Selection of Optimal Tunnel Route and Tunneling Method based on AHP Technique.

Case Study – Broadlands Hydropower Project

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Abstract: Selection of optimal tunnel route and tunnelling methods for head raise tunnel of a hydropower project is one of the most critical and complicated steps in its design stage. Since factors involved are highly diversified, the decision making process is quite complicated. In this study, the Analytical Hierarchy Process (AHP), a multi criterion decision making tool was employed to establish the optimal tunnel route and the most appropriate tunnelling method for the established optimal tunnel route. The optimal tunnel route was established by evaluating two tunnel route options with ten factor criterion. Four tunnelling alternatives were evaluated against relevant ten factor criterion in selecting the most suitable tunnelling method for the selected optimal tunnel route. Criterion were limited to geotechnical, geological, geomorphological, safety, technical, economical and socio-environmental aspects. Analysis reveals that, route B, which is having the overall composite weight of 0.513 (51.30%) is the optimal tunnel route and combination of Drill & Blast method (section III of route B) and New Austrian Tunnelling Method (sections I and II of route B) is the most appropriate tunnelling criteria along the selected tunnel route.

Keywords: Analytical Hierarchy Process, Rock mass classification systems, Rock slope stability analysis, Drill & Blast method, New Austrian Tunnelling method

1. Introduction

Route selection is the critical initial step in the process of design and construction of a tunnel. In planning a suitable tunnel route, the geological, geotechnical, hydrological, hydro geological, socio-environmental, economic and technical factors need to be taken into consideration. However, these factors are heavily diversified and hence the planning and decision making process becomes complicated. Internationally, it has been practiced and proven that Analytical Hierarchy Process (AHP) can be used effectively in finding solutions to such complicated decision making problems and even the adoptability to tunneling industry has been proven [1].

Similarly, selection of tunneling method is also critical and is a complex decision making process in tunnel engineering. The selected tunneling method should ensure mine safety with least hazard levels and it should also be technically, economically and socio-environmentally sound enough.

1.1 Scope and Objectives of the Study

This study was aimed at selecting the most suitable tunnel route and tunneling method for BHP.

This study is focused on a part of the head raise tunnel of the Broadlands Hydropower Project (BHP), which is one of the major ongoing hydropower construction projects in Sri Lanka. It is located in the Central Highlands; approximately ninety kilometers east of Colombo city. This will be the last hydropower project of the Kelani River basin. The considered part of the tunnel has two proposed route alternatives, Route A and Route B and the lengths are 1.2 km and 1.5 km respectively. The specific objectives of the study are to,

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1. Carry out a comprehensive engineering geological study and a cost analysis for the proposed tunnel routes.
2. Recommend the most suitable tunnel route using Analytical Hierarchy Process (AHP).
3. Recommend the most appropriate tunnelling technique for the selected tunnel route using AHP method.

2. Methodology

The following methodology was adopted in order to achieve the above mentioned objectives.

2.1 Data Collection

Data collection was performed in order to obtain maximum amount of relevant engineering geological information of the area such as rock mass characteristics and ground water conditions [2] as the accuracy of the decision totally depends on the reliability and adequacy of the data collected from both literature and field.

Number of field data collections were performed to collect necessary data using exposed rock outcrops.

2.1.1 Desk Study

Initial study was performed on the case histories in applying AHP for projects of similar nature [1], [3], [4] and [5]. Geology and the Geomorphology of the area was studied using 1:50,000 scale topography and geology maps with contours at 10 m intervals prepared by the Survey Department of Sri Lanka and the geological maps of the study area developed by JICA at the feasibility study stage of the project [6].

2.1.2 Field Data Collection

Rock texture, discontinuity orientations and their conditions were obtained from previously carried out borehole logs, rock outcrops at the tunnel trace as well as from the walls of partly excavated adit of tunnel route A.

Considerable amount of socio-environmental information were gathered through the discussions made with the experts engaged in the project and with the village community.

2.2 Engineering Geological Assessment

Comprehensive Engineering Geological Assessment for the area was carried out to study the engineering geological behaviour of the two tunnel routes. The assessment was

initiated with the development of engineering geological maps for the particular area and subsequently the longitudinal cross sections along the tunnel routes. This was further extended by performing rock mass classification and stability analysis against possible rock slope failures along tunnel walls. The results are summarized in Annexure 01.

2.2.1 Rock Mass Classification.

The rock mass classification was performed to examine the properties of the rock mass in a very systematic manner and classify rock mass in to different rock classes. This can effectively combine the findings from observations, experience and engineering judgment in providing a quantitative assessment of rock mass conditions. The rock mass classification was performed along two tunnel routes using Rock Mass Rating (RMR) [7] and Rock Quality Index (Q method) [8] to examine the quality of the surrounding rock masses in a systematic manner and to classify rock mass into different rock classes. Sample calculation has been included in Annexure 02 and the results are summarized in Tables 01 to 04.

Rock Mass Rating (RMR)

Rock mass along each tunnel route was sectioned, based on the engineering geological characteristics and then a rock mass condition assessment was performed for each section using rock mass rating system for parameters given below;

- I. Uniaxial compressive strength of rock material.
- II. Rock Quality Designation (RQD).
- III. Spacing of discontinuities.
- IV. Condition of discontinuities.
- V. Groundwater conditions.
- VI. Orientation of discontinuities.

In this system, rocks are classified as;

Class I -	Very good rock, RMR 81-100
Class II -	Good rock, RMR 61-80
Class III-	Fair rock, RMR 41-60
Class IV-	Poor rock, RMR 21-40
Class V -	Very poor rock, RMR <20

$$\text{Overall RMR} = \Sigma (L_i \times \text{RMR}_i) / L \quad \dots (1)$$

Where;

- L_i -Length of the specific tunnel section
- RMR_i -RMR value of the specific section
- L -Total length of the tunnel route

Rock Tunneling Quality Index (Q Method)

The Q index is used to classify rock mass around an underground opening and is used as a guide for the design of the tunnel support requirements [8]. The numerical value of the index Q varies on a logarithmic scale from the value 0.001 to a maximum value of 1,000. This is defined as;

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \quad \dots(2)$$

Where,

RQD	-	Rock Quality Designation
J_n	-	Joint set number
J_r	-	Joint roughness number
J_a	-	Joint alteration number
J_w	-	Joint water reduction factor
SRF	-	Stress reduction factor

In this system, rocks are classified as;

Class A	- Exceptionally good rock- Q 400-1000
	Extremely good rock- Q 100-400
	Very good rock- Q 40-100
Class B	- Good rock, Q 10-40
Class C	- Fair rock, Q 04-10
Class D	- Poor rock, Q 01-04
Class E	- Very poor rock, Q 0.1-01
Class F	- Extremely poor, Q 0.01-0.1
Class G	- Exceptionally poor, Q 0.001-.01

Similar to RMR, overall Q for each tunnel route was estimated as given below

$$\text{Overall } Q = \Sigma (L_i \times Q_i) / L \quad \dots(3)$$

Where;

L_i	- Length of the specific tunnel section
Q_i	- Q value of the specific section
L	- Total length of the tunnel route

2.2.2 Rock Wedge Stability Analysis

Failures along discontinuities, such as faults, bedding planes and joints are common during underground excavations in hard rock masses [9]. In this regard, stereonet analysis, which is a graphical technique [9], was performed considering only the major joint sets in the particular sections. Section 3.5 presents the results of the rock wedge stability analysis.

2.2.3 Tunnelling Cost Analysis

The tunnel construction cost per meter run of the two route options were evaluated for the purpose of tunnel construction cost comparison. The construction cost includes excavation and supporting cost. Data for cost items were obtained from Kukuleganga and Upper Kothmale Hydropower Projects in Sri

Lanka [10]. The results are summarized in Table 06 and 07 .

2.3 Applying Analytic Hierarchy Process (AHP)

There are many factors involved in the selection of tunnel route and tunneling method. Therefore, a multiple factor decision making approach was required for this analysis. In this regard, the AHP method, which was introduced by Prof. Thomas L. Satty in 1980 was adopted [11].

After identifying the problem, selection of criterion was carried out based on factors which are explicit in the problem stated.

Then the possible alternative solutions for the problem were identified and the solution process was proceeded to select the most appropriate alternative [11]. Figure 01 shows the structure of hierarchy for above three steps.

Figure 01 - Structure of Hierarchy for AHP

In selecting optimal tunnel route, the identified main criterion were: surrounding rock type, rock slope stability, tunnel overburden, tunnel geometry, geomorphology, tunnel construction safety, socio-environmental impacts, tunneling cost (drilling, blasting, supporting etc), construction duration and length of the tunnel route. The alternatives were Route A and Route B.

To identify the main criterion to be incorporated in the AHP model, the importance of above mentioned factors were assessed. For this purpose, a survey was conducted among 23 experts from different functional levels in local tunneling industry.

