Underground Space for Infrastructure Development and Engineering Geological Challenges in Tunneling in the Himalayas

Krishna Kanta Panthi

The Himalayan region in Asia covers an area of about 594,400 km^2, of which Nepal occupies approximately 25%. Nepal extends east to west about 890 km and has a width ranging from 150 to 250 km. Within this very short width, the altitude varies greatly, from about 100 m above sea level at its southern border to its maximum of 8,848m above sea level (Mt Everest) at its north, giving a very rough terrain and steep mountainous topography. Because of the great elevation difference over a very short distance, the climatic conditions of the country also vary greatly. The higher Himalayan range (above 3,500m) in the north has an alpine climate and is mostly covered by snow and ice. The climate changes to mild and warm at the Mahabharat range (lesser Himalayan range) and to sub-tropical hot weather at the deep valleys, the Siwaliks (Churia) and the Gangetic plain (Terai).

The increasing population trend and rapid urbanization is augmenting pressure and is a major challenge in the economic development of Nepal. The main economic resources of the country are water resources (energy, irrigation and drinking water), agriculture, tourism and agro-tourism based industries. Maximum utilization of these resources is inevitable, and is only possible by developing infrastructures such as hydropower schemes, irrigation systems, road networks, drinking water systems, etc. Development of all these infrastructures demands the utilization of underground space like tunnels and underground caverns.

This paper discusses the possible areas where tunnels and underground caverns are needed and may play an important role in socio-economic development of our nation, the major geological challenges faced while tunnelling, and methodologies useful for analysing engineering geological uncertainties.

Need for tunnelling in Nepal

The use of underground space is not new in this country. The early miners used underground caverns and tunnels of small dimensions to extract ore and minerals such as copper, iron, lead, cobalt, nickel and different types of coloured stones. However, modern and institutionalized tunnelling started with the excavation of tunnels and an underground powerhouse for the Tinau Hydroelectric Project located near the town Butwal. Since completion of the Tinau Project in the early 1970s, approximately 75 km of tunnels have been excavated.

There are principally four areas where tunnels and underground caverns are needed in Nepal. They include: (a) water conveying tunnels, (b) transport tunnels, (c) mining and (d) food storage facilities (Panthi 2004). For the time being most of the tunnelling is focused on hydropower, and to some extent in mining and irrigation.

Hydropower and tunneling

Being snow fed and very steep in their gradient, most of the major rivers originating in the Himalaya have considerable potential in hydropower generation. In particular, those rivers originating from the elevation above 3,500m are perennial. For this reason, Nepal has been gifted with considerable hydropower potential (see Figure 1).

Nepal has so far managed to develop only about 560 MW hydropower energy, and approximately 40% of the total population has access to it. Apart from domestic requirements, fast developing India could be an important hydropower energy market for Nepal, since India is experiencing a shortage of energy with ever increasing energy demand. It is estimated that by the year 2013 almost 220,000 MW installed capacity of electrical energy is required in India to cope with very rapidly growing economy. Today, the installed capacity of electrical energy in India is approximately 148,000 MW and hydropower contributes only 30,000 MW. Moreover, India is one of the major countries in the world that contributes considerably to global emissions of carbon dioxide. Consequently, the hydropower potential that exists in the Nepal Himalaya could be an environmentally friendly alternative energy source that could help fulfil not only the energy demands of India, but also help in reducing the carbon emission to the world (Panthi 2004).

As can be seen in Figure 1, a number of possible hydropower projects have already been studied in different river basins of Nepal and are ready for the materialization. A study carried out by Nepal's Water and Energy Commission Secretariat (WECS) of the Ministry of Water Resources (MOWR) indicates that more than 850 km of tunnelling needs to be done to develop already planned hydropower potentials in Nepal. Thus, tunnelling requirements for the development of Nepal's hydropower is enormous.

