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Stability And Water Leakage In Unlined/Shotcrete Lined Tunnel: A Case Study Of Headrace Tunnel Of Langtang Khola Hydroelectric Project, Rasuwa, Nepal

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Abstract
Building unlined tunnels in Nepal poses unique challenges because of the country's fragile geology and operation of unlined tunnel can result into instability due to hydro fracturing and massive leakage out of water. The primary concern in constructing unlined tunnels in Nepal is the safety and stability of the tunnel structure since they are more prone to structural instability. Therefore, thorough evaluations are necessary to ensure their longevity and safety. The purpose of this research is to discuss the difficulties faced during tunnel construction, determine the water leakage and carry out cost optimization, focusing specifically on the stability and water leakage of unlined tunnels on analyzing a case of Langtang Khola Hydroelectric Project, Langtang.

Keywords
Unlined tunnel, Stability, Water Leakage

1. Introduction

Tunneling for hydropower has been in practice for a long time in Nepal. From an engineering perspective tunneling in Nepal has many challenges due to the presence of jointed rock mass, sheared, and weak zones as we are tectonically in an active zone. Principally, the stability problems in tunneling in Nepal may be related to two major factors; non-geological and geological [1].The non-geological aspect pertains to the proficiency and knowledge acquired in tunneling, particularly with regard to the abilities to interpret information and make informed decisions throughout the planning and execution stages of tunneling projects. The significance of the capability to assess, appraise, and address stability concerns during the planning and construction phases, along with the tools, techniques, and technology employed in this process, cannot be overstated. An incorrect interpretation can potentially lead to substantial financial losses, amounting to millions. The non-geological factor is not considered in this research, and we are focused on geological factors. They are mentioned below [1]:

a) weak rock mass quality,
b) high degree of weathering and fracturing,
c) rock stresses and
d) groundwater effect.

Unlined tunnel refers to tunnels where there is only limited concrete or shotcrete to protect against tunnel collapse. Unlined tunnel required rock stresses higher than water pressure or else hydraulic fracturing may occur in unlined tunnel producing catastrophic impact to the project and the surrounding.In unlined tunnel we prefer low permeability to prevent leakage. The practice of unlined hydropower tunnels and shafts have been in present in the world from ages. The benefit of using unlined tunnels and/or shafts is a significant reduction in construction costs and construction time [2]. Construction of unlined tunnel is challenging yet very beneficial if done properly. Use of grouting is fruitful to reduce leakage from unlined tunnel. In the Himalayas, the longstanding practice has been to use entirely concrete-lined tunnels as the ultimate means of rock support, even for low-pressure headrace tunnels. However, this can be circumvented by harnessing the inherent self-supporting properties of the rock mass [3]. The true difficulty lies in the precise anticipation and measurement of potential water seepage, enabling the inclusion of cost implications in the planning phase of a water transportation tunnel project [4].Therefore, thorough evaluations of leakage out are necessary to ensure economic return and safety. The purpose of this research is to assess possible leakage from unlined tunnel and ensure stability.

2. Study Area

Langtang Khola Hydroelectric Project is a Run-of-River (ROR) project which is being developed in the Langtang basin at Gosainkunda Rural Municipality of Rasuwa district. The projects install capacity is 20 MW and about 2.98 km of headrace tunnel has been excavated and the HRT is situated in gneiss rock condition. The rated head for this project is 192 m with a design discharge of 12 cumes. The final size of head race tunnel will be 3.4m x 3.5 m however, in the last section for around 220 m the size will be around 3.0 m x 3.3 m. The tunnel is planned to unlined in most of the part due to presence of fairly strong rock mass and some very weak sections will be concrete lined.

On site visit and collection of data available from site, various types of rock were determined and classification on the basis of chainage.