In selecting the suitable tunneling method, the identified factors were rock mass properties, tunnel geometry, tunnel overburden, ability of mechanization, groundwater level and expected water inflow, tunnel construction safety, socio-environmental impacts, surface disturbances, time/cost considerations and local experience [1]. These factors were evaluated over three alternative tunneling methods namely drill and blast (D & B), cut and

cover (C & C), and New Austrian Tunneling Method (NATM). The Tunnel Boring Machine (TBM) option was not considered since it is uneconomical for short length tunnels.

For the assessment, a questionnaire with a five-point scale for each of the criterion had been prepared. The respondents were asked to rate each factor according to a five-point scale, based on the priority that should be placed for each factor.

A weight had been assigned to each alternative through a pair-wise comparison based on the studied geological, geotechnical and other relevant conditions. The pair-wise comparison matrices were made with the aid of the scale of relative importance defined by Satty, 2008 [11]. The relative priorities of alternatives were obtained by this comparison and hence the relative suitability of the available alternatives to serve the objective was defined.

Specimen calculation

Step 1:

Pair-wise comparison of route A and B against "Surrounding rock conditions"

According to rock mass classification, the average importance of route A over route B in terms RMR and Q values is nearly 25%. It is almost 1/4th of the scale. Therefore, surrounding rock type of route A is weakly important than route B. Referring to the table of relative importance defined by Satty, the intensity of importance is 3. This is marked on the Satty's scale of relative importance as follows.

Step 2:

Build up pair wise comparison matrix

According to the rules of AHP, the built up pair wise comparison matrix is as follows.

Surrounding rock type	Route A	Route B
Route A	1	3
Route B	1/3	1

The normalized principal Eigen vector (also called priority vector) (w) is calculated and given by;

$$w = \begin{bmatrix} 0.75 \\ 0.25 \end{bmatrix}$$

The priority vector provides relative weights of the two route alternatives against "surrounding rock conditions". The weight of Route A is 75% and the weight of route B is 25%.

Step 3:

Check for consistency

When many pair wise comparisons are performed, some inconsistencies may typically arise. Therefore consistency of judgment is checked as follows.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \dots (4)$$

Where CI is the consistency index, n is the size of the matrix and λ_{max} is the principal Eigen value.

For this specimen calculation,

$$n = 2$$

$$\lambda_{Max} = 4/3 \times 0.75 + 4 \times 0.25 = 2.0 \quad \dots (5)$$

$$\text{Hence, } CI = (2 - 2) / (2 - 1) = 0 \quad \dots (6)$$

According to AHP theory, if $\lambda_{Max} = n$, then the judgments have turned out to be consistent.

The composite weight of each alternative against all selected criterion can be determined using the decision matrix. Hence the relative suitability of the available alternatives is defined to serve for the objective.

The AHP method was applied twice separately to serve two initial objectives. First, to select the optimal tunnel route and then to select the most suitable tunneling method. The composite weights derived are summarized in Tables 08, 09 and 10.

3. Engineering Geological and Cost Assessment

3.1 Geographical Condition of the Area

The Broadlands Hydropower Project area is located in the central highlands; approximately ninety kilometres east of Colombo city. The area is widely underlain by Precambrian Gneiss. Two tributaries of the Kelani River, Maskeli Oya and Kehelgamu Oya join each other immediately downstream of the proposed dam site [6].

Kelani River forms a deep valley at the project area. The river bed elevation in this area is approximately 100 m from mean sea level. The

slopes on both banks rise to ridges of more than 500 m elevation.

For this study, only the area marked in green colour dotted line in Figure 02, which enclosed the selected tunnel route alternatives up to common main tunnel, was considered.

3.2 Engineering Geological Mapping

Engineering geological map of the particular site under study was developed as depicted in Figure 03 and exhibits the information of existing rock types, the arrangement of different rock beds below the ground, the details of existing structural geological features

of the area and the various topographical features.

3.3 Geological Subsurface Profiles along Tunnel Routes

Based on the available borehole logs and geological maps, sub surface profiles along the tunnel routes were developed. However, it should be emphasized that, most of the performed boreholes were not exactly aligned on the proposed tunnel routes and hence the sub surface conditions were interpreted using the nearest borehole data to come up with most reasonable geological sub surface profiles and presented in Figures 03 and 04.

Figure 02 - Tunnel Routes A and B in area Geology Map

Figure 03 - Geological Sub Surface Profile along Tunnel Route A

Figure 04 - Geological Sub Surface Profile along Tunnel Route B

3.4 Results of Rock Mass Classification

Relevant RMR and Q charts are provided in Annexure 03.

Table 01 - RMR and Rock Mass Quality and Supporting System along Route A

Tunnel section (m)	RMR	Rock mass quality	Supporting system
0-8	44	Fair	1 & 2
8-323	35	Poor	3 & 4
323-508	17	Very Poor	5 & 6
508-564	29	Poor	3 & 4
564-1200	43	Fair	1 & 2
Overall (Eqn (1))	38	Poor	

Table 02 - RMR and Rock Mass Quality and Supporting System along Route B

Tunnel section (m)	RMR	Rock mass quality	Supporting system
0-40	41	Fair	1 & 2
40-360	42	Fair	1 & 2
360-860	NA	-	-
860-1500	43	Fair	1 & 2
Overall (Eqn (1))	30	Poor	

Legend for supporting system

1. Systematic bolts 4m long, spaced 1.5-2 m in crown and walls with wire mesh in crown
2. 50-100 mm thick shotcrete in crown and 30 mm in walls
3. Systematic bolts 4-5m long, spaced 1-1.5 m in crown and walls with wire mesh
4. 100-150 mm thick shotcrete in crown and 100 mm in walls

5. Systematic bolts 5-6m long, spaced 1-1.5 m in crown and walls with wire mesh
6. 150-200 mm thick shotcrete in crown, 150 mm in walls and 50mm on face

Table 03 - Q value, rock mass quality and supporting system along Route A according to Q charts

Chainage (m)	Q	Rock mass quality	Supporting system category	
			Crown	Wall
0-8	4.750	Fair	1	1
8-100	3.770	Fair	4	1
100-220	1.430	Poor	4	4
220-323	0.530	very Poor	5	8
323-400	0.002	Exceptionally poor	8	7
400-508	0.067	Extremely poor	7	5
508-1200	5.000	Fair	3	1
Overall (eqn (3))	3	Poor		

Table 04 - Q value, rock mass quality and supporting system along Route B according to Q charts

Chainage (m)	Q	Rock mass quality	Supporting system category	
			Crown	Wall
0-200	0.9	Very poor	5	4
200-275	1.6	Poor	4	4
275-860	0	Cut and cover tunnel		
860-1500	5.6	Fair	3	1
Overall (eqn (3))	3	Poor		

3.5 Stereonet Analysis Results of Rock Joints

The stereonet plots as shown in Figure 05 to 07 were developed based on the major joint sets in the area, listed in Table 05. Individual plane failures are possible along all three joint sets. Out of them, most vulnerable is joint set 1 and least is joint set 3, which has the least dip. Wedge failures are possible along the combination of joint sets 1, 2 and 1, 3. The most vulnerable of them is the wedging along the intersection of joint sets 1, 2 for both routes.

Figure 05 - Stereonet Plot of Great Circles of

Rock Discontinuities with respect to Angle of Internal Friction for Route A Section 0-100 m

Figure 06 - Stereonet Plot of Great Circles of Rock Discontinuities with respect to Angle of Internal Friction - Route A Section 100-350m, Section 350-1500m and Route B Section 0-40m and Section 950 - 1500m

Results of the stereonet analysis are summarized in Figures 05, 06 and 07.

Figure 07 - Stereonet Plot of Great Circles of Rock Discontinuities with respect to Angle of Internal Friction - Route B Section 40 - 300 m

Table 05 - Orientation of Discontinuities

Joint	Strike	Dip
1	N 40 W	SW 70
2	N 55 E	SE 50
3	N 30 E	NW 50

3.6 Cost Analysis for Tunnel Route Alternatives

Based on the engineering geological assessment, the applicable excavation and tunnelling methods were identified.

Considering the outcome, the excavation and supporting cost per meter run of the two alternatives were estimated and summarized in Tables 06 and 07.

