

Comparison between predicted and actual rock mass conditions: a review based on tunnel projects in Nepal Himalaya

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ABSTRACT: *Even though the Himalayan region possess enormous potential for hydropower development there exists great challenge for the successful underground excavation due to complex geological set up of the region. It is generally accepted that the cost and time are of main concerns in any tunnelling project as these two factors influence greatly on the economic viability of the hydropower projects. Consequently, the accuracy of predicted geological conditions during planning phase plays an important role during its implementation, and the degree of accuracy in predicting, evaluating, and interpreting the quality of rock mass along the tunnel alignment is a key for the successful completion of any hydropower project.*

This paper is assessing and comparing the predicted and actual rock mass conditions along four recently constructed hydro-tunnels in Nepal Himalaya. The effect on the overall cost and construction time caused by the variations in rock mass quality of these tunnel projects are evaluated and discussed, and an evaluation is made on the preconstruction phase engineering geological investigations. Finally, a recommendation is given on the minimum level of geological investigation that may help improve the predictability of geological conditions and reduce the discrepancy between predicted and actual conditions to an acceptable level.

1 INTRODUCTION

The rock mass conditions along the alignment of any tunnel project is decisive with respect to its final cost and construction time required. To carry out a study on the economic viability of the tunnel project, the rock mass quality along the tunnel alignment has to be examined and estimated quantitatively before the start of tunnel excavation. This is done by engineering geological site investigation carried out at pre-construction phase planning and design of the project. Due to the fact that the rock mass is a complex material with many variable parameters, it is generally expected that there will be some degree of variations between predicted and actual rock mass conditions. This variation should, however, be within the acceptable limit so that excessive cost overruns and required construction time are controlled. Nevertheless, it is not always easy task to predict and estimate rock mass conditions along the tunnel alignment accurately enough in advance so that variations can be kept within the acceptable limit.

The only way to control the variations is to have a well planned and organized pre-construction phase engineering geological investigations. If high quality procedures are followed, it is possible to obtain final investigation results with high quality and within desired limit of variations in spite of geological uncertainties and difficulties. In regards to the Himalaya, some of the recently constructed tunnel projects in Nepal have not shown such results and have encountered unexpected ground conditions quite different from what was anticipated during pre-construction phase planning and design. This has caused additional cost and considerable delay in the project completions. In some cases, this situation has led to claims and contractual fight between the client and the contractor.

The main aim of this paper is thus to review and examine the level of pre-construction phase engineering geological investigations based on four tunnel projects in Nepal, see Figure 1. The discussions are focused mainly on the variations between predicted and actual rock mass conditions and on evaluation of the effects that this had on project cost and construction time. Further, recommendations are given on the pre-construction phase geological investigations required for future tunnel projects in Nepal, so that unexpected variations on rock mass conditions may be reduced in future. Project reports and other unpublished project data and information of pre-construction and construction phases (see reference) have been used as main basis for this review.

2 BRIEF DISCRPTION OF THE CASES

Most of the major rivers originating from the high and snow covered Himalaya have considerable potential in hydropower generation. According to Ministry of Water Resources of Nepal 2003, Nepal has an estimated theoretical hydropower potential of more than 83,000 MW, of which almost 50 percent is considered to be economically feasible. This is due to the fact that in the Himalaya, at elevations above 3,500 metres, precipitation occurs in the form of snow that gives perennial flow for rivers originating from above this elevation. In addition, Nepal experiences

an annual average precipitation of approximately 1500 millimetres. With this potential, many underground powerhouse caverns and tunnels are likely to be built in the future in this country. Tunnelling will not be limited to the hydropower sector only, as tunnelling is also required in other sectors such as transport, drinking water supply and irrigation, mining and storage facilities (Panthi, 2004). There are, however, many challenges in tunnelling in Nepal with high degree of uncertainty due to the complex geological setup of the Himalaya, see Figure 1.