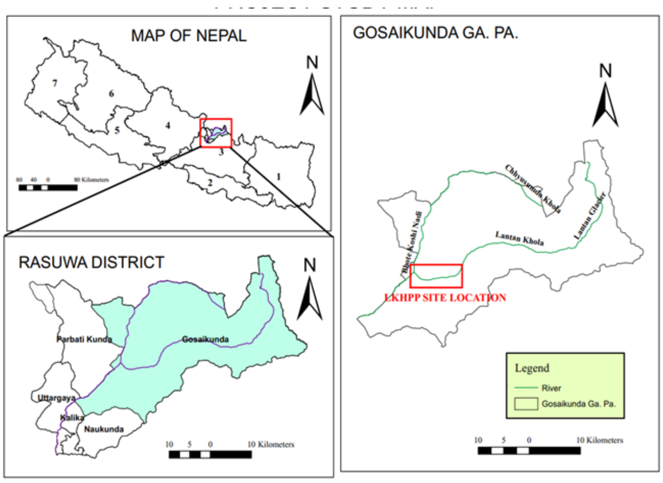

Figure 1: Langtang khola Hydropower Project

Table 1: Chainage and Rock Type Data

From Chainage	To Chainage	Rock Type
0+000	1+375	Kyanite Gneiss
1+375	1+490	Schistose Gneiss
1+490	1+950	Quartzite
1+950	2+105	Schistose Gneiss
2+105	2+985	Augen Gneiss

The rock mass classification of the Langtang Khola Hydroelectic Project was done from the measured Q-value. And most of tunnel section falls under support class I, II and III which helps us to conclude that this tunnel rock-mass is favorable to be unlined on judging on rock characteristics alone.

Table 2: Rock Mass Classification

Rock Support Class	Q-Value	% of Rock
Class I	Q>10	21.8
Class II	4<Q<10	38.5
Class III	1<Q<4	33.6
Class IV-A	0.4<Q<1	5.1
Class IV-B	0.1<Q<0.4	1.0
Class V-A	0.01<Q<0.1	0.1
Class V-B	Q<0.01	0.0

3. Methodology

The methodology and theories related with this paper has been explained as,

3.1 Design and Construction Principle of Unlined Tunnel

The philosophy that governs the design of the construction of unlined tunnel can be explained as,

3.1.1 Rule-of-thumb

Before 1970, there were no calculation used to locate unlined tunnel but was based on the condition that the tunnel should be located deep enough i.e., the internal water pressure was balanced by weight of overlying rock. But it was not applicable to all as some failures were observed in tunnel following this rule.

3.1.2 Updated rule-of-thumb

Updated rule-of-thumb was introduced. It provided a formula given below.

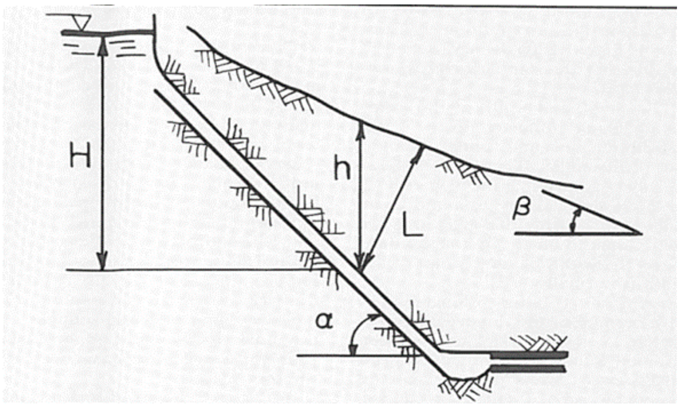

Figure 2: Updated Rule of Thumb

$$L > \frac{\gamma_w H}{\gamma_r \cos(\beta)} \tag{1}$$

Where,
L = Shortest distance between the surface and the point studied (in m),

Even this updated rule-of-thumb was not sufficient for design as some unlined tunnels which were accepted by this rule were observed to fail. In recent years there were tendency to measure stress near penstock location as there was huge pressure and unacceptable water loss was observed near it.

3.1.3 Design based on Finite Element Model

The process of designing an unlined tunnel using finite element modeling involves the initial step of conducting a comprehensive geotechnical investigation to gain insights into subsurface conditions and material properties. Subsequently, a finite element model is crafted, which encompasses the tunnel's specific geometry and the adjacent rock, while also incorporating suitable material models and boundary conditions. This model undergoes thorough analysis to evaluate stress, displacement, and overall safety, thereby ensuring the structural stability of the tunnel. In cases where issues arise, the design is adapted and corrected accordingly. Design chart for unlined pressure shafts based on relation between maximum static water head and depth of valley has been provided and in practise for designing of unlined tunnel and shafts[5].