Table 06 - Total Cost Distribution for Each Section of Tunnel Route A

Chainage (m)	0-8	8-100	100-220	220-323	323-400	400-508	508 - 1200
Cost for Crown	810,000.00	21,938,422.22	28,615,333.33	29,649,694.44	27,542,985.56	32,422,800.00	87,441,888.89
Cost for Wall	972,000.00	11,178,000.00	25,156,000.00	21,592,233.33	23,869,486.67	26,852,400.00	84,078,000.00
Cost for Invert	1,311,040.00	15,076,960.00	19,665,600.00	16,879,640.00	12,618,760.00	17,699,040.00	113,404,960.00
Total Cost (LKR)	3,093,040.00	48,193,382.22	73,436,933.33	68,121,567.78	64,031,232.22	76,974,240.00	284,924,848.89

Calculation of per meter cost for tunnel route A

Mobilization of contractor (LKR) = 300,000,000.00
 Temporary Arrangements (LKR) = 170,000,000.00
 Total Cost for 1200 m (LKR) = 1,088,775,244.44
 Cost per 1m (LKR)(According to 2007 rates) = 907,312.70
 To find the value in year 2015,

$$FV = PV \times (1 + r)^y$$

Where; FV is the future value = Value in year 2015
 PV is the present value = Value in year 2007 = Rs. 907,312.70
 r is the rate of interest = 4% (Obtained from Annual Report of Central Bank)
 y is the period in years = 8

Hence,

$$FV = \underline{1,241,720.09} \text{ (LKR)} \quad \text{Say } 1,245,000.00 \text{ (LKR)}$$

Table 07 - Total Cost Distribution for Each Section of Tunnel Route B

Chainage (m)	0-40	40-150	150-200	200-275	275-860	860-1500
Cost for Crown	11,514,444.44	31,664,722.22	14,393,055.56	17,859,436.27		80,871,111.11
Cost for Wall	8,041,176.47	22,113,235.29	10,051,470.59	15,077,205.88	263,250,000.00	77,760,000.00
Cost for Invert	6,461,600.00	17,769,400.00	8,077,000.00	12,115,500.00		103,385,600.00
Total Cost (LKR)	26,017,220.92	71,547,357.52	32,521,526.14	45,052,142.16	308,302,142.16	262,016,711.11

Calculation of per meter cost for tunnel route B

Mobilization of contractor* (LKR) = 180,000,000.00
 Temporary Arrangements* (LKR) = 150,000,000.00
 * For tunnel
 Total Cost for 1500 m (LKR) = 1,075,457,100.00
 Cost per 1m (LKR)(According to rates in year 2007) = 716,971.40
 To find the value in year 2015,

$$FV = PV \times (1 + r)^y$$

Where; FV is the future value = Value in year 2015
 PV is the present value = Value in year 2007 = 716,971.40
 r is the rate of interest = 4% (Obtained from Annual Report of Central Bank)
 y is the period in years = 8

$$FV = \underline{981,224.87} \text{ (LKR)} \quad \text{Say } 985,000.00 \text{ (LKR)}$$

4. Applying AHP

4.1 Selection of Optimal Tunnel Route

As described in section 2.3, the ten criteria were prioritized using the results obtained from the questionnaire survey. Figure 08 depicts the priority chart of criterion. Then the pair-wise

incorporated in the assessment of best tunnelling method. The priority chart for the criterion is presented in Figure 09.

The tunnel route was divided into following three sections based on the engineering geological characteristics;

Figure 08 - Criterion Priority Chart for Optimal Tunnel Route Selection

Table 08 - Overall Composite Weights for Tunnel Route Alternatives

Criterion	Tunnel construction safety	Surrounding rock mass condition	Socio environment impact	Cost (Drilling, Supporting)	Rock slope stability	Tunnel overburden	Geomorphology	Length of the tunnel route	Construction duration	Tunnel geometry	Composite weight
Weight	0.117	0.116	0.113	0.110	0.098	0.096	0.092	0.090	0.088	0.080	-
A	0.167	0.750	0.111	0.250	0.500	0.750	0.500	0.750	0.750	0.500	0.487
B	0.833	0.250	0.889	0.750	0.500	0.250	0.500	0.250	0.250	0.500	0.513

comparison matrices were developed and the weights of each alternative against each criterion were calculated as described in section 2.3 under specimen calculation. The overall composite weights are listed in Table 08.

From the overall composite ranking of the two routes, it can be concluded that the tunnel route B, having a rating of 0.513 (51.3%) is preferred over route A.

4.2 Selection of Suitable Tunnelling Method

During the analysis under section 4.1, it was revealed that the tunnel route B is the most appropriate option. Hence, from there onwards, characteristic features of tunnel route B were

1. Section I- From chainage 0 to 200 m
2. Section II -From chainage 200 to 940 m
3. Section III -From chainage 940 to 1500 m

Each section was analysed against the applicability of each technique according to specific engineering geological characteristic assessment using AHP technique. The overall composite weights for each section are listed in Tables 09 to 11.

As depicted in Tables 09 to 11, the results of AHP reveals that, NATM is preferred for section A and B, and Drill and Blast method is preferred for section C.

Figure 09 - Criterion Priority Chart for Tunnelling Method Selection

Table 09 - Overall Composite Weights for Section I

Criterion	Tunnel Construction Safety	Groundwater level and expected water inflow	Time/cost considerations	Surrounding rock mass condition	Socio-environmental impacts	Tunnel overburden	Ability of mechanization	Surface disturbances	Local experience	Tunnel geometry	Overall Composite weight
Weight	0.117	0.115	0.113	0.108	0.103	0.101	0.093	0.086	0.086	0.079	-
D & B	0.106	0.140	0.260	0.260	0.286	0.260	0.333	0.283	0.600	0.106	0.257
C & C	0.633	0.574	0.633	0.106	0.140	0.106	0.333	0.074	0.200	0.633	0.353
NATM	0.260	0.286	0.106	0.633	0.574	0.633	0.333	0.643	0.200	0.260	0.390

Table 10 - Overall Composite Weights for Section II

Criterion	Tunnel Construction Safety	Groundwater level and expected water inflow	Time/cost considerations	Surrounding rock mass condition	Socio-environmental impacts	Tunnel overburden	Ability of mechanization	Surface disturbances	Local experience	Tunnel geometry	Overall Composite weight
Weight	0.117	0.115	0.113	0.108	0.103	0.101	0.093	0.086	0.086	0.079	-
C & C	0.750	0.750	0.750	0.500	0.125	0.100	0.500	0.125	0.500	0.750	0.495
NATM	0.250	0.250	0.250	0.500	0.875	0.900	0.500	0.875	0.500	0.250	0.505

Table 11 - Overall Composite Weights for Section III

Criterion	Tunnel Construction Safety	Groundwater level and expected water inflow	Time/cost considerations	Surrounding rock mass condition	Socio-environmental impacts	Tunnel overburden	Ability of mechanization	Surface disturbances	Local experience	Tunnel geometry	Overall Composite weight
Weight	0.117	0.115	0.113	0.108	0.103	0.101	0.093	0.086	0.086	0.079	-
D & B	0.250	0.875	0.833	0.750	0.167	0.250	0.500	0.750	0.125	0.500	0.507
NATM	0.750	0.125	0.167	0.250	0.833	0.750	0.500	0.250	0.875	0.500	0.493

5. Conclusions and Recommendations

5.1 Conclusions

The study was limited to the tunnel routes, A, chainage 0-1200m and for route B, chainage 0-1500m, from that point onwards, both the tunnel routes follow a common path.

According to the geological cross sectional profiles developed along tunnel routes, considered portion of the tunnel route A passes through charnockitic gneiss, marble and biotite gneiss and tunnel route B passes through charnockitic gneiss, silty sand and biotite gneiss. Top overburden part of the profile along both the routes are covered by rock blocks, boulders and soils of gravel silty clay and silty sand. The engineering geological assessment revealed that the surrounding rock masses of both tunnel routes belong to the poor rock class.

The overall RMR value of the tunnel route A is greater than that of the tunnel route B and overall Q value of tunnel route A is much greater than tunnel route B.

Both RMR and Q values of tunnel route A is much closer to the fair rock class. Therefore, the quality of the surrounding rock mass of the tunnel route A is considerably preferable than that of tunnel route B.

From the performed stereonet analysis for the major joint sets of the area, the rock wedge failures are possible along both tunnel routes.

The cost analysis revealed that tunnel route B is cost effective than tunnel route A. Per meter cost difference between two tunnel routes is approximately 21%.

For the considered conditions and criterion, the final result of the Analytical Hierarchy Process (AHP) for tunnel route selections revealed that the route B is the most optimal tunnel route.

According to the AHP analysis performed for tunnelling technique selection for tunnel route B, chainage 0 to 940 m, tunnel excavation has to be carried out using NATM and chainage 900 to 1500 m, the tunnel excavation has to be performed using Drill & Blast method. Therefore it can be concluded that a combination of Drill & Blast and New Austrian Tunnelling method should be applied for the tunnel route B.

5.2 Recommendations

From above analysis following recommendations can be made.

1. Route B is the most suitable tunnel route to be applied for the considered tunnel section of Broadlands Hydropower Project.
2. Combination of Drill & Blast method and New Austrian Tunnelling Method should be adopted in constructing the tunnel along route B.
3. RMR and Q values should be further verified through an additional geotechnical investigation programme or during the tunnel driving stage and the appropriate supporting system should be decided accordingly.

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References

1. Ataei, M., Jamshidi, M., Sereshki, F. and Jalali, S. M. E., "Mining method selection by AHP Approach". *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 54, 2008, pp 103-117.
2. Palmström, A. and Strömme, B. "Engineering Geology and Rock Engineering Applied in the Design of Norwegian Tunnels", *The Conference on Tunnels for the Third Millennium*. Prievidza Slovakia, Norway, 1996, pp 1-16.
3. Ahmed, N. G. and Asmael, N. M., "A GIS-Assisted Optimal Urban Route Selection Based on Multi Criteria Approach". *The Iraqi Journal for Mechanical and Material Engineering, Special Issue (D)*, 2009, pp 556-567.
4. Triantaphyllou, E. and Maan, S. H., "Using the Analytic Hierarchy Process for Decision Making in Engineering Applications: Some Challenges", *Inter'l journal of Industrial Engineering: Applications and Practice*, Vol. 2, No 1, 1995, pp 35-44.