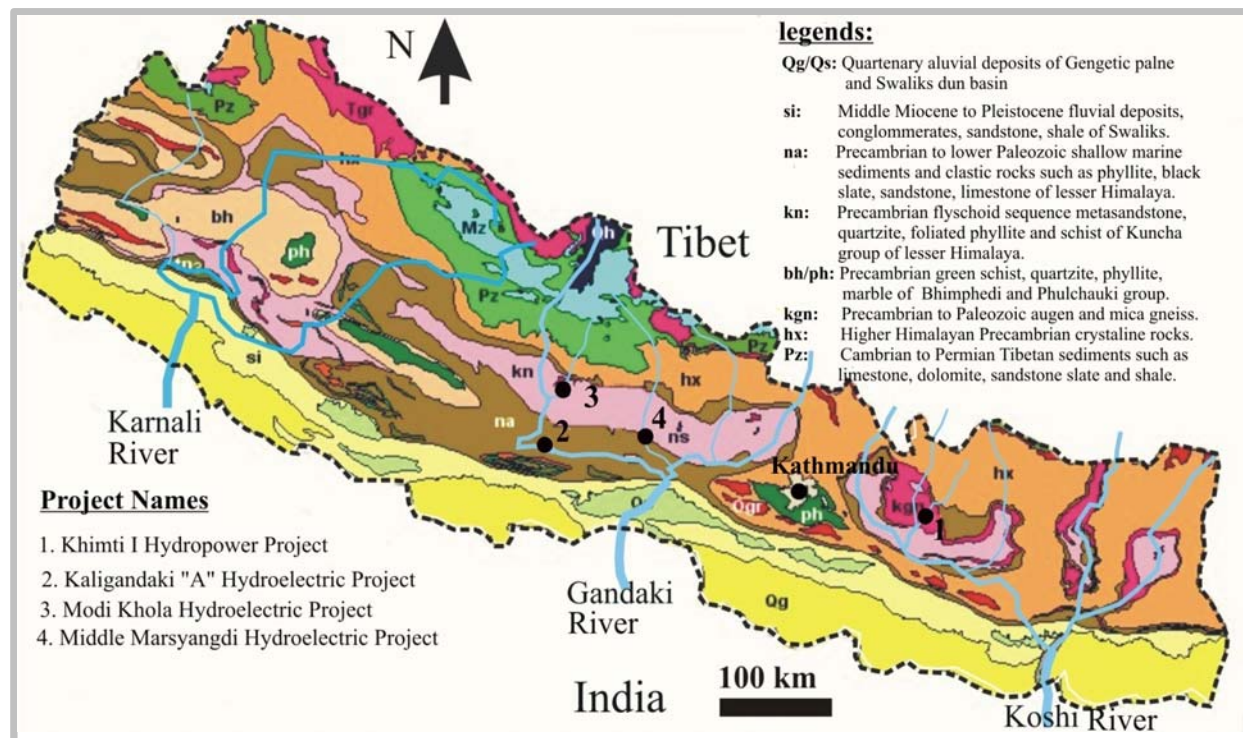


Figure 1. Project location and geology of Nepal Himalaya with three major river systems (Modified from the geological map of Nepal prepared by Department of Mines and Geology of Nepal given in Galay et al, 2001).

In addition to Himalayan geology, Figure 1 shows the three major river systems of Nepal and the location of the four tunnel projects that are discussed here as cases. These projects are; 1) Khimti I Hydropower Project, 2) Kaligandaki "A" Hydroelectric Project, 3), Modi Khola Hydroelectric Project and 4) Middle Marsyangdi Hydroelectric Project. The first three of these projects were recently completed and are now in commercial operation, The fourth, the Middle Marsyangdi Hydroelectric Project, is under construction.

2.1 K HIMTI PROJECT

The Khimti I Hydropower Project is located in the Himalayan region about 100 kilometers East of Kathmandu, see Figure 1. The Civil Construction Consortium (CCC), a Consortium between Statkraft Anlegg of Norway (now NCC) and Himal Hydro of Nepal, carried out the construction work on a turn key basis. The construction work was completed in 2000, and the project has been in commercial operation since then. The Project is owned by Himal Power Limited (HPL) and is among the first privately invested and owned hydropower projects in the country under BOOT concept. The Project has an installed capacity of 60 MW and generates approximately 350 GWh electrical energy annually. To generate this energy the Project utilizes water from the very steep Khimti River, which has an average gradient of about 7 percent. The Khimti I is a high head scheme, with a design discharge of 10.75 m³/s and it has a gross head of 684 meters. The total tunnel length of the waterway is approximately 10 kilometers, see Figure 2 left. The pressurized headrace tunnel is 7888 meters long with inverted D-shape and 14 square meters cross-section (CCC, 2002).

Geologically, the project lies in the crystalline Tamakoshi gneiss complex of the lesser Himalaya. Structurally the area is bounded or surrounded by a major fault system of the Himalaya called "the Main Central Thrust (MCT)", see Figure 1. As given in Figure 2 left, the rocks in the project area are mainly augen gneiss with frequent intercalation of chlorite and talcose schist. This intercalation is most frequent, with interval of 5-10 meters, at the downstream end of the headrace tunnel, whereas at the upstream stretch the interval is longer and augen gneiss is more fractured and open-jointed (Panthi and Nilsen, 2004).

