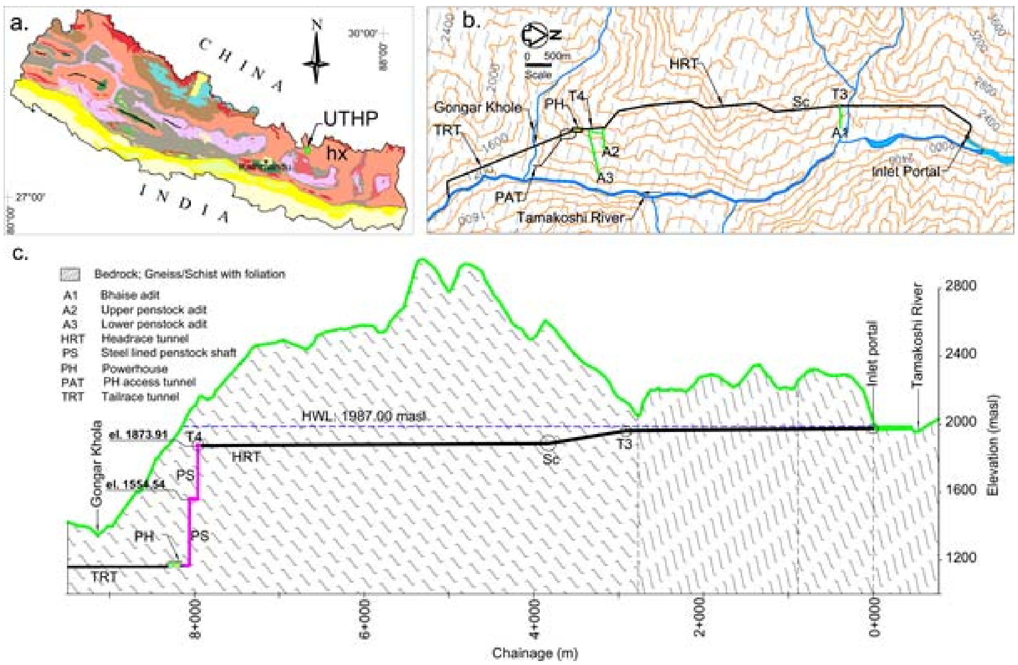

Figure 2. a) Location of the UTHP in geological map of Nepal; b) Layout plan of the headrace tunnel; c) Longitudinal profile along the tunnel alignment. NB: 'masl' is meters above sea level; 'HWL' is Head Water Level.

The total length of the headrace tunnel is 7960 m and the tunnel is designed with inverted-D shape having cross-sectional area of about 32 m^2 (tunnel width of 6 m). The excavation of headrace tunnel is completed in 2018 and is mainly supported with steel fiber shotcrete and bolting excluding short downstream segment close to surge shaft area. The maximum hydrostatic water head (H) at the downstream end of the headrace tunnel will reach to about 115m (1.15 MPa).

3.1 Geology of the project

Geologically, the Tamakoshi project is located in the Higher Himalayan Tectonic Formation of eastern Nepal Himalaya (Panthi & Basnet, 2018). Rock mass in this formation is mainly characterized by Precambrian high-grade metamorphic rocks consisting gneiss, quartzite, marbles, magmatite and granitic gneiss having the quality of rock mass comparable to the Scandinavian hard rocks. The detailed geological mapping of the project area during the feasibility study concluded that the rock types in the project area is mainly characterized as schistose gneiss with the content of mineral mica (Norconsult, 2005). The rock mass at the project area has foliation joints and two distinct cross joint sets (Panthi & Basnet, 2018). The general strikes of the foliation joints are WSW to WNW with dip angles of 350-750 NW to NE.

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3.2 Mapped rock mass quality

The rock mass quality along the headrace tunnel was mapped during tunnel excavation. The Q-system (Barton et al., 1974) of rock mass classification with added features such as spacing and persistence was used for the registration of rock mass quality. Figure 3 below shows registered rock mass quality distribution along the headrace tunnel. The Q-value varies mainly between good (Q-value exceeding 4.0) to very poor (Q-value less than 0.1) rock mass classes representing the hard rock mass influenced by joints and foliation planes. One can also observe in the figure that there are locations where Q-values are below 0.1, which represent mainly crushed or shear zones where the rock mass are weathered, sheared, fragmented and mixed with clay and fall between extremely poor to exceptionally poor rock mass class.

