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Geological mapping in the Nepal Himalaya: importance and challenges for underground structures

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ABSTRACT

Geological mapping is very important technique to predict geological condition for underground structures. It helps to construct geological model for site selection and designing of any underground structures. Geological uncertainty is directly proportional to the accuracy of geological mapping. More accurate geological mapping resulted fewer uncertainties. Precise delineation of faults, shear/weak zones and water bearing zones is important part of the geological mapping to predict uncertainties. Geological mapping to predict geological condition for underground structures is a challenge in the tectonically active Nepal Himalaya due to thrusting, faulting, folding and reverse metamorphism nature of rocks with difficult terrain and high overburden. The mapping for underground structures is mostly focus on rock mass properties, faults, weak/shear zones, fractured zone, joints, folds, weathering depth and ground water bearing zones. This paper highlights importance of geological mapping and challenges for underground structures with case studies of uncertainties faced due to poor geological mapping.

Keywords: Geological mapping, uncertainty, projection

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INTRODUCTION

Geological mapping is important tools to predict geological condition for underground structures. It helps to construct geological model for site selection and designing of any underground structures. Geological uncertainty is directly proportional to the accuracy of geological mapping. More accurate geological mapping resulted fewer uncertainties. Precise delineation of faults, shear/weak zones, fractured zones and problematic zone is important part of the geological mapping to predict uncertainties. Generally, geological condition is predicted based on surface rock outcrop and structures by projecting down to the level of underground structures. Hence, geological mapping to predict geological condition for underground structures is a challenge in the tectonically active Nepal Himalaya due to thrusting, faulting, folding and reverse metamorphism nature of rocks with difficult terrain and high overburden. The mapping for underground structures is mostly focus on rock mass properties, faults, weak/shear zones, joints, fractured zone, folds, weathering depth and ground water conditions. In Nepal, there is less drilling and geophysical investigations practice along a tunnel alignment due to difficult access, steep topography and difficulty of deep drilling and hence, mostly rely on geological mapping interpretation. This paper highlights importance of geological mapping and challenges for underground structures with case studies of uncertainties faced due to poor geological mapping.

GEOLOGY OF THE NEPAL HIMALAYA

The Nepal Himalayas comprises majority of metamorphic and sedimentary with few granite intrusions. Three major thrust fault systems, namely, Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT), divide the rocks of the Himalayas into Siwalik, Lesser Himalaya and Higher Himalaya from south to north. The MBT and HFT are active faults that can create major problems during construction of any infrastructures. On the other hand, based on the field evidences, the MCT is no longer active and will not to create problems. Besides these major thrust faults, there are several minor fault and shear zones. Most of all faults and shear zones systems generally extend from east to west of Nepal, which are oriented parallel to foliation with north dipping. Most serious georisks in development of underground structures are generated by faults and shear zones (Sunuwar 2011). These faults and shear zones are responsible for posing georisks, and therefore, precise geological maps showing faults and shear zones are crucial for development of any underground structures.

IMPORTANCE AND CHALLENGES

Geological mapping remains the best way of depicting 3-D geological model for underground structures. 3D geological model dictates to finalise the location of underground structures by visualising georisks and minimising expected risks. In addition geological map dictates planning and location of sub-surface site investigations and in situ tests which will optimise cost of site investigation. The more accurately the geology of a proposed tunnel can be ascertained, the more accurate will be the cost estimates. In mountainous terrains, it is not practical to drill throughout the tunnel alignment and hence, more rely on geological mapping prediction. In addition geological mapping will reduce drilling and sub-surface investigation cost by identifying crucial problematic areas to investigate.

In addition, Rawlings and Eastaff (1974) also suggested that under high rock cover (> 500 m), steep topography and difficult access conditions, reliance has to be placed upon the interpretation of geological mapping. Despite that, only the surface geological mapping is not sufficient to predict the properties of the subsurface rock and soil for design.

Geological mapping challenges are summarised below:

- Tracing of contact due to different dipping beds, z-drag folding, recumbent folding, window etc. in different sloping terrains.
- Accurate projection and interpretation of rock beds, faults, fold, ground water etc. due to thrusting, folding, inverted metamorphism, window structure etc.
- Identification of faults and shear zones due to low angle dipping along the foliation plane, vegetation, steep terrains
- Actual evaluation of effect of faults in field for underground structures
- Actual prediction of rock mass conditions at the level of tunnel based on surface exposure
- Unavailability of precise geological maps in small scale and aerial photographs in small scale,
- Inaccessible sites due to steep topography and remoteness
- Ground water prediction due to difficult topography, high overburden, loose deposits and limited natural springs.