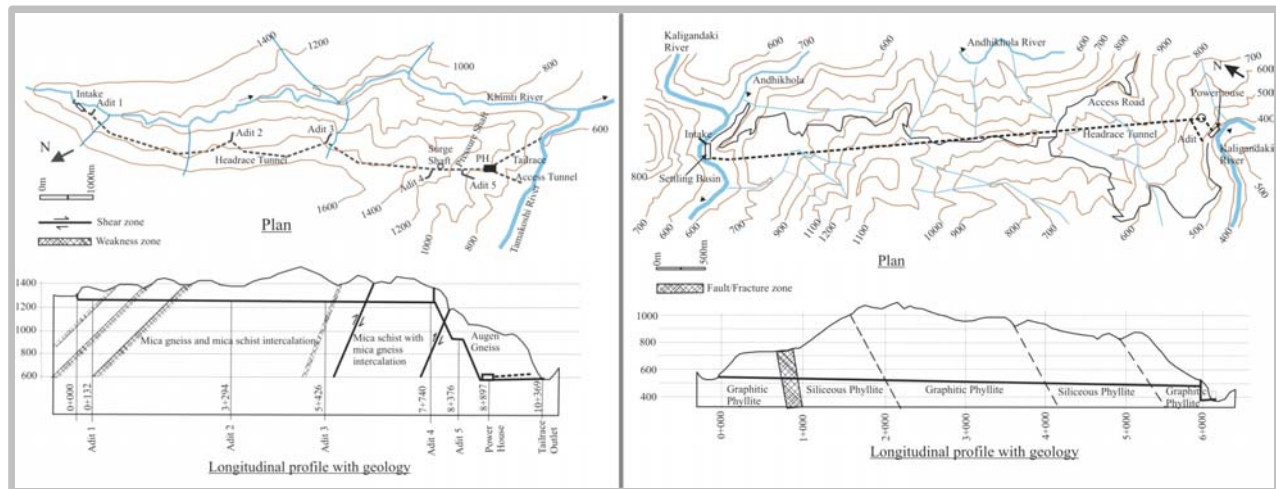


Figure 2. Topographic maps and profiles with geology for Khimti I Hydropower Project (left) and for Kaligandaki "A" Hydroelectric Project (right)

2.2 KALIGANDAKI PROJECT

The Kaligandaki "A" Hydroelectric Project is located in the mid hills of the lesser Himalaya in the western development region of Nepal about 180 km west of Kathmandu, see Figure 1. The civil work contract of this project was awarded to Impregilo Spa of Italy in January 1997. The construction work was completed in the summer of 2002 and the project has been in commercial operation since then. The Project is owned by Nepal Electricity Authority (NEA), an undertaking of the His Majesty's Government of Nepal (HMGN). This Project is the largest run-of-river scheme ever constructed in Nepal. It has an installed capacity of 144 MW and is capable of generating 842 GWh electrical energy annually. To generate this energy the Project utilizes a 45 kilometers long loop of a relatively flat bedded Kaligandaki River in a shortcut diverting the water through a 5950 meters long headrace tunnel with approximately 60 square meters excavation cross-section, see Figure 2 right. The Project is a medium head scheme (net head 115 meters) with a rated design discharge of 141 m³/s (Panthi and Gouro, 2001).

Geologically, the project area lies in the lesser Himalayan highly deformed rock formation, consisting of Precambrian to lower Paleozoic shallow marine sediments such as slate, phyllite and dolomite, see Figure 1. The headrace tunnel of this project mostly passes through highly deformed phyllite that varies in mineral composition and degree of metamorphism. The phyllite is of poor quality and is thinly foliated and highly weathered (NEA, 2002). The maximum elevation difference between the top of the hill and tunnel alignment is approximately 625 meters, see Figure 2 right. Due to high overburden, the weak rock mass along the tunnel alignment has squeezed severely. During tunnel excavation this caused considerable problems in many sections of the headrace tunnel.

2.3 MODI KHOLA PROJECT

The Modi Khola Hydroelectric Project is located on the right bank of Modi River, a tributary river of the Kaligandaki River, in the western development region of Nepal, see Figure 1. The construction work for the underground section of the project was awarded to the joint venture of Himal Hydro and Statkraft Anlegg (NCC Norway) in 1996. The construction work was completed in 2001, and the project has been in commercial operation since then. This Project is also owned by the Nepal Electricity Authority (NEA). The Project has an installed capacity of 14.7 MW and is capable of generating 91 GWh electrical energy annually. The Project is a run-of-river scheme with a medium head of approximately 67 meters and a design discharge of 27.5 m³/s (NEA, 2000a). As indicated in Figure 3 left, the project has a total underground waterway length of approximately 2 km, including a 1503 meters long headrace tunnel with a cross section of approximately 15 square meters, a 50 meters deep vertical pressure shaft and a 430 meters long pressure tunnel (Himal Hydro, 2000).

Geologically, the Project area lies in the Precambrian sequence of the lesser Himalayan meta-sedimentary rock formations, see Figure 1. As shown in Figure 3 left, the bedrock along the underground water ways is dominated by massive, greenish quartzite with intercalation of white quartzite and sheared, phyllitic greenschist. During tunnel excavation, the pressure tunnel had to cross a major fault zone where considerable stability problems related to rock squeezing as well as severe ground water inflow were faced. However, the tunnel excavation went relatively

smoothly with few surprises, and the major weakness zones were crossed without major difficulties (Himal Hydro, 2000).