3.2 Stability Assessment

Tunnel needs to be stable and favorable rock mass must be present to support unlined tunnel. For this research purpose two stability analysis were considered which are briefly described as follows.

3.2.1 Singh et al. (1992) criterion

This empirical approach generates a relationship between rock mass quality (Q value) and overburden (H) [6].

$$H = 350 \cdot Q^{1/3} \tag{2}$$

Squeezing Condition:

$$H \gg 350 \cdot Q^{1/3} \tag{3}$$

Non-Squeezing Condition:

$$H \ll 350 \cdot Q^{1/3} \tag{4}$$

3.2.2 Criterion of Goel et al. using Rock Mass Number (N)

It is crucial to accurately predict both non-squeezing and squeezing ground conditions when assessing stability. The approach introduced by Singh et al. necessitates the quantification of the Q-value, which relies on the Stress Reduction Factor (SRF). Quantifying the SRF rating can be challenging, leading Goel et al. to suggest an alteration using the concept of the rock mass number (N). Essentially, N can be thought of as Q with an SRF value of 1. [6]

$$N = [Q]_{\mathrm{SRF}=1} \tag{5}$$

A line demarcates the squeezing and non-squeezing case and the equation of this line is given below

$$H = (275 \cdot N^{0.33}) \cdot B^{-0.1} \tag{6}$$

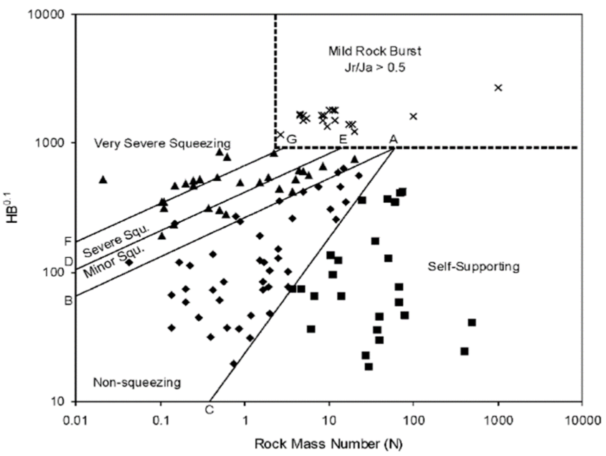

Figure 3: Plot between rock mass number(N) and $HB^{0.1}$ for predicting ground conditions [6]

Squeezing condition:

$$H \gg (275 \cdot N^{0.33}) \cdot B^{-0.1} \tag{7}$$

Non-squeezing condition:

$$H \ll (275 \cdot N^{0.33}) \cdot B^{-0.1} \tag{8}$$

where,
H = Overburden
N = Q-value without SRF
B = Span (width or diameter)

3.3 Leakage Analysis

After completing tunnel stability analysis we need to quantify the leakage as it is another important parameter in unlined tunnel. Thus, leakage analysis is a crucial part of study if the tunnel is planned to be unlined. A semi-empirical approach was proposed by panthi [7] and [4] that analyzes the following parameters: hydro-static head (H), joint set number (Jn), joint roughness (Jr), joint alternation (Ja) and joint permeability factor (fa) to estimate the specific leakage (qt) whose unit is l/min/m in unlined or shotcrete lined tunnel.

$$q_t = f_a \cdot H \cdot \frac{J_n \cdot J_r}{J_a} \tag{9}$$

The value of joint permeability can be estimated using equation below.

$$f_a = \frac{J_p}{D \cdot J_s} \tag{10}$$

Jp=Joint Persistence (max. up to 25mm)
Js=Joint Spacing of most frequently occurring systematic joint set