ACCURACY OF GEOLOGICAL PROJECTION

Majority of metamorphic rocks in Nepal Himalaya are formed from sedimentary rocks. Sedimentary rocks are formed under comparatively uniform conditions over relatively large areas. The areal extent and its original composition do not much change even subsequent metamorphism, folding and faulting. Hence, this permits relatively accurate interpretation between data points and projection to the depth of a tunnel in metamorphic and sedimentary rocks. However, continuous extent can be dissected by thrusting or faulting. In Nepal Himalaya major faults and shear zones are along the foliation plane or bedding plane and persistence is more than a kilometre (Fig. 1). Hence, projection of major faults down to 500m will be more accurate unless there is no pinching and bulging nature. Deeper is the tunnel less confident is geological prediction due to folding, faulting and overriding structures. However prediction is difficult in gently dipping strata with undulation orientated parallel to the tunnel alignment which requires very careful interpretation during projection with the help of perpendicular sections. Similarly granite and orthogneiss are less predictable and the accuracy of project is of the same order as their area extent. The contact of a cross cutting granite body is less reliable feature.

GEOLOGICAL MAPPING AND PREDICTION

Geological mapping for underground structures should cover rock types, rock mass properties, discontinuities, structures and landslide thickness. Special focus shall be given to delineate faults, shear zones, weak zones, and joints for tunnel and underground structures. Accurate projection of faults, shear/weak zones and rock strata along the tunnel alignment are very essential for design, fixing alignment, selecting rock support, deciding construction technology, cost estimation and planning.

Geological mapping by untrained personnel can lead to errors in interpretation that can be of concern right through into the design stage. Hence, geological mapping should be carried out by experienced geologist who has ability to distinguish and predict geological conditions and problems for underground structures.

Key features to consider for Geological mapping:

- Strong and weak rock distribution and orientation
- Stratigraphic sequence and major structures
- Fault, weak zone, shear zone, fractured zone and folds
- Joint sets, spacing, apertures, persistence and other properties
- Karst features in gypsum, anhydrite, limestone and dolomite.
- Low cover, saddle, depressions, scarp, dense linear vegetation, springs, relief, landslides, sudden change in rock outcrop
- Details route map to understand repetition sequence of weak and strong rock and fault, shear zones, fracture zone
- Weathering depth and topography
- Springs, seepage, wide steep joints, gully crossings, fracture zone for prediction of ground water conditions
- Road cutting section, opposite side rock outcrops, observation from opposite banks, topographic features will give more geological information
- Loose deposits and depth: colluvium, alluvium, diluvium, debris flow and residual soil

Major areas of focus during geological mapping are summarized below:

Rock types

High strength and good quality rock is preferred for tunnelling and laying of foundation whereas low strength and

Fig. 1: Example of more than a kilometre continuous foliated sedimentary origin metamorphic rocks.

poor quality rock mass will require heavy structures and flexible rock support to prevent differential settlement in foundation and rock squeezing in tunnels. Hence, identification of low strength rocks like phyllite, shale, chlorite-talc schist, mica bands, serpentine, chalk, evaporite, soap stone, pyrite etc. are prerequisites to fix the alignment for tunnels and design related undertakings. Stratigraphic sequence, major structures, grade of metamorphism and contact are also important.

Identification of fault, shear/weak zones

Identification of faults in Nepal Himalaya is challenging due to low angle dipping faults system along foliation plane, accessibility, steep topography, poor rock exposures and vegetation (Sunuwar 2011). However, faults and shear zones leave some evidences at surfaces which are clues for identification.

Some of techniques with evidences are summarised below:

- Aerial photo and satellite images: linear features, depression, trough, upset stream courses and line of landslides.
- Field evidences: shearing effect, fault gouge, crushed zone, displacement, striation, springs, pressure ridges and repetition of rock sequence.
- Morphological features: depression, saddle, ridge, deep gully, topographic relief, line of vegetation, springs, series of landslides and line of darker colour.
- Sub-surface investigations: Geophysical survey (seismic, ERT, GPR), trenching and drillings

Remote sensing techniques are useful to identify faults/shear zones by using aerial photos and satellite images. Likewise field evidences such as gouge, sheared, slickensides, displacement and scarp are physical way to identify faults/shear zones in good rock exposures. However, field evidences are not easily observe in the terrains where bedrocks cover by thick soil cover, vegetation, and deep weathering. In such terrains morphological features such as depression, saddle, deep gully, extensive vegetation etc. are more useful evidence to identify (Fig. 2). Google earth image is very useful to delineate faults/shear zones. In addition, drilling and geophysical methods (seismic, electric resistivity, ground penetrating radar) are useful to detect and identify faults.