5. Zolfani, S. H., Rezaeiniya, N., Zavadskas, E. K., & Turskis, Z., "Forest Roads Locating Based On AHP and Copras-G Methods: An Empirical Study Based On Iran", *E M Ekon. Manag.* 2011, 4, pp 6-20.
6. Japan International Corporation Agency, *Study of Hydropower Optimization in Sri Lanka, Final Report, Vol. I main report. Sri Lanka: Ceylon Electricity Board*, 2004.
7. Indian Bureau of Mines, *Application of Rock Mechanics in Surface and Underground Mining*, 2014, pp 34-51.
8. *Using the Q- system – Rock Mass Classification and Support Design*, Norwegian Geotechnical Institute, 2013, pp.10-40.
9. Hoek, E. and Bray, J.W., *Rock Slope Engineering*. 3rd ed., Institution of Mining and Metallurgy, London, 2005, pp 37-81.
10. Maeda - Nishimatsu Joint Venture, *Upper Kotmale Hydropower Project. Bid for Lot 02 Main Civil Works*.
11. Saaty, T. L., "Decision making with the analytic hierarchy process" *Int. J. Services Sciences*, Vol. 1, No. 1, 2008, pp 83-98.

Engineering Geological Assessment along Tunnel Route A

Route Section (m)	Engineering Geological Evaluation	Q Value	RMR Value	Surrounding Rock Pattern according to	
				Q	RMR
0-8	Terrain is rock platform, bedrock is pale greenish gray to gray color charnokitic gneiss, exposed, attitude is N10°W and SW∠65°. The bedrock depth on the cave top is 12~32m. Tunnel route penetrates the fracture zone F1, 1-2 m wide, attitude is N80°W and NE∠70°. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "Fair".	4.75	44	Fair	Fair
8-100	This section consist of gray ~ gray white marble rock, measured attitude is N10°W and SW∠65°, the bedrock depth on the cave top is 40~60 m. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "Fair".	3.77	35	Fair	Fair
100-220	This section consist of gray ~ gray white marble rock, measured attitude is N10°W and SW∠65°, the bedrock depth on the cave top is 12~15 m. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "Poor".	1.43	35	Poor	Poor
220-400	In this section, tunnel route penetrates the fracture zone F2, 60-90m wide, attitude is N20°W and SW∠35°, rock mass is broken. According to borehole logs BB 5 and ZK 8, the fracture zone consist of yellowish - brown mylonite. According to obtained RMR and Q values, the surrounding rock type is "exceptionally poor".	0.002	17	Exceptionally poor	very Poor
400-508	In this section, tunnel route penetrates the fracture zone F2, 60-90m wide, attitude is N20°W and SW∠35°, rock mass is broken. According to borehole logs BB 5 and ZK 8, the fracture zone consist of yellowish - brown mylonite. According to obtained RMR and Q values, the surrounding rock type is "extremely poor" and rock stability is extremely poor.	0.07	17	Extremely poor	very Poor

Route Section (m)	Engineering Geological Evaluation	Q Value	RMR Value	Surrounding Rock Pattern according to	
				Q	RMR
508-620	Tunnel route pass through gray ~ dark gray biotite gneiss, attitude is N10°W and SW∠ 40°. The bedrock depth on the tunnel top is 60~65 m. Tunnel penetrates the fracture F3, with mylonite as the major part, and cataclasites as partial part, the attitude is N15°W and SW∠45°, the rock mass is broken. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "very poor".	5.000	29	Fair	very Poor
620-850	As there is no borehole after 620 m chainage, it is assumed the geological condition is same as 508-620 section. Tunnel route pass through gray ~ dark gray biotite gneiss, attitude is N10°W and SW∠ 40°. According to stereo net analysis based on three major joint sets in this region, surrounding rock is unstable and may generate unstable blocks and wedges.	5.000	46	Fair	Poor
850-900	As there is no borehole after 620 m chainage, it is assumed the geological condition is same as 508-620 section. But due to the fracture F4, the conditions may be slight differ. Tunnel route pass through gray ~ dark gray biotite gneiss, attitude is N10°W and SW∠ 40°. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "Fair".	5.000	41	Fair	Fair
900-1200	As there is no borehole after 620 m chainage, it is assumed the geological condition is same as 508-620 section. Tunnel route pass through gray ~ dark gray biotite gneiss, attitude is N10°W and SW∠ 40°. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "Fair".	5.000	46	Fair	Fair

Engineering Geological Assessment along Tunnel Route B

Route Section (m)	Engineering Geological Evaluation	Q Value	RMR Value	Surrounding Rock Pattern According to	
				Q	RMR
0-40	Terrain is rock platform, bedrock is pale greenish gray to gray color charnockitic gneiss, exposed, attitude is N15°W and SW∠45°. The bedrock depth on the tunnel top is 06~10 m. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "very poor".	0.89	41	very poor	Fair - poor margin
40-200	Weakly weathered pale greenish gray to gray color charnockitic gneiss, the attitude is N10°W and SW∠40°. The bedrock depth on the tunnel top is 06~08 m. Tunnel route penetrates the fracture zone F1, 1-2 m wide, attitude is N80°W and NE∠70°. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "poor".	0.54	42	very poor	Fair - poor margin
200-275	Fully weathered to weakly weathered gray ~ gray white marble, the attitude is N8~17°W and SW∠38~48°, the structural face doesn't develop, rock is broken. The bedrock depth on the tunnel top is 06~08 m. From the stereo net analysis based on three major joint sets in this region, surrounding rock is said to be unstable and may generate unstable blocks and wedges. According to obtained RMR and Q values, the surrounding rock type is "very poor".	0.53	42	very poor	Fair - poor margin
275-750	Tunnel route pass through 5 ~22 m thick silty sand layer. According to CT3 and CT4 borehole logs, Highly decomposed materials available at tunnel depth. Rock mass classification is not applicable.	NA			
750-860	In this section, tunnel route penetrates the fracture zone F2, 60-90m wide, attitude is N20°W and SW∠35°, rock mass is broken. According to borehole logs BB 5 and ZK 8, the fracture zone consist of yellowish - brown mylonite. Only RMR value can be obtained and accordingly, surrounding rock is "very poor".		1		Very poor
860-1500	The tunnel penetrate through gray ~ dark gray biotite gneiss, the attitude is N25~65°W and SW∠20~80°, cave body penetrates fault F3 and F4 with width of 8~10m. According to RMR and Q values, rock mass is "fair"	5.58	43	Fair	Fair

Specimen Calculation for Rock Mass Classification

Route Option	A
Chainage (m)	508-620
Referred Borehole No	BB6

Rock Mass Quality (Q)

Parameter	Value	Rate
Rock Quality Designation (RQD)	100	-
Joint set number (J_n)	-	6
Joint roughness number (J_r)	-	3
Joint alteration number (J_a)	-	2
Joint water reduction factor (J_w)	56	0.2
Stress reduction factor (SRF)	-	1
Q value	5.000	
Rock Mass Quality	Fair	

Rock Mass Rating (RMR)

Parameter	Value	Rate
1. Uniaxial compressive strength of rock material.	15-20	2
2. Rock Quality Designation (RQD).	50	8
3. Spacing of discontinuities.		10
4. Condition of discontinuities.		11*
5. Groundwater conditions.		0
6. Orientation of discontinuities.		-2
RMR	29	
Rock Type	Poor	

4. Condition of discontinuities.	Condition	Rate
Discontinuity length (Persistence)	>20	0
Separation (Aperture)mm	1-5 mm	1
Roughness	unsmooth-smooth	2
Infilling	Soft	2
Weathering	unweathered	6
Total rate		11*

Guidelines for excavation and support of 10 m span rock tunnel in accordance with the RMR system (After Bieniawski 1989)

Rock mass class	Excavation	Rockbolts (20mm diameter, fully grouted)	Shotcrete	Steel sets
I – Very good rock RMR: 81-100	Full face 3 m advance	Generally no support required except spot bolting.		
II- good rock RMR: 61-80	Full face 1-1.5 m advance. Complete support 20m from face	Locally, bolts in crown 3m long, spaced 2.5m with occasional wire mesh.	50mm in crown where required.	None
III - Fair rock RMR: 41-60	Top heading and bench 1.5- 3m advance in top heading. Commence support after each blast. Complete support 10m from face	Systematic bolts 4 m long spaced 1.5-2m in crown and walls with wire mesh in crown.	50-100 mm in crown and 30mm in sides.	None
IV- Poor rock RMR: 21-40	Top heading and bench 1.0-1.5m advance in top heading. Install support concurrently with excavation, 10m from face	Systematic bolts 4-5m long, spaced 1-1.5m in crown and walls with wire mesh.	100 -150mm in crown and 100 mm in sides.	Light to medium ribs spaced 1.5m where required.
V - Very Poor rock RMR: 21-40	Multiple drifts 0.5- 1.5m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting.	Systematic bolts 5-6m long, spaced 1-1.5m in crown and walls with wire mesh. Bolt invert.	150-200mm in crown. 150 mm in sides, and 50mm on face.	Medium to heavy ribs spaced 0.75m with steel lagging and forepoling if required. Close invert.