Transport and tunnelling

A balanced, coordinated, well-managed and efficient transport system is a precondition for the sustainable development and economic growth of a country like Nepal. Except for the southern flatland and some inner valleys, there are many limitations for the development of good air and rail transport in Nepal. Thus, the most suitable mode of transport is an efficient road network. The development of such road network will make it possible to link different parts of the country and commercial hubs, contributing largely to the nation's economic and social development (Panthi 1998).

At present, a total of approximately 20,000 km of road have been built in Nepal, of which 29% are blacktopped with fair to good quality, 25% are gravel surfaced, and the remaining are earthen surfaced. The present situation of road networking is unsatisfactory and poses a considerable demand on the need for improving the existing road system. Connecting the mountainous part of the country with good quality roads to the southern flat Gangetic plain (Terai), where high level of economic activity exists, is very much needed. Such North-South running highways will play an important role in linking Nepal with the fast growing economies of neighbouring India and China.

The Himalayan region as a whole is affected by a constant tectonic uplifting as well as downcutting effects by several river systems. The action of tectonic activity and the monsoon on the predominantly fragile and deeply weathered rock mass of the Siwaliks and lesser Himalaya make steep mountain slopes highly unstable and erosion prone. Many rock and soil slope failures occur during the monsoon season along the road cut slopes, not only obstructing the transport movement, but also creating considerable human and property damage. Figure 2 shows an example of the Prithivi Highway, which is the only reliable gateway to capital city, Kathmandu, from the rest of the country.

As shown in Figure 2, a major rock/soil slide started to develop in July 1999 at Krishnabir, located 83 km west of Kathmandu. The slide was further aggravated during the monsoon of 2000 with a massive movement of the slope, and is still active in every monsoon. According to Regmi and Sitaula (2003) almost 360 hours of complete road closure occurred during the two monsoon periods in 2000 and 2001 as a result of this slide, and similar closures are routine in every monsoon period.

Based on the Nepalese Government's Tenth National Plan (NPC 2003), special attention should be placed on regional and sub-regional cooperation for the integrated development of the transport sector in South Asia. The standard of major east-west and north-south highways, must, therefore be improved so that these highways can be converted into regional commercial routes with high rates of return. The Tenth Plan also emphasizes the minimization of investment costs as well as of environmental degradation during design, construction, maintenance and rehabilitation of such road systems.

The quality target set by the government for major highways is only possible to achieve if road tunnels are introduced on the highways running through mountainous parts of the country. The introduction of such road tunnels will not only reduce the road length, but also make it possible to avoid the areas that are very steep and vulnerable to slope failures and risk of rock falls. An example of such an undertaking is the planned Kathmandu–Hetauda direct link, with approximately 60 km road length including three road tunnels with total length of 8 km. If this road project is implemented, it will shorten the existing 224 km long route to only 60 km, making it the shortest connection from the southern flatland to Kathmandu and north to Tibet, China (Panthi 1998).

Other infrastructures and tunneling

The other areas of infrastructure development where tunneling is required in Nepal are irrigation, water supply, mining and storage facilities. Even though there are many possibilities for excavation of tunnels and underground caverns in these areas, very little has been done so far, excluding a few kilometers of tunneling for irrigation and mining. The introduction of underground storage caverns, for example, may help in the reduction of electrical energy.

Even though the possibilities for the development of tunnels and underground caverns are great in Nepal, many uncertainties and challenges exists in this field due to the complex geological setup of the Himalaya.

Engineering geological challenges in tunneling

For economically viable tunneling, it is crucial to have a method characterized by cost effectiveness and flexibility to adopt in changing ground conditions, and by accuracy in the prediction of rock mass quality during planning. The design phase decision in selecting tunnel alignment and predicting the rock mass quality and rock support requirement has direct influence on the overall cost and time requirement of any tunneling project. See Figure 3.