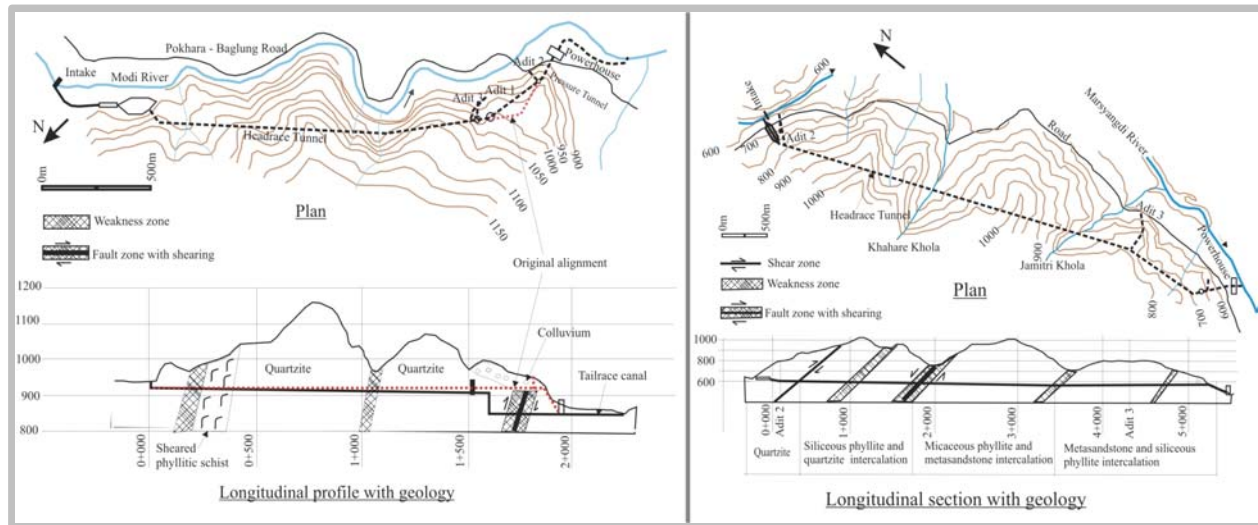


Figure 3. Topographic maps and profiles with geology for Modi Khola Hydroelectric Project (left) and Middle Marsyangdi Hydroelectric Project (right)

2.4 MIDDLE MARSYANGDI PROJECT

The Middle Marsyangdi Hydroelectric Project is located in the western development region of Nepal in Lamjung District, see Figure 1. The project is on the right bank of the Marsyangdi River, which is a major tributary of the Gnadaki River system. This project is also owned by Nepal Electricity Authority (NEA) and is a medium sized run-of-river scheme with planned installed capacity of 69 MW. It will be capable of producing 380 GWh electrical energy annually. The construction work begun in early 2002, and the project is still under construction at present. The project is a medium head scheme with a gross head of approximately 110 meters and a design discharge of 80 m³/s (NEA, 1998). The project consists of a 68 meters high dam, three underground settling chambers, a 5,300 meters long headrace tunnel with 32 square meters cross-section, a surge shaft, various construction adits, a 385 meters long penstock and a semi-underground powerhouse, see Figure 3 right.

Geologically, the Project lies in the lesser Himalayan meta-sedimentary rock formations, see Figure 1. The main rock types at the project area are quartzite and phyllite with intercalation features. As shown in Figure 3 right, the upstream short section of the headrace tunnel, intake, underground settling basins and diversion facilities of the project are located in high to medium weathered, fractured and thinly foliated quartzite. The remaining downstream section of the headrace tunnel and other underground structures are mostly passing through jointed, sheared and thinly foliated micaceous and siliceous phyllite. The phyllite of the area is intercalated with bands of meta-sandstone. As can be seen in Figure 3 right, the headrace tunnel will be crossing some major weakness and fault zones, representing considerable challenges during construction.

3 REVIEW OF PRE-CONSTRUCTION INVESTIGATIONS

The main goal of a pre-construction phase engineering geological site investigations for underground hydropower projects is to characterize the rock mass conditions of the project site and to locate tunnels and other underground openings in as good rock quality as possible. Optimization of the tunnel alignment is important not only for reducing the risk and uncertainty associated with the tunnel stability, but also for reducing the project cost and construction time. The location of tunnel projects is not always fixed based on the geological conditions alone. In many cases, topographic as well as hydrological and hydraulic conditions play important roles in fixing the inlet and outlet of a tunnel project. The geological conditions of the site of interest may vary widely as each site will have its own characteristics, and thus there is no standard investigation procedure that will be the only correct way in all cases (Nilsen and Palmstrøm, 2000). However, by thorough investigation, design and planning, it is in theory always possible to find the best alternative and the most cost effective solution.

A review of the pre-construction phase engineering geological investigations carried out for the four tunnel projects described in section 2 has been made, and the findings are summarized in Table 1.

Table 1. Performed planning and design phase engineering geological investigations of the four cases.