It should be noted that above table has not had a major revision since 1973. In many mining and civil engineering applications, steel fiber reinforced shotcrete may be considered in place of wire mesh and shotcrete.

Estimated support categories based on the tunneling quality index Q (After Grimstad and Barton, 1993)

Support categories

- ① Unsupported or spot bolting
- ② Spot bolting, **SB**
- ③ Systematic bolting, fibre reinforced sprayed concrete, 5-6 cm, **B+Sfr**
- ④ Fibre reinforced sprayed concrete and bolting, 6-9 cm, **Sfr (E500)+B**
- ⑤ Fibre reinforced sprayed concrete and bolting, 9-12 cm, **Sfr (E700)+B**
- ⑥ Fibre reinforced sprayed concrete and bolting, 12-15 cm + reinforced ribs of sprayed concrete and bolting, **Sfr (E700)+RRS I +B**
- ⑦ Fibre reinforced sprayed concrete >15 cm + reinforced ribs of sprayed concrete and bolting, **Sfr (E1000)+RRS II+B**
- ⑧ Cast concrete lining, **CCA** or **Sfr (E1000)+RRS III+B**
- ⑨ Special evaluation

Bolts spacing is mainly based on Ø20 mm

E = Energy absorption in fibre reinforced sprayed concrete

ESR = Excavation Support Ratio

Areas with dashed lines have no empirical data

RRS - spacing related to Q-value

Si30/6 Ø16 - Ø20 (span 10m)
D40/6+2 Ø16-20 (span 20m)

Si35/6 Ø16-20 (span 5m)
D45/6+2 Ø16-20 (span 10m)
D55/6+4 Ø20 (span 20m)

D40/6+4 Ø16-20 (span 5m)
D55/6+4 Ø20 (span 10m)
D70/6+6 Ø20 (span 20m)

Si30/6 = Single layer of 6 rebars,
30 cm thickness of sprayed concrete

D = Double layer of rebars

Ø16 = Rebar diameter is 16 mm

c/c = RSS spacing, centre - centre

The Economic Comparison of Reservoir Type and Run of the River Type Hydropower Plants: A Case Study for Upper Kotmale Hydropower Plant

H.A.H. Amanda, W.A.D.S. Wijayapala, J.R. Lucas and W.J.L.S. Fernando

Abstract: Due to the severity of impacts predicted due to climate change issues, Greenhouse Gas (GHG) emissions need to be considered as a factor even for hydropower because of the identified emission possibilities associated with large reservoirs. Thus, when planning a large hydropower project at a selected location, it is important to decide on the type of power plant based on an economic comparison including environmental considerations. The existing 150MW, Talawakele run of the river type hydropower plant and the previously planned reservoir type Caledonia hydropower plant were selected for comparison in this study. Net greenhouse gas emissions from both projects were estimated based on several estimating techniques and for the economic comparison, the levelized cost of electricity of both projects were calculated. Results show that the unit cost of electricity generation from run of the river type is substantially lower (around LKR 4 per kWh) than that of reservoir type. On the other hand, as Upper Kotmale is a peak-serving plant, a separate comparison was done considering the night peak operation. Results show a loss to the country (around LKR 2 billion per year) by energy reduction due to not implementing the reservoir type Caledonia hydropower plant. It is concluded that for future large hydropower developments in the world, a similar study should be carried out before deciding to downsize the reservoir. The study has further concluded that GHG emission considerations are not strong enough to discourage reservoir type new hydropower plant developments.

Keywords: Reservoir, run of river, hydropower, GHG emissions, levelized cost

1. Introduction

When planning a large hydropower project at a selected location, it is important to decide whether to construct a reservoir type or Run of the River (ROR) type based on an economic comparison including environmental and other considerations. There are environmental, social and economic impacts of hydropower projects which cannot be neglected, especially for large hydropower plants.

Owing to the severity of impacts predicted to be caused by climate change, GHG emissions need to be considered even for hydropower because of CO₂ and CH₄ emissions associated with large reservoirs. Disturbance to the ecosystem or loss of ecosystem is a negative impact to the environment including deforestation, impacts on fish owing to flow reduction and aesthetic effects on waterfalls. Reduced flow across waterfalls may cause reductions in tourism. Resettlement is a critical social impact caused by large hydropower projects. The economic advantage of reservoir type is the ability to store water and hence to be dispatched during both wet and dry seasons. Dry seasons affect the river flow of ROR type and hence the electricity generation.

The objectives of this research are to estimate the quantifiable advantages and disadvantages of reservoir type and ROR type hydropower generation, and to assess the economic impacts of converting reservoir type hydropower projects to ROR type hydropower projects at the design stage. In addition to costs related to power plants, costs related to environmental, social and economic impacts of hydropower are considered for project comparison.

Almost all the major hydropower potential has been developed in Sri Lanka by now. Out of the two existing large ROR type hydropower plants, Upper Kotmale Hydropower Project (UKHP) was taken as the case study for this

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research. However, as there are other countries with untapped potential of hydropower, this research outcomes will especially be important to them.

2. Literature Review

Worldwide research publications on comparison between reservoir type and ROR type hydropower plants were studied to identify the research gap.

A study [1] has been conducted focusing on the Amazonian regions of Bolivia, Brazil, Colombia, Ecuador and Peru, where a large untapped hydropower potential is available, qualitatively comparing the reservoir type and ROR type based on the climate change impacts. The study concludes that it will be necessary to invest in reservoirs to increase the margin of reserve and cope with climate change. The study also indicates the local, social and environmental impacts associated with the exploitation of hydropower. Another study [2] has also been conducted based on the climate change impacts of hydropower, focusing on Central and South American regions where 60% of the electricity demand is met through hydropower. Building new storage reservoirs is given in it as a potential adaptation measure.

A review [3] done for Yunnan in China, qualitatively compares small and large hydropower projects for their environmental implications and socio-economic consequences. A comparison [4] between large and small hydropower projects in Tibet, based on the CO₂ equivalent states that small hydro performs better in terms of environmentally friendly development and low carbon energy than large hydro. In Tibet, large hydropower plants are essential to meet the large and growing electricity demand.

A study [5] from Western Himalayan region of India on environmental sustainability of ROR hydropower projects has been conducted. It presents a public perception cum data collection study on environmental impacts of small and large ROR hydropower projects. It concludes that every environmental impact of small hydropower is not “small” as compared to large hydropower and ignoring environmental impacts of small hydropower may not be a good practice in the Himalayan region.

A case study [6] has been conducted for Uma Oya hydropower project in Sri Lanka incorporating economic and socio-

environmental considerations into project assessment but GHG emissions from reservoir has not been considered in that.

Findings in the last two decades indicate that hydropower reservoirs produce GHGs as CO₂ and CH₄, raising the question whether hydro power based generation is a clean and green electricity source [7],[8]. Most of the past world studies [9],[10],[11],[12],[13] focused on GHG emissions from hydropower reservoirs due to flooded organic matter decaying under water and the quantifications were based on long term field measurements. The results were summarized for tropical and non-tropical regions separately.

Latest research findings on methods of GHG emissions from hydropower and quantification of them were studied because it is an emerging study area at present. The study done by A.B. Hidrovo *et al.*, “Accounting for GHG net reservoir emissions of hydropower in Ecuador”[8], presents a rough and holistic estimate of net annual GHG emissions from reservoirs in the absence of long term field measurements. It is difficult to estimate the costs related to all ecological impacts of hydropower projects and their research covered only deforestation.

3. Case Study

There are many reservoir type large hydropower projects in Sri Lanka [14] but only two large ROR type projects, namely Upper Kotmale Hydropower Project (UKHP) (150MW) and Kukule Ganga Hydropower Project (70MW) are in operation at present. These two were constructed during the recent past, compared to the time period in which the other reservoir type projects were implemented in Sri Lanka. Out of the above two, UKHP was selected for the case study in this research.

For UKHP, an earlier planned (1985-1987) Caledonia reservoir type project and the already implemented Talawakele ROR type project are taken for comparison. These two sites are located at Kotmale Oya in Nuwara Eliya District, Central Province, Sri Lanka. The distance between the two locations is about 10km. Table 1 gives the salient features of these two projects. The estimated cost of Caledonia reservoir project is given in 1986 prices. This price to be adjusted to 2014 prices for the economic comparison under this study and adjusted project cost is shown in Table 11.