As can be seen in Figure 3, as soon as the rock mass quality decreases (higher class), there is a dramatic increase in rock support cost. For example, for very poor (class 5) and exceptionally poor (class 7) rock mass quality, the rock support cost can be more than 250 and 350%, respectively, of the excavation cost.

The past tunneling experience in Nepal shows that the accuracy of planning phase geological investigations for underground works has often been rather poor. In addition, the compressional tectonic stress regime in the Himalaya has resulted in intense deformation of the rock mass, making it highly folded, faulted, sheared, fractured and deeply weathered. This complex geological setting has caused considerable stability problems (uncertainties) and is a great challenge for successful tunneling. The geological uncertainties for underground openings are related to two major factors: non-geological and geological. See Figure 4.

The non-geological factors are connected to the level of skill and expertise gained by experience and the interpretation and decision making skills during the planning and construction phases of tunnelling projects. The ability to evaluate and tackle the stability issues during planning and construction and the tools, methods and technologies used in that process have great significance, since erroneous interpretation may result in the loss of millions (Panthi 2006).

The geological factors are related to the geological complexity of the region. As can be seen in Figure 4, complexity is represented mainly by four engineering geological characteristics that have caused major stability problems during tunnelling in Nepal. These are: (a) weak rock mass quality, (b) high degree of weathering and fracturing, (c) rock stresses, and (d) groundwater effect. The major geological uncertainties and challenges that have been faced in tunnelling in Nepal are briefly summarized below.

Rock mass quality

Among the most distinct inherent properties of the rock mass in the Himalaya is the strength anisotropy (schistocity) caused by the preferred orientations of mineral grains or directional stress history. The bedding and foliation that exist in the sedimentary and metamorphic rocks of Himalaya have made them highly directional concerning strength and deformability. As a result of this directional behavior with respect to strength and deformability, many rocks in the region are highly incompetent. This directional behavior leads to a considerable reduction on the self-supporting capability of the rock masses while tunneling. Figure 5 is an example of tunnel collapse caused by this directional anisotropy of a typical Himalayan phyllite. Many such failures occurred on the recently constructed headrace tunnels of 144 MW Kali Gandaki ‘A’ Hydropower Project and on the 60 MW Khimti-I Hydropower Project in Nepal. The highly deformable rocks such as shale, slate, phyllite, schist and micaceous gneiss show such directional behavior and are weak bonded along the foliation plane.

Another major feature of the highly deformed rock mass of the Himalaya is frequent intercalation between different rocks and shear bands. Such intercalation is observed at interval of even less than 50 centimetres. See Figure 6.

In many occasions, thin bands of very weak and highly deformed rocks such as slate, phyllite, schists and sheared mylonites are intercalated within the bands of relatively strong and brittle rocks such as gneiss, quartzite and dolomite. These small bands of weak rock mass are squeezed and highly sheared within these stronger layers of rock mass (Panthi 2004); i.e., typical mixed face conditions. Being weaker in their mechanical characteristics and highly schistose, these shear bands lack sufficient bonding/ friction and have reduced self-supporting capability. This phenomenon of directional behaviour and intercalation of the rock mass in the Himalaya has resulted in severe stability problems during tunnel excavation.

Weathering and fracturing

In the Himalaya, fracturing is caused either by active tectonic movement or due to gravity effect. The combination of active tectonic movement and the region’s complex climatic conditions (dynamic monsoon) lead to aggravated weathering of the fractured rock mass. Being formed from the process of fracturing, shearing and hydrothermal alteration, the fractured rock mass, weakness zones and fault zones provide an environment for weathering to intensify. Accordingly, the weathering effect may reach more than hundred meters below the surface. Tunneling in such environment needs to be carefully addressed concerning rock mass quality evaluation at the planning and implementation stages.

There are two main effects of rock weathering and fracturing with respect to tunnel stability in the Himalaya. The first is the immediate tunnel collapse during excavation, since the rock mass loses its cohesion (friction) and is unable to selfsustain even for a very short period until the temporary support is placed. Figure 7 shows an example of weathering-induced tunnel collapse that was triggered due to deep weathering at the pressure shaft on the Khimti Project.