Projects / Descriptions		Khimti I	Kali-Gandaki “A”	Modi Khola	Middle Marsyangdi	Remarks if any
Feasibility stage	Desk studies based on existing geological information and pre-feasibility study	yes	yes	yes	yes	In general very limited geological investigation was done during pre-feasibility
	Air photo studies and interpretations	yes	yes	yes	yes	Available in scale 1:50,000 and 1:125,000
	Surface geological mapping	yes	yes	yes	yes	Of the project area.
	Seismic refractions	yes	yes	yes	yes	At specified locations. Mostly at surge tank and headwork areas
	Electrical resistivity	-	-	-	yes	At the suspected fault zone areas
	Core drilling	yes	yes	yes	yes	Focused mainly on intake, surge shaft and powerhouse area.
	Laboratory testing	yes	yes	-	yes	Involving rock strength parameters and mineralogical testing.
Design and contract stage	Review of the feasibility study investigations	yes	yes	-	yes	Review followed also site visits
	Detailed surface mapping	yes	yes	-	yes	Few days of surface investigation at Khimti project
	Additional core drilling	-	yes	-	yes	Concentrated to intake and powerhouse areas
	Additional geophysical investigations	-	-	-	yes	Electrical resistivity survey on the suspected fault zone areas.
	Exploratory test Adit excavation	-	yes	-	yes	
	Rock stress measurements	-	yes	-	yes	Hydraulic fracturing test at Kaligandaki and small jack test at Middle Marsyangdi
	Laboratory testing	-	yes	-	yes	Further investigation, including dilatometer test

Table 1 illustrates the variations in level and types of engineering geological investigations performed during pre-construction phase for these four tunnel projects in Nepal. As can be seen, the level of investigations carried out at Khimti I and Modi Khola Projects is relatively low, and much lower than for the other two projects. Most of the geophysical investigation, core drilling and laboratory testing for the projects were for headworks, surge tank and powerhouse areas. This indicates that for the headrace tunnel alignment of these four projects the rock mass quality assessment, stability analysis and quantity predictions were based mostly on desk studies, aerial photo interpretation and surface geological mapping.

4 PREDICTED VERSUS ACTUAL ROCK MASS CONDITIONS

Due to the complexity of the rock mass, it can hardly be avoided to end up with some degree of discrepancy between the predicted and actual rock mass conditions and between the predicted and actual rock support. However, this variation should be within acceptable limits so that the tunnel cost and construction time are kept well under control. As discussed in section 3, the level of pre-construction phase engineering geological investigations has varied considerably for the cases in Nepal. In the following, the differences between the respective cases will be discussed, and an attempt will be made to explain the main discrepancies between predicted and as-built

4.1 ROCK MASS QUALITY AND ROCK SUPPORT

The characterization of rock mass quality is very essential during pre-construction phase geological investigations since it is the only way to estimate required tunnel rock support and construction time. Without estimating the quantity of rock support and construction time it is not possible to evaluate the economic viability of a tunnel project during planning. To investigate the accuracy of the pre-construction phase predictability in rock mass characterization in Nepal, comparison of predicted and actual rock mass conditions and predicted and actual rock support for the four cases has been made. The results are presented in Figure 4 and 5.