Table 1 - Project features

Item	Caledonia Reservoir [15]	Talawakele ROR
Catchment (km ²)	235.80	310.60
Dam type	concrete gravity	concrete gravity
Dam height (m)	70.00	34.00
Gross storage capacity (MCM)	45.10	2.50
Effective storage capacity (MCM)	30.00	0.80
Reservoir/pond Area (km ²)	2.25	0.25
Rated head (m)	614.00	473.00
Maximum turbine discharge (m ³ /s)	40.00	36.90
Installed capacity (MW)	214.00	150.00
Estimated Annual Energy (GWh)	664.00	409.00
Project cost (million LKR)	7,920 (base year 1986)	53,040 (base year 2014)

The original proposal of Talawakele ROR had suggested to take tributary diversions to the main stream (Kotmale Oya) in order to get a larger catchment area. Accordingly, the annual energy generation was originally estimated as 512.00 GWh in the Environmental Study in 1995, but five waterfalls were to be impacted due to that proposal. Therefore, all the tributary diversions were cancelled. That resulted in the reduction of the annual energy to 409.00 GWh in the implemented Talawakele ROR project.

4. GHG Emissions from Hydropower Projects

In reservoirs/ponds, there are decomposed organic matter (flooded and upstream organic matter). These organic matters produce CO₂ and CH₄ which reach the water surface layer and release to the atmosphere by diffusion. CH₄ is also released by bubbling. These bubbles are produced in the methanogenesis process. Less CO₂ bubbles are also produced because CO₂ has a higher solubility than CH₄. GHG are again released to the atmosphere by degasification when the water passes through the spillways of the dam and turbines. This is due to the change of temperature, pressure and turbulence. GHG are also released to the atmosphere by diffusion in the downstream river. The previously generated turbulence helps the gases to be easily diffused to the air.

These emissions can be precisely determined by long term field measurements. In the absence of long term field measurements, a complete, rough and holistic estimate of net GHG emissions from hydropower projects per year (E_n) can be obtained from the Equation 1[8].

$$E_n = E_e + E_r + E_{tsd} + E_{com} \quad \dots(1)$$

Where,

E_e = GHG emissions due to the loss of ecosystem (pre-flooding)

E_r = GHG emissions from reservoir

E_{tsd} = GHG emissions from turbine, spillway and downstream river (post-flooding)

E_{com} = GHG emissions from construction, operation and maintenance

4.1 Estimation of Emissions from Loss of Ecosystem

The formula of photosynthesis and respiration [8], [16] was applied to estimate E_e . This is given in Equation 2.

The particular element called amylase is related to growth of dry matter in a plant. Dry matter weight of a plant type can be obtained from its Net Primary Production (NPP) data [8]. Table 2 gives typical NPP values for tropical forest and cultivated land [17].

Table 2 - NPP values

Land Type	NPP (dry matter (g)/m ² /year)
Tropical forest	1,500.00
Cultivated land	650.00

Table 3 gives the land use prior to inundation for the two selected projects.

Table 3 - Land use of the selected projects

Land Use	Caledonia Reservoir		Talawakele ROR	
	Land Type	Area (ha)	Land Type	Area (ha)
Dam site and reservoir	Tea	232.00	Tea	33.80
Resettlement area	Tea	368.00	Tea	26.20
Power house and switchyard	Tea	15.00	Forest	14.20

Based on the information in Table 2 and Table 3, the loss of dry matter production, and hence the CO₂ emissions per year of the two sites are

estimated as follows. NPP of tea plantations was assumed to be that of the available cultivated land data in literature.

- Loss of dry matter production due to loss of tea plantations in Caledonia reservoir project
 $= 650\text{gm}^{-2}\text{yr}^{-1} \times (232+368+15) \times 10^4 \text{m}^2$
 $= 3,997.50 \text{ ton/year}$

Hence, $E_e = 1.63 \times 3,997.50 \text{ ton CO}_2/\text{year}$
 $= 6,515.93 \text{ ton CO}_2/\text{year}$

- Loss of dry matter production due to loss of tea plantations and forest in Talawakele ROR project
 $= 650\text{gm}^{-2}\text{yr}^{-1} \times (33.80+26.20) \times 10^4 \text{m}^2 +$
 $1500\text{g m}^{-2}\text{yr}^{-1} \times (14.20) \times 10^4 \text{m}^2$
 $= 603.00 \text{ ton/year}$

Hence, $E_e = 1.63 \times 603 \text{ ton CO}_2/\text{year}$
 $= 982.89 \text{ ton CO}_2/\text{year}$

4.2 Estimation of Emissions from Reservoir

When land is inundated, decaying organic matter under water results in GHG emissions. This GHG emission was estimated using Equation 3 [8],[18].

$$E_r = E_f \times A_e \quad \dots(3)$$

Where,

E_f = Mean reservoir emission factor

A_e = Area of reservoir/pond

Following long term field measurements data, past studies [8],[19],[20] have shown that reservoir GHG emissions decay exponentially against reservoir life.

According to Zhang et al [18], it is almost impossible to determine this reservoir GHG emissions precisely in the absence of long term field measurements. Therefore, Zhang et al has applied directly a constant mean reservoir emission factor for the total reservoir lifetime. It showed that, boreal regions have a significantly lower GHG emissions than tropical regions. The boreal region is defined as the zone having a definite winter with snow, and a short summer, generally hot [21].

Sri Lanka is a tropical country. Long term field measurements has not been done in Sri Lanka yet. Therefore, constant mean E_f of tropical regions was selected for this research for the total power plant lifetime as given in Equation 3.

$$\text{Tropical } E_f = 2,771.60 \text{ g CO}_2\text{eq m}^{-2}\text{yr}^{-1} [18]$$

Table 4 - Reservoir/Pond areas

Reservoir/Pond	Area (km ²)
Caledonia reservoir	2.25
Talawakele pond	0.25

GHG emissions from reservoir/pond are estimated as follows based on Equation 3.

- E_r from Caledonia reservoir
 $= 2,771.60 \text{ g CO}_2\text{eq m}^{-2}\text{yr}^{-1} \times 2.25 \times 10^6 \text{m}^2$
 $= 6,236.10 \text{ ton CO}_2\text{eq/year}$
- E_r from Talawakele pond
 $= 2,771.60 \text{ g CO}_2\text{eq m}^{-2}\text{yr}^{-1} \times 0.25 \times 10^6 \text{m}^2$
 $= 692.90 \text{ ton CO}_2\text{eq/year}$

It should be noted that there may be differences between reservoir and ROR pond water behaviour. Water is always stored in the reservoir but in Talwakele pond, water is collected during the day time and used during the night peak hours. This may affect reservoir/pond GHG emission patterns, which have not been considered here.

4.3 Estimation of Emissions from Turbine, Spillway & Downstream River

According to Hidrovo et al [8], out of the total direct GHG emissions (E_r and E_{tsd}), 45% would come from the reservoir and 55% would come from turbine, spillway and downstream. Therefore, E_{tsd} was determined by Equation 4 [8].

$$E_{tsd} = \frac{E_r \times 55}{45} \quad \dots(4)$$

- E_{tsd} from Caledonia project
 $= 7,621.90 \text{ ton CO}_2\text{eq/year}$
- E_{tsd} from Talawakele ROR project
 $= 846.88 \text{ ton CO}_2\text{eq/year}$

4.4 Estimation of Emissions from Construction, Operation & Maintenance

Life Cycle Impact Assessment (LCIA) is an accepted tool which allows to identify the potential environmental impacts associated with a product or service, throughout its entire lifespan [22]. A LCIA has been performed by Hidrovo et al [22] to determine E_{com} .

For this research, LCIA's performed for reservoir type and ROR type hydropower projects were studied from literature. E_{com}

values of the two case study projects were estimated accordingly.

4.4.1 E_{com} of Caledonia reservoir project

Turconi et al [22] have critically reviewed case studies involving LCA of electricity generation from hydropower and found that E_{com} was in the value range of 11-20 kg CO₂-eq/MWh for dam reservoirs. Zhang et al [23] used LCA to compare two reservoir hydropower schemes, one with a concrete gravity dam (CGD) and the other with an earth-core rockfill dam (ECRD). They have found that the CGD scheme had a higher E_{com} (11.11 kgCO₂-eq/MWh) than ECRD.

Caledonia reservoir also has a CGD and hence the best available approximation of E_{com} for Caledonia was made as 11.00 kgCO₂-eq/MWh.

$$\text{Total } E_{com} = (11 \text{ kgCO}_2\text{-eq/MWh}) \times 664 \times 10^3 \text{ MWh} \\ = 7,304.00 \text{ ton CO}_2\text{-eq/year}$$

4.4.2 E_{com} of Talawakele ROR project

H. Hondo [24] performed LCIA for ROR type hydropower projects and found that a ROR (plant life: 30 years, plant factor: 45%) with small reservoir had E_{com} value as 11.00 kgCO₂-eq/MWh. The variation of that with plant life and plant factor is given in Table 5 and Table 6 [24].

Table 5 - Effects of lifetimes on E_{com}

Lifetime (years)	10	20	30 (ref)	50	100
E_{com} (kgCO ₂ -eq/MWh)	30.00	16.00	11.00	8.00	5.00

Talawakele ROR has a plant life of 50 years. Therefore, E_{com} value was approximated as 8.00 kgCO₂-eq/MWh which was a reduction by 3.00 kgCO₂-eq/MWh than the reference.