As shown in Figure 7, a sink hole was formed all the way to the surface due to the collapse in this tunnel. Several such collapses were witnessed along the headrace tunnel and pressure shaft of Khimti project. The second effect is the condition that is produced by weathering for water inflow and leakage from the tunnels, since many open channels may be formed along the fractures in the rock mass.

Stress induced problems

The third major stability problem faced during tunneling in the Himalaya is stress anisotropy. Due to topographic reasons, most of the tunnel projects are constructed in the Siwaliks and lesser Himalayan zones, where highly deformed rocks such as shale, mudstone, siltstone, slate, phyllite, schist, schistose gneiss and highly sheared fault gouge and mylonites are present. In general, highly deformed rock mass have very weak rock mass strength, and tunneling through such rock mass may cause severe squeezing as soon as the overburden stress exceeds the rock mass strength. The severe squeezing has been observed even in relatively low overburden, where tunnels pass through highly sheared fault zones with extremely poor rock mass (Panthi and Nilsen 2007). An example of severe squeezing occurred in the pressure tunnel of Modi Khola projects and in the headrace tunnel of Kali Gandaki 'A'. See Figure 8.

The Modi pressure tunnel passes through highly sheared fault gouge, representing intercalation of highly sheared and decomposed schist mixed with completely crushed quartzite at an overburden of about 75 meters. The squeezing was so severe that the applied support of steel ribs and shotcrete was completely buckled and collapsed (HH 2001). In the case of Kali Gandaki headrace tunnel, squeezing occurred in many sections. Figure 8 right shows a section where more than 50 cm of horizontal convergence occurred at an overburden of approximately 450 m. In this tunnel that passes through highly sheared Himalayan phyllite, a maximum of up to 75 cm of tunnel deformation was recorded at a section with an overburden of approximately 600 m (NEA 2002; Panthi and Nilsen 2007).

Severe squeezing in tunnels is extremely difficult to tackle and is a major challenge in tunneling through the Himalaya rock mass. In fact, no universal solution exists that may be used to control instability caused by tunnel squeezing of such magnitudes. The most effective solution is to carry out uncertainty analysis in predicting squeezing in advance and increase the excavation size for compensating to the predicted squeezing and install sufficient support.

Inflow and leakage

The fault zones, sheared zones, fractured and weathered rock mass of the Himalaya are highly permeable and water bearing. Tunneling through such permeable zones always represent great difficulties and considerable challenges. Figure 9 shows examples of severe water leakage and inflow problems at the Khimti headrace tunnel and the Modi pressure tunnel. As can be seen in the Figure, the severity of the problems caused by inflow and leakage are huge in the Himalaya. In many occasions several weeks and months and a huge amount of resources were spent to control the inflow and leakage problems.

As seen in Figure 9 left, water leakage problems are not only limited to the excessive inflow during tunneling, but also are relevant for a tunnel constructed for conveying water, where there is a high risk of losing valuable water after the completion due to leakage (Panthi and Nilsen 2005). It is a great challenge to establish methods or tools for predicting possible water inflow and leakage so that proper steps for tackling such problems may be considered in advance.

Methodology for uncertainty analysis

It is a fact that the key to success or failure of any tunneling project is the quality of the rock mass that the tunnel passes through and rock support measures that are applied during tunnel excavation. In this respect, accurate evaluation, analysis and interpretation of the rock mass quality play significant roles.

A major challenge therefore is to address geological uncertainties so that cost effectiveness and safer tunneling may be achieved. In this respect, the engineering geological uncertainty analysis methodology proposed by Panthi (2006) in evaluating uncertainty and risk associated with the rock mass quality evaluation, potential tunnel squeezing and possible inflow and leakage could be an alternative. The main focus of this methodology is a combined probabilistic and risk based approach. The main principle of this methodology is shown in Figure 10.