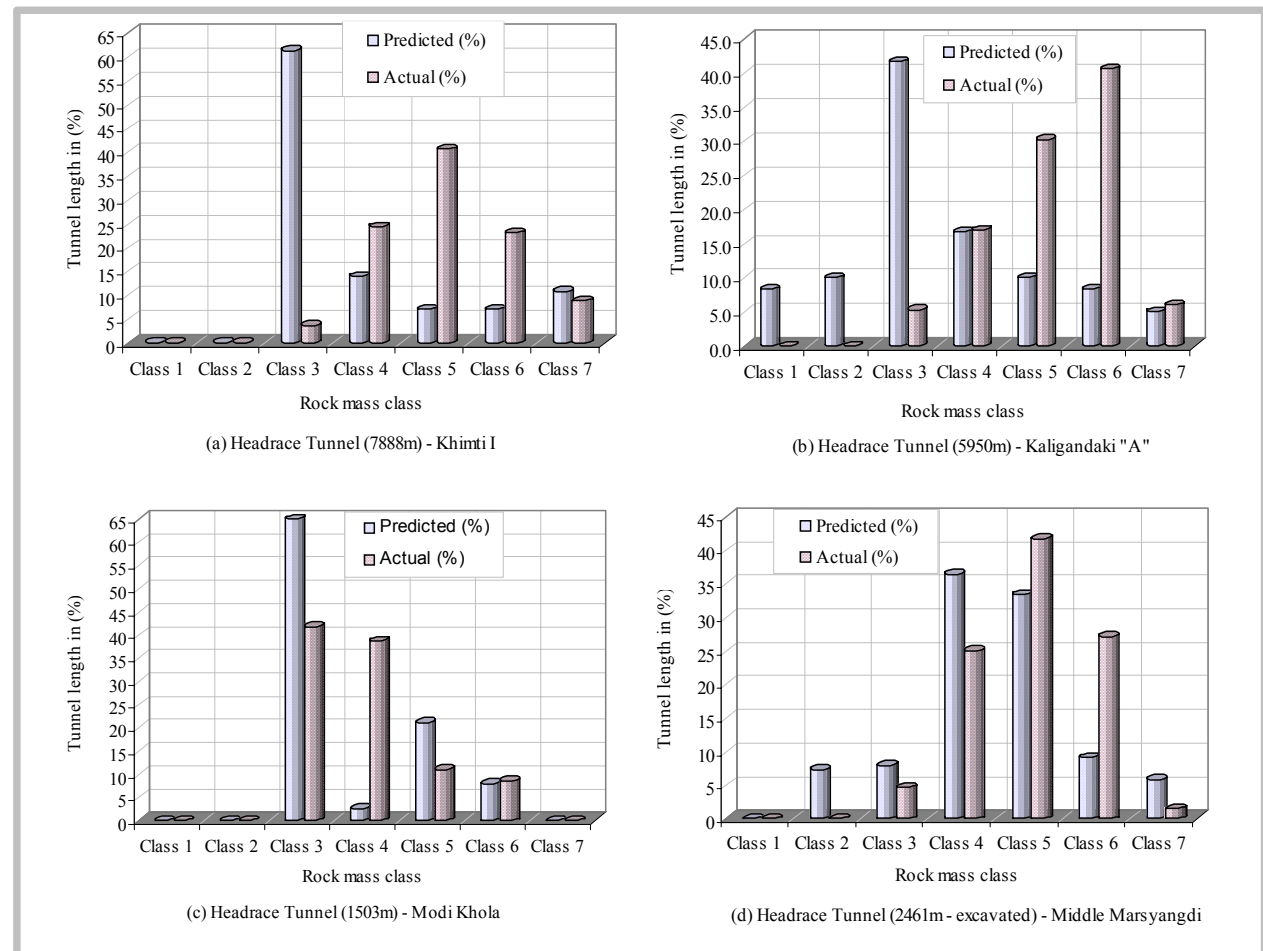


Figure 4. Predicted and actual rock mass conditions of the four tunnel cases located in different geological conditions in Nepal. The rating of the rock mass class indicates: Class 1 – Extremely good; Class 2 – Very good; Class 3 – Fair to good; Class 4 – Poor; Class 5 – Very Poor; Class 6 – Extremely poor and Class 7 – Exceptionally poor.

As shown in Figure 4, there are considerable differences between predicted and actual rock mass quality in these four projects. It is interesting to note that the discrepancy for Modi headrace tunnel seems slightly smaller than for the other three projects even though the difference for class 4 is quite significant. This may be explained by the fact that this tunnel is located in very steep topography where the rock masses are well exposed. The headrace tunnel of Middle Marsyangdi also seems to have relatively small discrepancy. However, it is too early to come to a final conclusion for Middle Marsyangdi since the comparison is based on only approximately 50 percent tunnel that has been completed by August 2004. Given the level of pre-construction phase investigations, see Table 1, and the rock exposure that could be mapped along the road that passes almost parallel to the tunnel alignment, see Figure 3 right, it would be reasonable to expect that the difference should have been smaller. In contrast to these two projects, the discrepancies for Khimti I and Kaligandaki "A" are unexpectedly high. As a result of large discrepancy in rock mass quality, the differences between predicted and applied rock support are also large, see Figure 5.

As shown in Figure 5b, the maximum discrepancies are related to rock bolts and shotcrete, whereas the discrepancy in the concrete consumptions at Kaligandaki "A" is rather small. That is logical since the whole headrace tunnel was planned with a final concrete lining at the planning phase to improve tunnel smoothness and to reduce

friction loss. Figure 5 also justifies the finding of Figure 4a and 4b that the actual rock mass quality was much poorer than predicted. Not surprisingly, this large increase in rock support requirement resulted in considerable increase in cost and construction time.

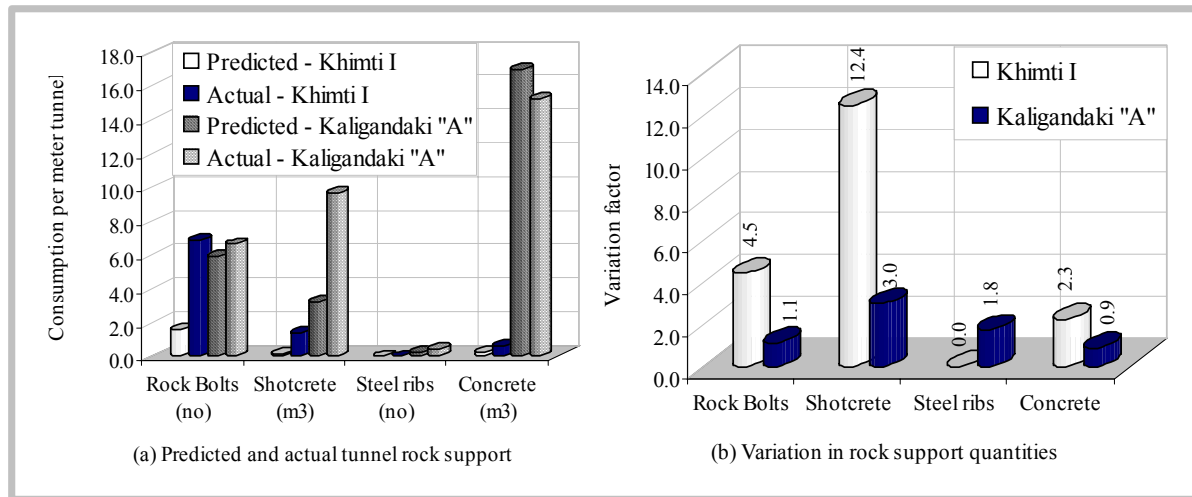


Figure 5. Predicted and actual rock support (left) and discrepancy in rock support quantities (right) for the headrace tunnel of Khimti I and Kaligandaki "A" Projects (1.0 means predicted = actual).