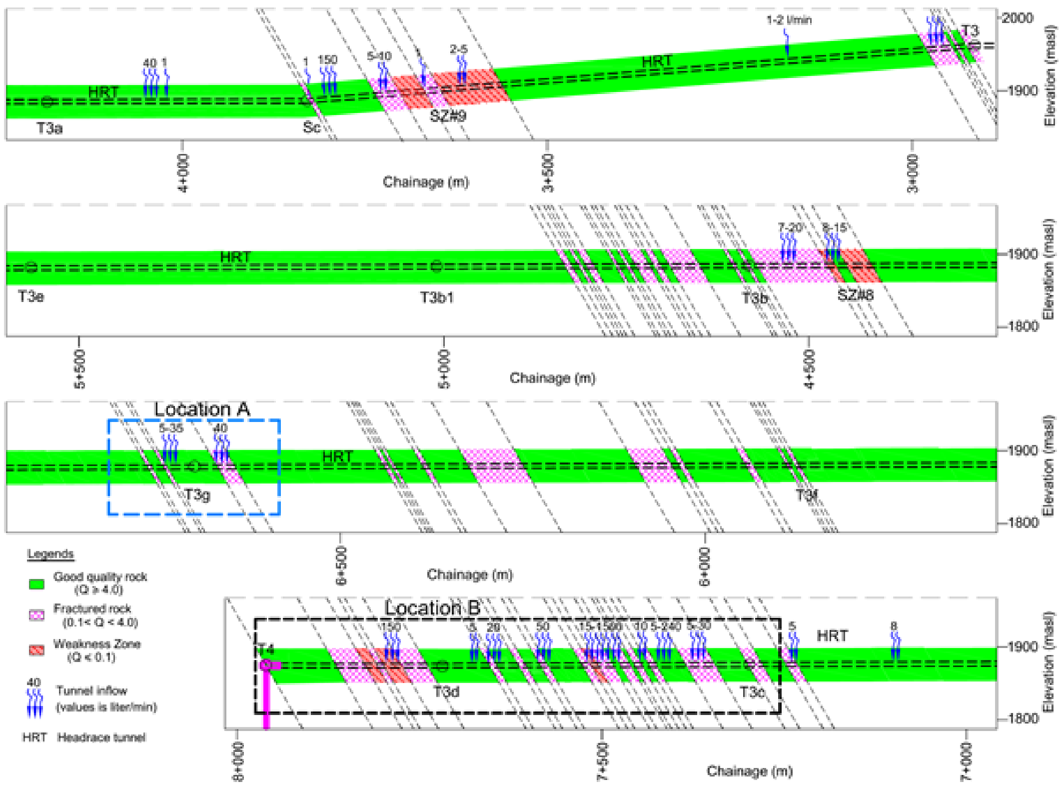

Figure 3. Registered rock mass quality and inflow condition along the headrace tunnel from chainage 2+914 (T3) to chainage 7+960 (T4).

As one can see in Figure 3, almost 80 percent length of the headrace tunnel has good quality rock mass. However, about 700 m length of the mapped headrace tunnel has fractured rock mass and approximately 200 m tunnel stretch meets the rock mass of the shear bands and fracture zones. It is emphasized here that the rock mass at the downstream end of the headrace tunnel (downstream from chaingae 7+300) where the static water pressure will reach to its maximum of 1.15 MPa is very critical and mainly dominated either by fractured rock mass or rock mass of the shear and fracture zones.

3.3 Mapped jointing conditions

In general, the orientation of the joints with respect to the orientation of the length axis play an important role in the extent of leakage from unlined or shotcrete lined pressure tunnel. More importantly, the joints that are perpendicular to the direction of the minimum principal stress are even more vulnerable for hydraulic jacking to occur. The emphasis should therefore be given to identify these joints from the planning and design phases of such tunnels and continue mapping during tunnel excavation. The general orientation of different joint sets at both study locations of the UTHP headrace tunnel (location A and location B in Fig. 3) are plotted in the stereographic project (Fig. 4).