Table 6 - Effects of plant factors on E_{com}

Plant factors (%)	-10 pts	-5 pts	45 (ref)	+5 pts	+10 pts
kgCO ₂ -eq/MWh	14.00	13.00	11.00	10.00	9.00

Talawakele ROR has a plant factor of 30% and hence the values in Table 6 were plotted, as shown in Figure 1, to obtain E_{com} at that plant factor.

Figure 1 - Variation of E_{com} with plant factor in a ROR scheme with small reservoir

Extrapolation from Figure 1, gives the E_{com} value for Talawakele ROR as 15.30 kgCO₂-eq/MWh, which is an increase of E_{com} by 4.30 kgCO₂-eq/MWh from the reference.

Based on these findings, the best available approximation of E_{com} for Talawakele ROR project was made as 12.30 kgCO₂-eq/MWh, with 50 year plant life and 30% plant factor.

$$\text{Total } E_{com} = (12.30 \text{ kgCO}_2\text{-eq/MWh}) \times \\ 409 \times 10^3 \text{ MWh} \\ = 5,030.70 \text{ ton CO}_2\text{-eq/year}$$

4.5 Total Emissions

The net GHG emissions per year E_n of Caledonia reservoir project and Talawakele ROR project were calculated and tabulated as in Table 7.

Table 7 - Net GHG emissions (E_n) per year

Parameter	Caledonia Project (ton CO ₂ -eq/year)	Talawakele Project (ton CO ₂ -eq/year)
E_e	6,515.93	982.89
E_r	6,236.10	692.90
E_{tsd}	7,621.90	846.88
E_{com}	7,304.00	5,030.70
E_n	27,677.93	7,553.37

The specific GHG emissions have also been calculated and tabulated in Table 8.

Table 8 - Specific GHG emission

Project	GWh/year	Total GHG Emission (ton CO ₂ -eq)/year	Specific GHG Emission (g CO ₂ -eq/kWh)
Caledonia	664.00	27,677.93	41.68
Talawakele	409.00	7,553.37	18.47

It can be seen that even the GHG emissions from reservoir type hydropower projects are negligible compared to that of thermal power projects where specific GHG emissions are several hundred grams per kWh.

5. Economic Comparison of Selected Hydropower Projects

When making a decision on selecting a project among several project alternatives, technical feasibility and economic viability are two important criteria to be considered in engineering projects. The technical feasibilities of the two selected projects for comparison were ensured from their feasibility study reports. The decision making has been based on their economic viability.

5.1 Levelized Cost of Electricity (LCOE)

The economic comparison between the two types of plants was carried out by determining LCOE for each case.

$$LCOE = \frac{\text{Total Lifetime costs (LKR)}}{\text{Total Lifetime Energy Output (kWh)}} \dots(5)$$

The costs and benefits of the two types of plants were estimated as detailed below.

5.2 Loan Details

Financing for the UKHP was provided by Japan International Cooperation Agency (JICA) and the details are shown in Table 9.

Table 9 - Loan details of Talawakele ROR project

Parameter	Loan Details
Donor	Japan International Cooperation Agency (JICA)
Agreement	2003
Grace period	10 years
Loan repayment period	30 years
Average interest rate	0.93% on Japanese Yen (JPY)
Adjusted interest rate	10.65% on Sri Lankan Rupees (LKR)

5.3 Project Cost and Loan Amount

The project cost and the loan amount of the implemented Talawakele ROR project were calculated from the annual cost distribution data during the construction period. The result summary is given in Table 10.

Table 10 - Project cost and loan amount of Talawakele ROR project

Parameter	Value
Project cost (base year 2014) (million LKR)	53,040
Original loan amount (million LKR)	47,251
Loan as a percentage from project cost (%)	89.00
Adjusted loan amount at the end of grace period (million LKR)	51,834

The project cost of Caledonia reservoir was taken from the Feasibility Study report [1]. The percentage of the original loan amount from the project cost was estimated as 89.00% to maintain the same conditions in both projects for comparison. The project cost summary for the Caledonia reservoir case is given in Table 11.

Table 11 - Project cost and loan amount of Caledonia reservoir project

Parameter	Value
Project cost (base year 1986) (million LKR)	7,920
Adjusted project cost in 2014 (million LKR)	116,860
Original loan amount (million LKR)	104,005
Adjusted loan amount at the end of grace period (million LKR)	114,092

For this study, loan repayment schedules of Talawakele ROR and Caledonia reservoir projects were considered during the 30 years of loan repayment period. The purpose was to obtain the cash outflow from capital repayments and interest payments (finance cost) in order to use for LCOE calculations.

5.5 Plant Operation and Maintenance Cost

Actual O&M costs of the implemented Talawakele ROR type hydropower plant were obtained for year 2014, 2015 and 2016. The plant was commissioned on 14th July 2012 [25] and the O&M cost could be exactly obtained since 2014. Those annual O&M costs are given in Table 12.

Table 12 - O&M cost of Talawakele ROR type hydropower plant

Year	O&M Cost (million LKR)
2014	114.00
2015	140.00
2016	160.00

These costs were extrapolated to obtain the O&M costs for the rest of lifetime.

Figure 2 - O&M cost variation of Talawakele ROR type hydropower plant

O&M costs of Caledonia reservoir type hydropower plant were assumed to be proportionate to the plant capacity and hence the calculation of those were based on the O&M costs of Talawakele ROR type hydropower plant. A sample calculation is given below.

$$\begin{aligned} \text{O\&M cost of Caledonia reservoir plant in 2014} \\ \text{(million LKR)} &= \frac{(23 \times 1 + 92)}{150 \text{ MW}} \times 214 \text{ MW} \\ &= 164 \end{aligned}$$

5.6 Carbon Trading

Carbon trading, which is also called Clean Development Mechanism (CDM), is an international market introduced by the Kyoto Protocol (KP) as a global strategy to combat global warming [26].

In this study, the average carbon trading price from August 2005 to November 2017 was calculated as Euro 11.87/ton CO₂. Average Euro to LKR exchange rate for the same period was calculated based on the CBSL data (1 Euro = 155.48 LKR). The converted average carbon trading price of 1,845.58 LKR /ton CO₂ was taken for the calculations in this study.

If UKHP was implemented under CDM, the GHG emission reduction compared to baseline emissions defined for CDM projects, could have been sold via carbon trading to earn an income. In this study, that was considered as benefits for both projects.

Grid Emission Factor (GEF) is a parameter to determine the baseline emissions for CDM projects in the renewable energy sector and waste heat/gas recovery sector. It refers to CO₂ emission factor associated with each unit of electricity provided by an electricity system

[27]. The last updated GEF (in 2016) of Sri Lanka was taken for the calculations in this study.

$$\text{GEF in Sri Lanka} = 0.8199 \text{ ton CO}_2/\text{MWh} [28]$$

GHG emission reduction from Caledonia reservoir project compared to CDM baseline emissions

$$\begin{aligned} &= (0.8199 \times 664 \times 10^3 - 27,677.93) \text{ ton CO}_2/\text{year} \\ &= 516,736 \text{ ton CO}_2/\text{year} \end{aligned}$$

$$\begin{aligned} \text{Hence, CDM benefit (million LKR/year)} &= \\ (\text{LKR}1,845.58/\text{tonCO}_2) \times 516,736 \text{ tonCO}_2/\text{year} \\ &= 954 \end{aligned}$$

GHG emission reduction from Talawakele ROR project compared to CDM baseline emissions

$$\begin{aligned} &= (0.8199 \times 409 \times 10^3 - 7,553.37) \text{ ton CO}_2/\text{year} \\ &= 327,786 \text{ ton CO}_2/\text{year} \end{aligned}$$

$$\begin{aligned} \text{Hence, CDM benefit (million LKR/year)} &= \\ (\text{LKR}1,845.58/\text{tonCO}_2) \times 327,786 \\ \text{tonCO}_2/\text{year} \\ &= 605 \end{aligned}$$

5.7 Levelized Cost of Electricity Calculation and Economic Comparison

With above costs and benefits, two cash flows were prepared and Net Present Value (NPV) of total costs and NPV of energy were calculated considering the lifetime of the plants. The results are given in Table 13.

Table 13 - LCOE calculation summary

Parameter	Caledonia Reservoir Project	Talwakele ROR Project
NPV (Costs) MLKR	101,242	45,300
NPV (Energy) GWh	6,583.44	4,055.16
LCOE (LKR/kWh)	15.38	11.17

From Table 13, it can be seen that the LCOE from Talawakele ROR project is substantially lower compared to the Caledonia reservoir type project.

6. National Benefit

Reservoirs can store water and hence the expected operation during peak demand hours can be obtained in both dry seasons and wet seasons of a year. In ROR, the flowing water is collected and stored during the day time in dry seasons in order to operate during the night peak. The expected peak operation may not always be possible because the stored water

amount may not be sufficient to cover the entire peak period which is from 18.30 hours to 22.30 hours in Sri Lanka.