Instead of single point method of stability analysis for tunnels and underground caverns that is being generally used the proposed methodology gives much more reliable results.

Conclusion

The need for tunneling in Nepal, as in the Himalayan region in general, is enormous, particularly for hydropower development. Due to active tectonic movement and dynamic monsoon, the rock mass in the Himalaya is relatively weak and highly deformed, schistose, weathered and altered. Predicting rock mass quality, analyzing stress induced problems, in particular tunnel squeezing, and predicting inflow and

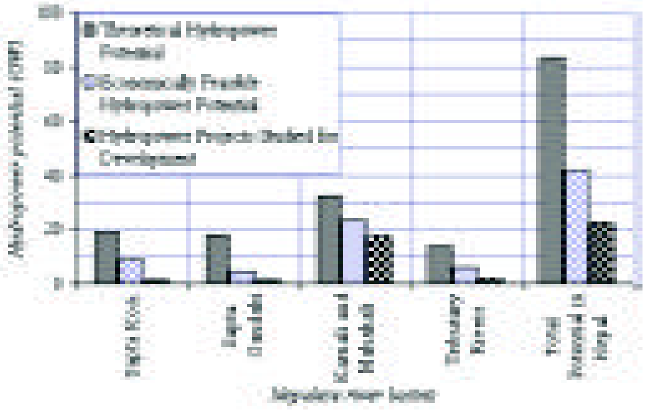

Figure 1. An estimated total hydropower potential of Nepal covering different river basins of the country (based on MOWR 2003)

Figure 2. A major slide at Krishnabir along the Prithvi Highway, 'A main gateway to Kathmandu Valley'. Slope protection works with gabion (left) and the extent of slope failure (right)

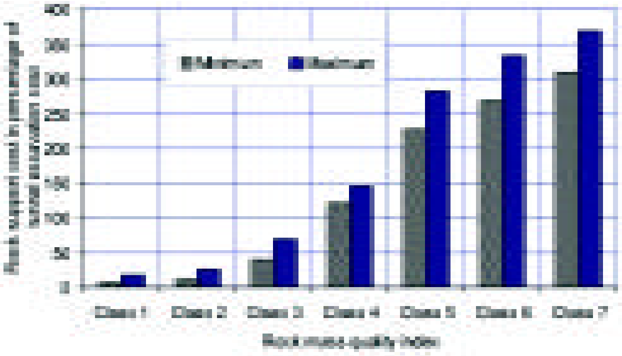

Figure 3. Approximate rock support cost for different rock mass classes (minimum and maximum for small and large section tunnels, respectively) (Panthi 2006)

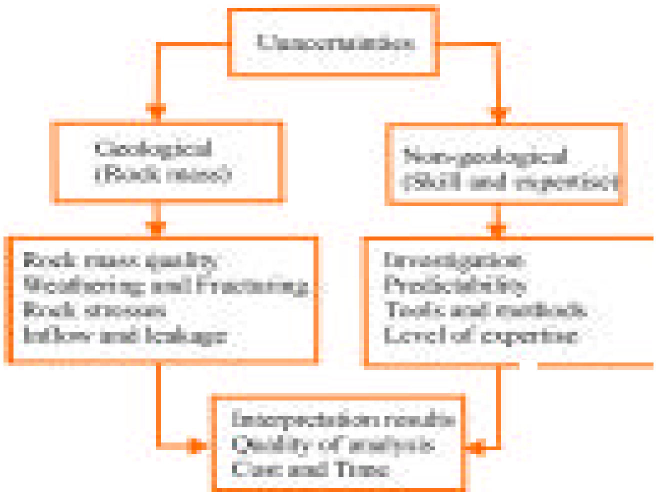

Figure 4. Two types of uncertainties for an underground opening.