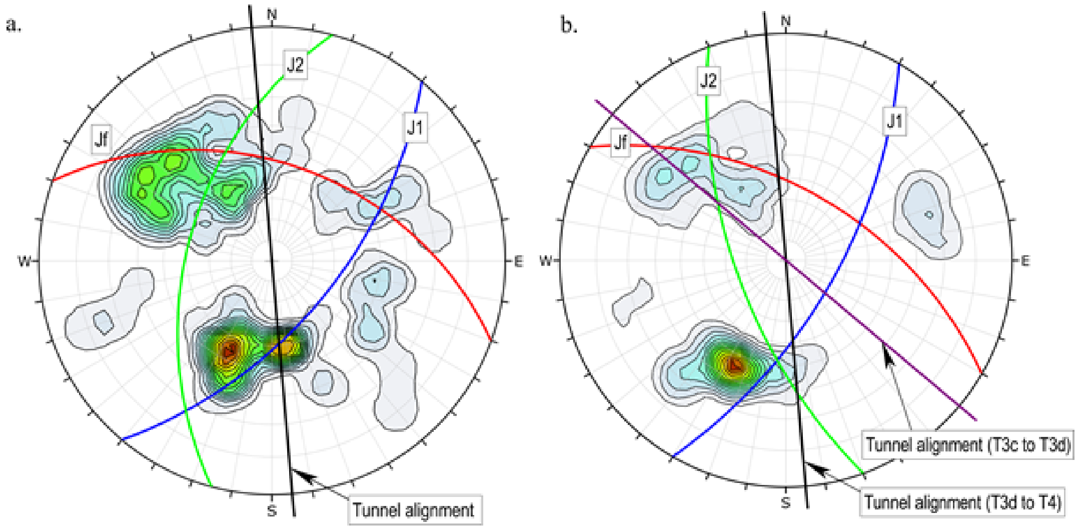

Figure 4. Orientation of the joints and tunnel alignment; a) Joints mapped from chainage 6+500 m to 6+800 m (Location A), and b) Joints mapped from chainage 7+500 to chainage 7+960 (Location B).

Characteristics of the joints like spacing, persistence, aperture, infilling, etc. should be defined to understand both mechanical and hydraulic behavior of the joints. Basnet & Panthi (2018) studied the joint details from T3 to T4. The mapped joints along the tunnel in good quality rock mass are mostly tightly healed and intact excluding some cross-joints that are filled with silty clay with a thickness 1 to 2 mm. In addition, quartz and feldspar veins of up to 20 cm thick are occasionally glued within the foliation joints. The fractured rock mass on the other hand consist mainly the joints filled with permeable silty clay of thickness between 5 to 10 mm. In areas where there exists shear zones, the filling thickness in the joints reach up to 100 mm. In case of the weakness / fracture zones, the rock mass in these areas are heavily jointed and permeable in nature where joints are filled with silty clay. The average joint spacing is about 15 m in good quality rock mass, about 10 m in fractured rock mass and less than 5 m in fracture zones.

4 LEAKAGE ASSESSMENT

Water leakage exceeding specified limit from the unlined or shotcrete lined pressure tunnel of hydropower projects is not desirable. On the other hand, it is challenging to make an unlined or shotcrete lined pressure tunnel completely free from leakage. Besides, it is possible to limit the leakage to a certain limit by using modern ground improvement technique such as discussed by Panthi (2013). Merritt (1999) recommended that the maximum allowable limit of specific leakage for most of the unlined or shotcrete lined tunnels should be 0.3 l/min/m tunnel, which is too strict requirement and will be costlier than full concrete lining of the whole length of tunnel. Panthi (2006) recommended a leakage limit maximum up to 1–1.5 l/min/m tunnel, which is achievable and is very cost effective solution. The leakage assessment is thus an important part of the study if a hydropower developer wishes to optimize construction costs by using unlined or shotcrete lined pressure tunnel for hydropower projects.

In the following, a quantitative assessment of the leakage potential from the headrace tunnel of UTHP is carried out using the approach described in the Chapter 2 of this article. The assessment approach suggested by Panthi (2006 and 2010) and described in Chapter 2 is used to calculate the specific leakage (q_t) from the headrace tunnel. A total number of 487 mapped tunnel data from the headrace tunnel between T3 and T4 (Fig. 3) are used in estimating leakage. The leakage estimation is first carried out for each rock mass quality class and finally for whole tunnel stretch consisting different rock mass classes. Statistical values of different parameters and calculated specific leakage are given in Table 1, and a chainage wise leakage values are shown in Figure 5.

Table 1. Assessment of leakage through shotcrete lined headrace tunnel of the UTHP at full hydrostatic water pressure using Panthi (2006 and 2010) approach

Rock mass quality	Statistical value	J_s	D	f_a	H	Rock mass parameters			q_t
		m	m	l/min/m^2	m	J_n	J_r	J_a	l/min/m
Good quality rock ($Q \geq 4.0$)	Min	-	144	0.003	29	3	1.0	0.8	0.4
	Mean	15	400	0.005	91	6	1.8	2.2	2.7
	Max	-	533	0.012	115	12	3.0	6.0	12.4
	Sd	-	101	0.002	27	2	0.7	0.8	2.5
Fractured rock ($0.1 < Q < 4.0$)	Min	-	135	0.004	15	3	0.5	1	0.2
	Mean	10	439	0.007	53	8	1.6	3.3	3.1
	Max	-	652	0.019	90	18	3.0	8.0	26.3
	Sd	-	143	0.004	17	3	0.6	1.6	2.3
Weakness Zone ($Q \leq 0.1$)	Min	-	260	0.009	10	9	0.5	5.0	1.1
	Mean	5	483	0.011	26	17	1.0	8.4	1.8
	Max	-	535	0.019	65	20	1.0	10.0	2.3
	Sd	-	65	0.002	13	5	0.1	1.0	0.5
Overall between T3 to T4 with varying rock mass quality	Min	-	135	0.003	28	3	0.5	0.8	0.2
	Mean	10	416	0.006	93	8	1.7	3.0	2.7
	Max	-	652	0.019	115	20	3.0	10.0	26.3
	Sd	-	113	0.003	25	4	0.7	2.0	2.6