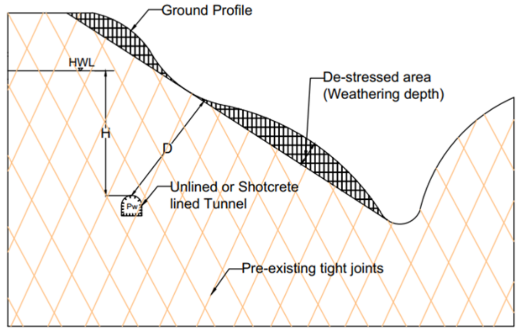

Figure 4: Idealized Topographic Arrangement

4. Result and Discussions

Tunnel stability depends on Rock Mass Quality and Mechanical Processes [7]. There are many methods for analysis of tunnel stability. Empirical method is purely based on experience and comparison. The stability analysis which were carried out on the Headrace tunnel(HRT) of Langtang Khola Hydroelectric Project(LKHPP) are given below.

4.1 Singh et al. (1992) approach

On analysis of unlined Headrace tunnel using singh et al.. approach it was found that only chainage 1+250m, 1+235m and 1+228.95m were squeezing and rest were not squeezing which was verified on site as well as on this section we had to install support class IV-B and higher referring to greater support provided with steel ribs.

Table 3: Singh et al. analysis of LKHPP

Description	1+228.95	1+235	1+250
Overburden (m)	263.01	264.85	268.53
Q-Value with SRF	0.2	0.2	0.25
Singh et al.	204.68	204.68	220.49
Result	Squeezing	Squeezing	Squeezing

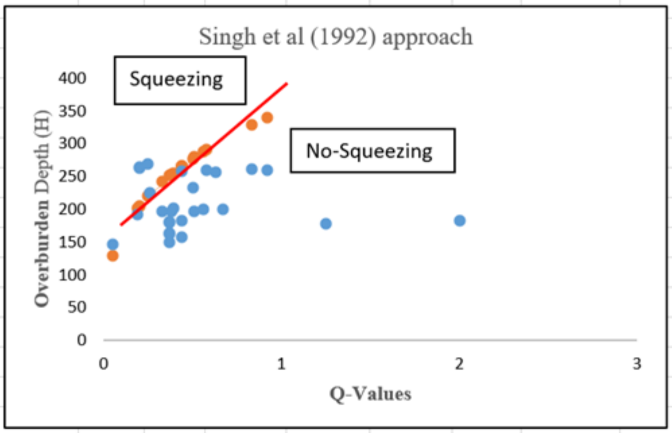

Figure 5: Output from Singh et. al.

4.2 Goel et al. approach

Goel based its empirical approach on the value of Q-method without SRF. On analysis of LKHPP using this approach three sections were predicted to be squeezing.

Table 4: Goel et al. analysis of LKHPP

Description	1+228.95	1+235	1+250
Overburden (m)	263.01	264.85	268.53
Q-Value without SRF	1	1	1.25
Result	Squeezing	Squeezing	Squeezing

4.3 Block Stability Analysis

Block formed by intersection of joints can cause problem in unlined tunnel as it has chance of failure when favorable condition is present so in order to analyze the block, we are using Unwedge software. Critical sections identified from site investigation were taken and their joint data were collected which was analyzed using Unwedge. In this program wedge are subjected to gravity loading only, stress field are not taken into consideration that may affect the factor of safety.

4.3.1 Chainage 1+366m

Three joint set are measured and wedge analysis was carried out as shown in the Figure 6. One of the block was found to be unstable which required support.

Table 5: Parameter of Unwedge Software

Observation	Value	Unit
Unit Weight of Rock	2.7	t/m^3
Unit Weight of Water	0.00981	t/m^3
Cohesion	10	33.6
Friction Angle	30	degree

4.4 Leakage Analysis

The extent of water leakage from tunnels during their operation is influenced by various factors, including the level of jointing, the size of joint apertures, the condition of infilling, the spacing of adverse joint sets, the persistence of these joints, the hydrostatic water pressure, the distance from the tunnel to the surface topography, and the orientation of the joint set-in relation to the slope of the valley side. On analysis of leakage using semi empirical approach using the Equation 9 and 10, we were able to quantify leakage as shown in Figure 7.