4.2 VARIATION IN PROJECT COST AND TIME

It is logical that large discrepancy in rock mass quality has a direct effect on the project cost and time. Such discrepancy gives room for claims from the contractor since he will need additional resources to deal with the more difficult conditions and to accomplish the additional amount of rock support needed. Resulting such cases, the client and contractor may engage for unnecessary contractual debate and dispute that may last for very long. As a consequence, the completion of the project within projected construction schedule may not be possible and considerable delay may be the result. Such unpleasant situation may also lead to additional economic loss due to revenue lost by delayed start of the project operation and by increased interest during construction.

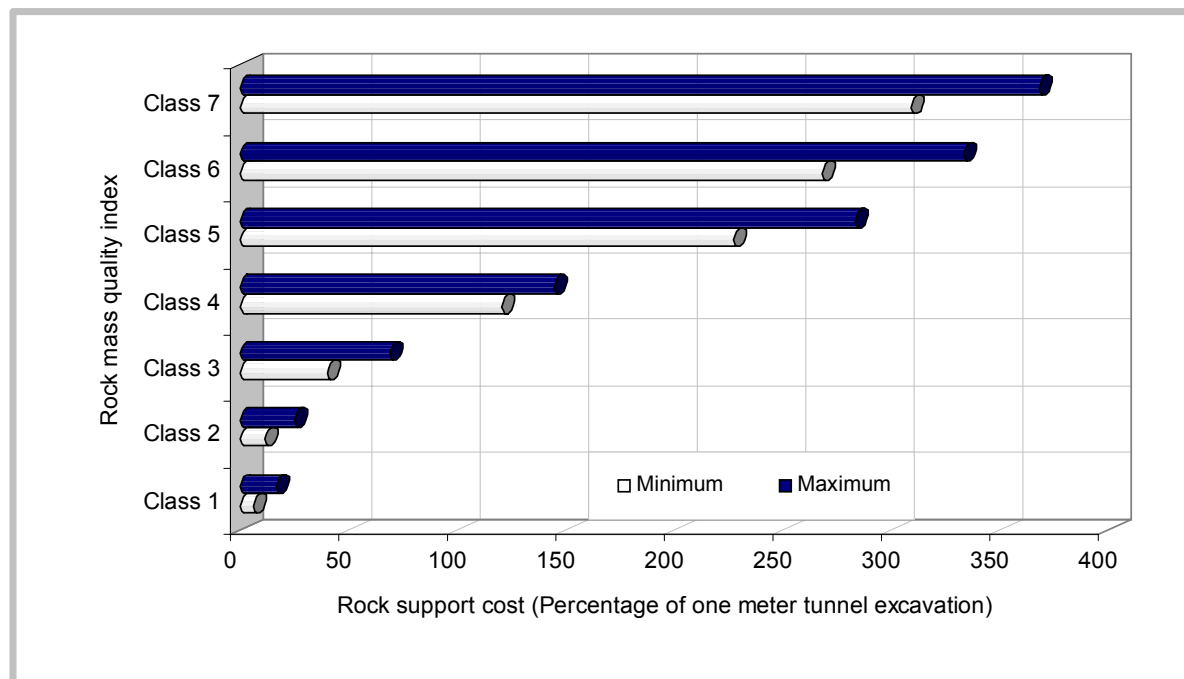


Figure 6. Estimated rock support cost as a percentage of one meter tunnel excavation cost for different rock mass class

For the headrace tunnels of Khimti I and Kaligandaki "A", where considerable discrepancies in rock mass quality and rock support were experienced, the increase in rock support cost amounted approximately five and two folds,

respectively, of what was originally estimated. In addition, the discrepancies had considerable impact on the construction. The Kaligandaki “A” project was delayed by almost one and half years and for the headrace tunnel at Khimti the contractor was forced to open a new adit and accelerate the excavation work to meet the construction target set in project contract.

The cases discussed here are important lessons for the planning of future projects. As a planning tool for new projects, assessment of the cost implication that may be caused by changes in rock mass conditions will be very useful. Based on the cases that have been described in this paper, such a tool has been developed, and is presented in Figure 6. The figure defines the relative support cost for the different rock mass classes, and illustrates the cost impact caused by change in rock mass quality. As can be seen, as soon as the rock mass quality decreases, there is a dramatic increase in rock support cost. For very poor (class 5) and exceptionally poor (class 7) rock mass quality, the rock support cost can be more than 250 and 350 percent, respectively, of the excavation cost. The Figure 6 does not include the additional cost due to additional time required in excavation and rock support installation.