As one can see in Table 1, the average specific leakage from the headrace tunnel of the UTHP from chainage 2+914 m to 7+960 m is estimated to about 2.7 l/min/m tunnel. The maximum leakage of 26.3 l/min/m tunnel is estimated at the tunnel stretch where rock mass is fractured and open jointed whereas the lowest average value is estimated at the area with a rock mass with very good quality having tight and heled joints (Fig. 5).

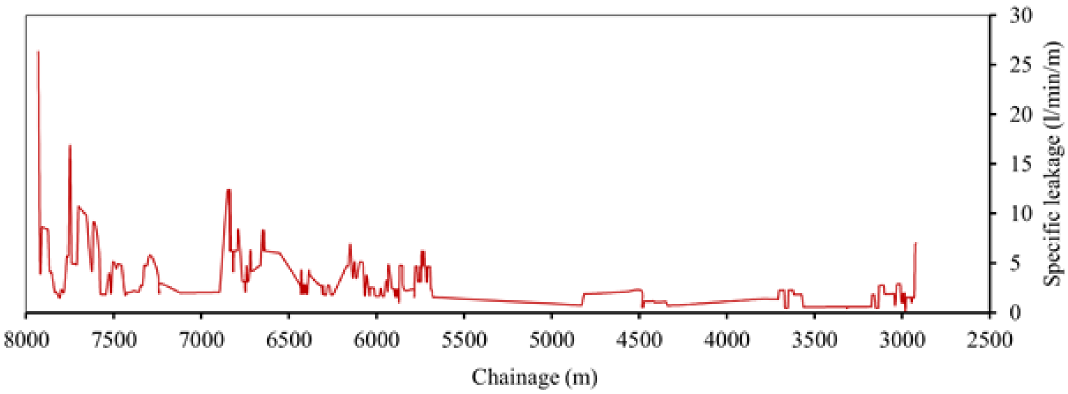

Figure 5. Estimated specific leakage (q_t) from the headrace tunnel of UTHP using Panthi (2006) approach.

As one can see in Figure 5, higher leakage values are estimated particularly at the downstream end of the headrace tunnel, especially downstream from chainage 5+700 m. At this tunnel stretch, an average specific leakage of about 5.4 l/min/m tunnel is estimated. The total water leakage out of this 2200 m tunnel length may exceed over 200 l/sec, which is quite considerable. Furthermore, the leakage possibility is even more dramatic at the far downstream part of the headrace tunnel from chainage 7+300 m from where an average leakage of 7 to 10 l/min/m tunnel may occur, which may lead to a leakage of over 100 l/sec from 660 m tunnel stretch. The assessment indicates that the likelihood of water leakage exceeding the limit prescribed by Panthi (2006) from the headrace tunnel stretch downstream from chainage 5+700 m is considerable if the tunnel is left without any further mitigation. It is emphasized that this is the tunnel stretch where Basnet and Panthi (2018) indicated that there is a high risk of hydraulic jacking due to marginal level of the minimum principal stress magnitude prevailing at this part of the tunnel.

5 CONCLUSION

The assessment made in this manuscript on the leakage potential from high pressure headrace tunnel of Upper Tamakoshi Hydroelectric Project (UTHP) shows that open joints and joints filled with silt and clay having low stiffness may lead to hydraulic jacking and water leakage during operation of UTHP. The specific leakage estimated along the headrace tunnel suggests that the downstream part of shotcrete lined headrace tunnel has high leakage risk needing mitigation measure before test water filling. Particularly, the tunnel stretch downstream from chainage 5+700 m has high degree of vulnerability regarding water leakage. Furthermore, a remark on the values of permeability factor (f_a) and hydrostatic head (H) is worth to be made here because the leakage depends not only on the three Q-value parameters described by Equation 1 but also with the values of f_a and H. The permeability factor (f_a) at the UTHP vary between 0.003 to 0.019 l/min/m^2 with a typical mean value of 0.06 l/min/m^2 whereas hydrostatic water head (H) varies between 30 to 120 m at the UTHP headrace tunnel. Finally, it is emphasized here that this estimation is based on the mapped records of Q-value parameters and the mapping itself is a subjective issue and the estimated values may subject to vary than as estimated here.

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