National benefits due to night peak operation of Caledonia reservoir and Talawakele ROR hydropower plants were calculated as detailed below.

Installed capacity = 214
 Annual energy (GWh) = 664
 LCOE (LKR/kWh) = 15.38
 Night peak hours per day = 4
 Annual night peak generation (GWh)
 $= 214 \times 4 \times 365 \times 90\% \times 10^{-3}$
 $= 281.20$
 Annual cost of generation during night peak (million LKR)
 $= 281.20 \times 15.38$
 $= 4,325$
 Similarly, calculations were made for Talawakele ROR hydropower plant. Accordingly,
 Annual night peak generation (GWh)
 $= 197.10$
 Annual cost of generation during night peak (million LKR)
 $= 197.10 \times 11.17$
 $= 2,202$

Case 1: assuming rated operation of UKHP during the total night peak period of a year,

Annual financial loss or negative national benefit due to not having the Caledonia reservoir plant (million LKR)
 $= 4,325 - 2,202 = 2,123$

According to the results shown in Case 1, even though the Talwakele ROR hydropower plant operates in its full capacity (assuming every year is a wet year), there is an annual loss of LKR 2,123 million to the country by not having the Caledonia reservoir plant for peak serving.

Case 2: based on the actual night peak operation data of UKHP obtained from System Control Centre (SCC) of Ceylon Electricity Board (CEB), annual financial loss,

Table 14 - night peak generation of UKHP on actual basis and financial loss or negative national benefit by not having Caledonia reservoir plant

Year	Night Peak Generation (GWh)	Annual Cost of Night Peak Generation (million LKR)	Annual Financial Loss (million LKR)
2014	172.00	1921	2,404
2015	187.00	2089	2,236
2016	146.00	1631	2,694

SCC daily records the maximum output (MW) of UKHP during the night peak operation and the time it occurred. In this study, it was assumed that the plant operated with that output for the total night peak period in the respective days. Accordingly, the generated night peak energy were calculated for each year from 2014 to 2016 as shown in Table 14.

The results of Case 1 and Case 2 are summarized and given in Table 15.

Table 15 - Annual financial loss or negative national benefit based on rated and actual operation of Talawakele ROR project

Year	Case 1: Loss (million LKR)	Case 2: Loss (million LKR)
2014	2,123	2,404
2015	2,123	2,236
2016	2,123	2,694

7. Conclusions and Recommendations

It is concluded that GHG emission considerations are not strong enough to discourage reservoir type new hydropower plant developments.

According to the LCOE results, it can be concluded that the ROR type has the overall economic benefit in the case of UKHP, but if the project objective is solely to capture the maximum hydropower potential or peak serving, it can be concluded that the reservoir type has a better overall economic benefit to the country.

It is recommended that for similar future large hydropower developments, a detailed similar study to be carried out before taking the decision on reservoir construction for hydropower generation. A case by case study is recommended to be conducted because the environmental factors such as the impact of flooding, melting snow and ice, etc. vary from location to location. The methodology presented in this study can be followed for such studies with suitable modifications where necessary.

Although hydropower projects do not have zero GHG emissions, as per this study, they are much less compared to thermal power plants. In view of grave need for limiting the average global temperature increase to 2 °C by the end of this century and the GHG emission reduction commitments made at the COP21 at

Paris, it is recommended that as many large-scale hydropower projects as possible to be implemented capturing all possible hydropower potential in the world.

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References

- Schaeffer, R. *et al.*, "The vulnerable amazon: the impact of climate change on the untapped potential of hydropower systems," *IEEE Power. Energy. Mag.*, vol. 11, no. 3, pp. 22-31, Apr. 2013.
- Harrison, G. P. and Whittington, H. W., "Vulnerability of Hydropower Projects to Climate Change," *Proc. IEE - Gener. Transm. Distrib.*, vol. 149, no. 3, pp. 249-255, May 2002.
- Hennig, T. *et al.*, "Review of Yunnan's Hydropower Development. Comparing small and large Hydropower Projects Regarding their Environmental Implications and Socio-economic Consequences," *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 585-595, Nov. 2013.
- Zhang J. *et al.*, "Review on the Externalities of Hydropower: A Comparison between Large and Small Hydropower Projects in Tibet based on the CO₂ Equivalent," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 176-185, Oct. 2013.
- Kumar, D. and Katoch, S. S., "Environmental Sustainability of Run of the River Hydropower Projects: A Study from Western Himalayan Region of India," *Renewable Energy*, vol. 93, pp. 599-607, Aug. 2016.
- Morimoto, R., "Incorporating Socio-Environmental Considerations into Project Assessment Models using Multi-Criteria Analysis: A Case Study of Sri Lankan Hydropower Projects," *Energy Policy*, vol. 59, pp. 643-653, Aug. 2013.
- Yang, L. *et al.*, "Progress in the Studies on the Greenhouse Gas Emissions from Reservoirs," *Acta Ecologica Sinica*, vol. 34, no.4, pp. 204-212, Aug. 2014.
- Hidrovo, A. B. *et al.*, "Accounting for GHG net Reservoir Emissions of Hydropower in Ecuador," *Renewable Energy*, vol. 112, pp. 209-221, Nov. 2017.
- Descloux, S. *et al.*, "Methane and Nitrous Oxide Annual Emissions from an Old Eutrophic Temperate Reservoir," *Science of The Total Environment*, vol. 598, pp. 959-972, Nov.2017.
- Santos, M. A. D. *et al.*, "Estimation of GHG Emissions by Hydroelectric Reservoirs: The Brazilian Case," *Energy*, vol.133, pp. 99-107, Aug. 2017.
- Demarty, M. and Bastien, J., "GHG Emissions from Hydroelectric Reservoirs in Tropical and Equatorial Regions: Review of 20 years of CH₄ Emission Measurements," vol.39, pp. 4197-4206, Jul. 2011.
- Demlas, R., and Lacaux, C. G., "Emissions of Greenhouse Gases from the Tropical Hydroelectric Reservoir of Petit Saut (French Guiana) Compared with Emissions from Thermal Alternatives," *Global biogeochemical Cycles*, vol.15, no.4, pp. 993-1003, Dec. 2001.
- Santos, M. A. D. *et al.*, "Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants," *Energy Policy*, vol.34, no.4, pp. 481-488, Mar. 2006.
- [Online]. Available: <https://www.ceb.lk/power-plants-list/en>.
- Japan International Corporation Agency, "Feasibility Study on Upper Kotmale Hydroelectric Power Development Project," Ceylon Electricity Board, Sri Lanka, Final Rep., Aug. 1987.
- Guo, Z. *et al.*, "Ecosystem Functions, services and their values - a case study in Xingshan County of China," *Ecological Economics*, vol. 38, no. 1, pp. 141-154, Jul. 2001.
- World Heritage Encyclopedia. *Primary Production*[Online].Available: <http://www.ebooklibrary.org/Articles/Primary%20production?&Words=primary%20production>.
- Zhang, J. *et al.*, "Review on the Externalities of Hydropower: A Comparison between Large and Small Hydropower Projects in Tibet based on the CO₂ equivalent," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 176-185, Oct. 2013.

19. Demarty, M., and Bastien, J. "GHG Emissions from Hydroelectric Reservoirs in Tropical and Equatorial Regions: Review of 20 years of CH₄ Emission Measurements," vol.39, pp. 4197-4206, Jul. 2011.
20. Demlas, R. and Lacaux, C. G. "Emissions of Greenhouse Gases from the Tropical Hydroelectric Reservoir of Petit Saut (French Guiana) Compared with Emissions from Thermal Alternatives," *Global biogeochemical Cycles*, vol.15, no.4, pp. 993-1003, Dec. 2001.
21. [Online]. Available:
https://definedterm.com/boreal_region.
22. Turconi, R. *et al.*, "Life Cycle Assessment (LCA) of Electricity Generation Technologies: Overview, Comparability and Limitations," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 555-565, Dec. 2013.
23. Zhang, S. *et al.*, "Carbon Footprint Analysis of two Different Types of Hydropower Schemes: Comparing Earth-Rockfill Dams and Concrete Gravity Dams using Hybrid Life Cycle Assessment," vol. 103, pp. 854-862, Sep. 2015.
24. Hondo, S. "Life Cycle GHG Emission Analysis of Power Generation Systems: Japanese Case," *Energy*, vol. 30, no. 11-12, pp. 2042-2056, Aug-Sep. 2005.
25. Ceylon Electricity Board. (2004). *Upper Kotmale Hydropower Project* [Online]. Available: <http://www.ukhp.lk>.
26. Batagoda, B. M. S., "Carbon Trading: A New International Business Opportunity in Sri Lanka," *Economic Review*, pp. 41-62, Jun/Jul. 2008.
27. Rocamora, A. and Amellina, A. (2017, November). *IGES List of Grid Emission Factors* [Online]. Available: <https://pub.iges.or.jp/pub/iges-list-grid-emission-factors>.
28. [Online]. Available:
<http://energybalance.axioo.com/>.