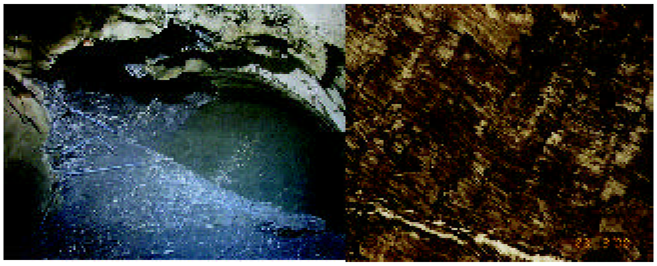

Figure 5. Headrace tunnel collapse at Kali Gandaki 'A' Hydroelectric Project (left) and tunnel face showing thin foliation plane with very weak bond (right) (Panthi 2006)

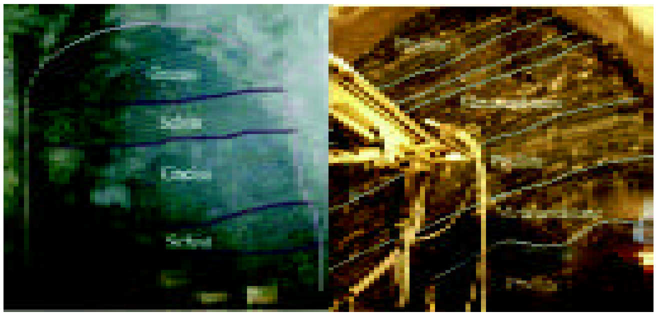

Figure 6. Intercalation between gneiss and schist at Khimti headrace tunnel (left) and intercalation between phyllite and metasandstone at Middle Marsyangdi headrace tunnel (right) (Panthi 2006)

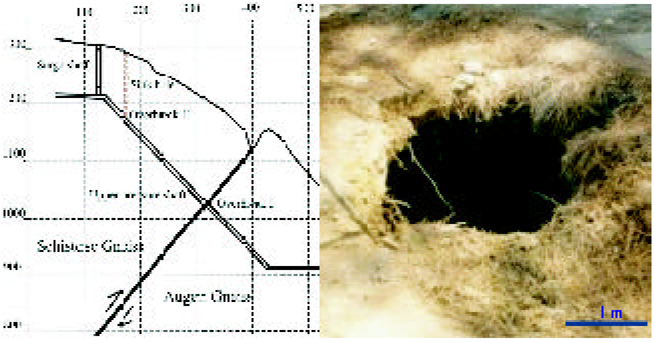

Figure 7. Cross section profile of the upper pressure shaft (dimension in meters) showing a tunnel collapse (left) and a sink hole of the same collapse that reached the surface (right) at Khimti Hydropower Project (Panthi 2006)

Figure 8. Severe squeezing at Modi pressure tunnel (left) and Kali Gandaki headrace tunnel (right) (Photo: Himal Hydro 2001 and Impregilo SpA 1989)

Figure 9. Water leakage from adit 2 of Khimti headrace tunnel after early water filling (left) and mass inflow of water mixed with debris from a shear fault at the pressure tunnel of Modi Khola (right) (right photo: Himal Hydro 1998)

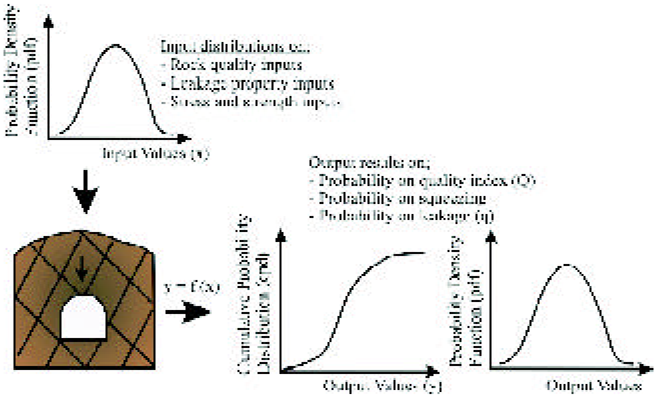

Figure 10. Principle sketch of Uncertainty and Risk Analysis Model for a tunnel project (Panthi 2006)

leakage often have been found extremely difficult during the planning stage. Considerable discrepancies have been found between predicted and actual rock mass conditions, resulting in significant cost and time overrun for most of the tunneling projects. Finding innovative solutions for quantifying geological uncertainties and assessing risk are therefore key factors for cost effective and optimum future tunneling through Himalayan rock mass.