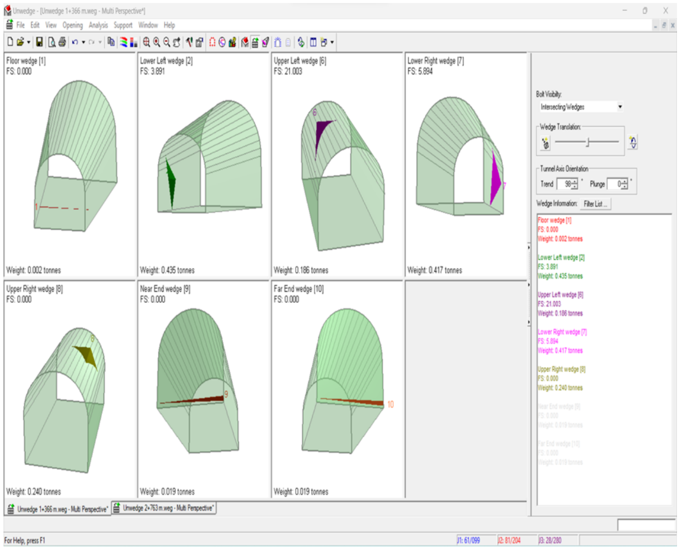

Figure 6: Output from Unwedge Block Analysis

Table 6: Cost Optimization

Description/ Leakage	0.8 l/min/m	0.9 l/min/m	1.1 l/min/m
Total Leakage (l/min/m)	2385.6	2683.8	3280.2
Present Value of Loss due to Leakage	32,372,212.22	36,418,738.75	44,511,791.81
Grand total cost of Consolidation Grouting (NRs)	42,673,761.90	42,673,761.90	42,673,761.90
Difference in cost of grouting and present value of revenue loss	(-10,301,549.68)	(-6,255,023.15)	1,838,029.91
Interpretation of the cost optimization	Grouting not required	Grouting not required	Grouting required

The leakage from semi-empirical analysis seems to have two peaks, first peak at range of 1+470 to 1+560 m with maximum leakage at 1+560 m of 29.3 lit/min/m and second peak at range from 2+460 to 2+640 m with maximum leakage of 27.8 lit/min/m at 2+520 m.

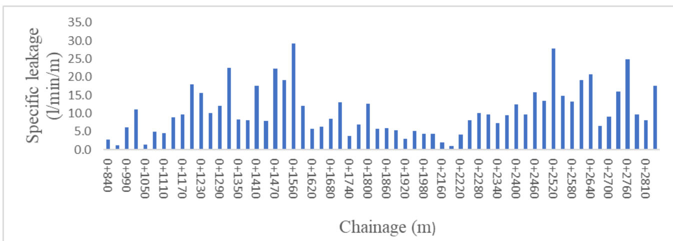

Figure 7: Water leakage quantified on HRT

4.5 Cost Optimization and Specific Leakage

Specific water leakage out of the tunnel in unlined/ shotcrete lined tunnel is difficult to stop completely as rock mass and shotcrete lining tends to have permeable nature. Even if the unlined tunnel is stable there might be a possibility of leakage which poses even greater threat to the operation and create other hazards near the site. The major aspect of unlined water tunnel is the control of water leakage and for Nepal, according to Panthi [4], the maximum leakage allowed is 1.5 l/min/m tunnel in general but we have further optimized the allowable water leakage by analyzing the cost of applying grouting and considering the loss of energy due to water leakage.

On the cost analysis as shown in Table 6 it was clear that any leakage above 1.1 l/min/m from the tunnel will cause economic loss. So, the leakage from HRT should be limited up-to 1.1 l/min/m, as shown in Figure 8. Grouting needs to be done in-order to limit the leakage and as mentioned on Table 6, no need to consider grouting up to 0.9 l/min/m as the cost of grouting will be more than the total revenue loss for 30 years of operation.