5 EVALUATION ON INVESTIGATION APPROACH

Since every tunnel project is unique, the rock mass conditions and the required level of pre-construction phase engineering geological investigation will vary from one project to another. However, all tunnelling projects require engineering geological investigations giving a satisfactory knowledge about the geology of the area of concern. It is also always advantageous to have a through review of all geological investigations by independent panels of experts. This may help identifying challenging ground conditions more accurately and problem areas such as highly permeable fracture zones, weakness zones, fault zones, weak rock masses and high stress areas may be easier identified during pre-construction phase planning and design (Nilsen, 1999).

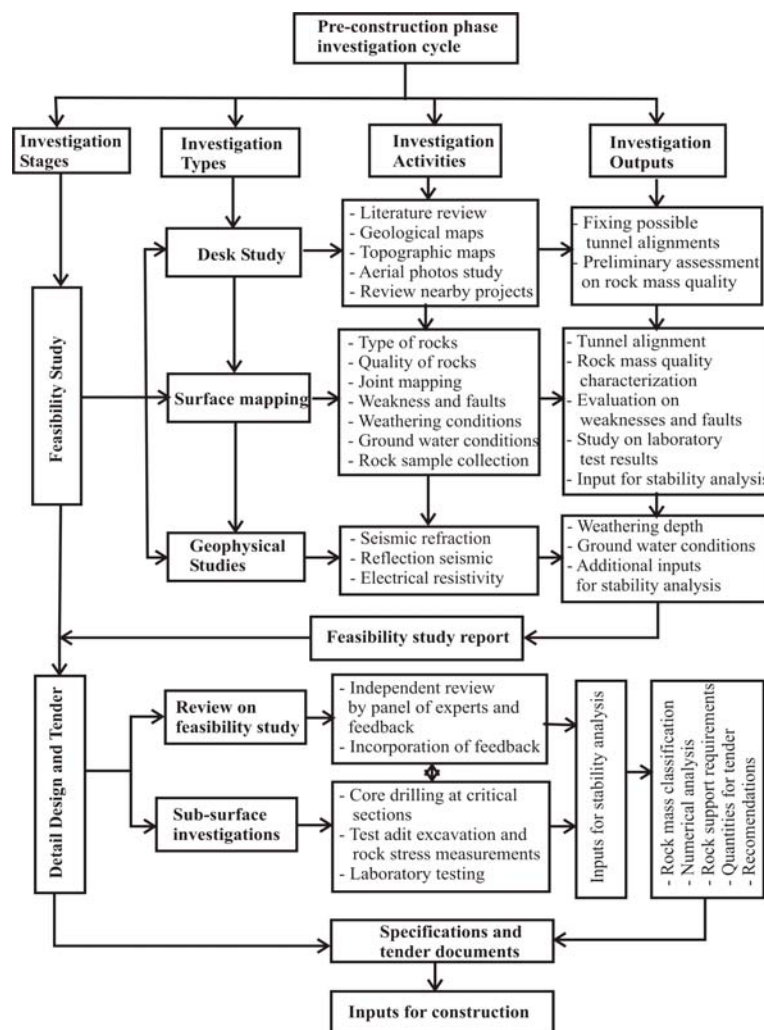


Figure 7. Recommended pre-construction phase engineering geological investigation procedure.

Based on the cases reviewed earlier, it is assumed that the large discrepancies between the predicted and actual rock mass conditions have been caused by three main factors; 1) rather poor or insufficient engineering geological investigations and testing carried out during planning and design phases, 2) complex geological conditions with deep weathering making it difficult to predict actual rock mass conditions by surface mapping and 3) the level of past experience in tunnelling and engineering geological investigation technique suitable for Himalayan geological conditions may have been insufficient. In author's opinion, if a thorough, stepwise procedure of geological investigations as shown in principle in Figure 7 is followed, it will definitely be possible to increase the level of accuracy in evaluating and predicting the quality of rock mass. The additional investigation cost will be small compared to what may be saved during the planning and construction phases.

It should be emphasized that engineering geological mapping and following up during excavation are crucial for a successful completion of the project. Even when very detailed investigations have been carried out from the surface, this is of great importance.

6 CONCLUDING REMARKS

The review of the four tunnelling projects in Nepal has revealed high discrepancies in predicted versus actual rock mass quality, and also in predicted versus actual rock support. Particularly this is the case for Kaligandaki and Khimti headrace tunnels, where much poorer rock quality than expected have caused significant impact on the overall cost and construction time. The review also shows that there have been considerable discrepancies in the type and level of investigations carried out.

All the tunnel projects are unique in their nature. Consequently, the type and level of pre-construction phase engineering geological investigation should always be adjusted to the geological complexity and the type of project. If a planned tunnel project is relatively short and is situated in good quality rock formation and the rocks in the area are well exposed, review of the geological conditions based on published literature, study on aerial photographs and a few days of surface investigations by an experienced team of engineering geologist may give sufficient information. However, in most cases the project site is not so ideal in the Himalaya. In most cases, due to active tectonics and monsoon effect, the rock mass in the region is highly fractured, faulted, intercalated and weathered, and often also soil-covered. Therefore, a thorough, stepwise investigation approach as suggested in Figure 7 should be adopted. This approach may represent a slightly higher investigation cost, but may help saving millions during construction.

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