In this respect, a probabilistic approach of uncertainty analyses that the author has proposed in his PhD research (Panthi 2006) is believed will be appropriate to deal with the most important geological uncertainties reflecting Himalayan rock mass conditions. A geological uncertainty analysis model concept based on the software program '@Risk' should be applied for this purpose.

The proposed uncertainty analyses methodology includes rock mass quality evaluation based on the Q-system of rock mass classification, tunnel squeezing based on Hoek and Marinos approach, and analysis of water leakage through water tunnel. The degree of correlation between simulated results achieved by the '@Risk' model and values actually measured in the tunnel is discussed and the sensitiveness and effect of variations in the value of each input parameter and sensitivity of equations and methods used to analyze geological uncertainties are evaluated. The conclusion is that the proposed uncertainty analysis approach gives very promising results and has a great potential for analyzing tunnel projects in the Himalayan rock mass conditions.

Krishna Kanta Panthi *holds a PhD degree in rock mechanics. He is Chief Executive Officer, Hydro-Tunneling and Research Center, Dhobighat, Lalitpur District, GPO 8975, EPC 1522, Kathmandu, Nepal; tel: (+977.1)621.6596.*

Corresponding address: krishnapanthi@gmail.com.

References

HH (Himal Hydro), 2001, *Construction Repor*t, Kathmandu: Modi Khola Hydroelectric Project.

NPC (National Planning Commission), 2003, *Tenth Plan*, Kathmandu: Government of Nepal. URL: www.npc.gov.np (unofficial translation, 4 October 2004).

NEA (Nepal Electricity Authority), 2002, *Project Completion Report*: Vol. IV-A, *Geology and Geotechnical Report* and Vol. V-C, *Geological Drawings and Exhibits*, Kathmandu: Kali Gandaki ‘A’ Hydroelectric Project, Nepal Electricity Authority.

Panthi, K.K., 1998, *Direct Link between Hetauda and Kathmandu: Evaluation of Proposed Road Tunnels, Nepal* (MSc thesis), Trondheim, Norway: Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology.

__ 2004, Tunnelling challenges in Nepal, pp. 4.1–4.15 in *Proceeding of the Norwegian National Tunnelling Conferenc (‘Fjellsprengningsteknikk Bergmekanikk/Geoteknikk 2004’*, Oslo).

__ 2006, *Analysis of Engineering Geological Uncertainties Related to Tunneling in Himalayan Rock Mass Conditions* (PhD dissertation), Trondheim, Norway: Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology. URL: www.diva-portal.org/ntnu/abstract.xsql?dbid=711.

Panthi, K.K. and Nilsen, B., 2005, Significance of grouting for controlling leakage in water tunnels: A case from Nepal, pp.931-937 in *Proceedings of the ITA-AITES 2005 World Tunnelling Congress and 31st ITA General Assembly* (Istanbul).

__ 2007, Uncertainty ~~an~~alysis of tunnel squeezing for two tunnel cases from Nepal Himalaya, *International Journal of Rock Mechanics and Mining Sciences*, 44: 67-76.

Regmi, S.K. and Sitaula, T.P., 2003, Krishnabhir slide: A case study, pp.156-163 in *Proceedings of the International Seminar on Sustainable Slope risk Management for Roads* (Kathmandu, March), Katmandu: Department of Roads, Government of Nepal, in association with Permanent International Association for Road Congress.