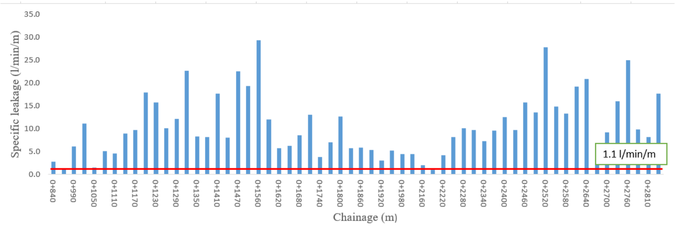

Figure 8: Allowable leakage in HRT from Cost Analysis

4.6 Site Observation

Even though the LKHPP headrace tunnel is unlined, the performance seems to be satisfactory as there is no major problem only five steel ribs of support class IV-B has been installed. On detail investigation of tunnel major problems encountered are listed below.

Table 7: Critical Sections and Problem identified on site

Chainage (m)	Observation
1+228.95	Water ingress, weakness zone, Construction occurring by placing ribs
1+235	Huge over-break and hanging rock mass needs immediate support
1+250	Weakness so ribs have been placed
1+575	Fragmented and weak rock mass
1+620	Fragmented, jointed rock mass
2+520	Shear band

4.7 Stability and Safety with respect to Geological Condition

On observation of LKHPP headrace tunnel there was no significant problem detected as almost all section (except few meters) needed no support and work was being carried on with only rock spot bolts even which was not done throughout the tunnel so, tunnel seems fairly stable and no squeezing was detected.
On regards of safety, it was noted that until site visit there was no case of tunnel collapse or any other tunnel related problem or incident that harmed the safety of personal working there. But two accident incidents were informed to me by the site in charge which was due to poor handling of equipment rather than tunnel related problem.

5. Conclusion

In this research, stability and water leakage analysis of head race tunnel of Langtang khola Hydroelectric Project was carried out. Upon site investigation it was observed that unlined tunnel was being constructed with very minimum spot bolts and still no case of tunnel collapse or incidents of accidents were recorded till date. Some problematic sections were recorded whose stability assessment were carried out and no serious issue was detected as shown in analysis in earlier chapter. From the study the conclusion drawn were as follows

1. On empirical analysis, Singh et al. approach shows three critical sections were predicted to be squeezing and from Goel et al. approach only three sections were shown to be squeezing, thus tunnel seems to be fairly stable and On assessment of joint orientation and tunnel trend the alignment seems to be good thus minimum problem has been detected till date during excavation which was confired from Site Visit.
2. From consultation with site personals, it was found that rock responded favorably during unconfinement while advancing the tunnel as no squeezing or collapse has been encountered till date as per site personal.
3. As Langtang Khola Hydroelectric project has about 2.98 km of HRT and head of 192 m from the optimization, we recommend to minimize specific leakage to 1.1 l/min/m and, any leakage below this limit will have no economic consequences to the project so no need to reduce below this range and if the leakage is allowed to be above 1.1 l/min/m for the interval of 30 years it will lead to significant loss of revenue which is not feasible.
4. From block stabiliy analysis on a critical section shown in Figure 6, ruptures seen on site visit, shows the requirement of providing sufficient support on that block before complete collapse.

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References

[1] Krishna Kanta Panthi. Tunnelling challenges in nepal. In *Proc. in Norwegian National Tunnelling Conf*, 2004.

[2] Einar Broch and Arild Palmström. The design of unlined hydropower tunnels and shafts: 100 years of norwegian experience. *Int. J. Hydropower Dams*, 24:72–79, 2017.

[3] Kiran K Shrestha and Krishna Kanta Panthi. The use of self supporting capacity of rock mass for sustainable hydropower: An analysis of the middle marsyangdi headrace tunnel, nepal. *Hydro Nepal: Journal of Water, Energy and Environment*, 6:18–26, 2010.

[4] Krishna Kanta Panthi and Bjørn Nilsen. Uncertainty analysis for assessing leakage through water tunnels: a case from nepal himalaya. *Rock mechanics and rock engineering*, 43:629–639, 2010.

[5] Einar Broch. Development of unlined pressure shafts and tunnels in norway. 1984.

[6] Bhawani Singh and R.K. Goel. *Engineering rock mass classification*. Elsevier, 2011.

[7] Krishna Kanta Panthi. Analysis of engineering geological uncertainties related to tunnelling in himalayan rock mass conditions. 2006.