Projection of rock types, faults and shear zones down to the level of tunnel alignment based on the rock exposures and orientation observed at surface to predict rock mass and soil condition should be accurate although it is tricky and challenging task.

One misleading example of a major fault can be considered for precise geological map. A major fault is shown in Regional Geological Map (Fig. 3) at Tamakoshi River area of Dolakha district which separates the augen gneiss and phyllite. In the field at near confluence of Khimti Khola and Tamakoshi River, there is a sharp contact between Augen gneiss and Kuncha phyllite and hence, there is no any physical evidence for presence of the fault (Fig. 3) which has negative effect on underground structures. In addition, there is always big

Fig. 2: Morphological evidence of a fault

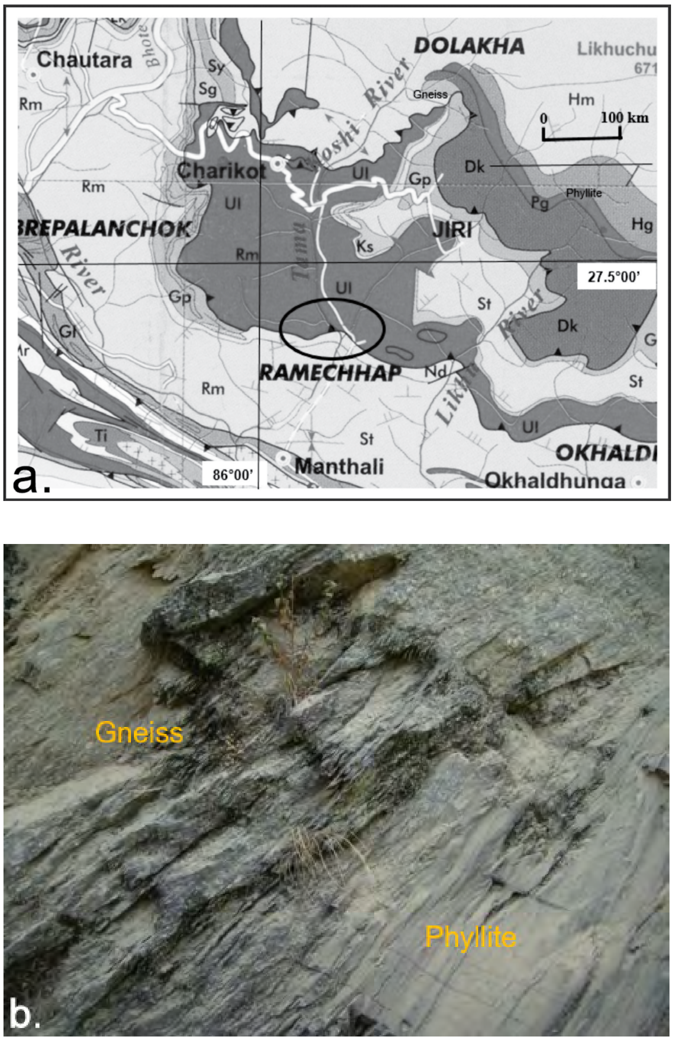

Fig. 3: a. The Midland thrust showing in regional geological map (published by Himalayan map house, author unkown), b. sharp boundary between augen gneiss and Kunchha Phyllite observed near confluence of Khimti Khola and Tamakoshi River area in Dolakha district which confirms no shearing evidence from engineering point of view.

concern to cross the Main Central Thrust (MCT) because some designer still thinks it is active. Actually, the MCT is represented by high-grade (straurolite, kyanite, silliminite minerals) metamorphic rocks on hanging wall and low grade metamorphic rocks on footwall. It is no longer active based on the field evidences and engineering point of view the MCT is not problematic for underground structures. It is thick zone of low to high grade metamorphic rocks and not a single line as shown in any geological map. Likewise placing of MCT is also challenge. There are other minor faults with very sharp contact or with no physical weakness in regional geological map which may not have significant influence for underground structures. Therefore, it is very essential to check physical evidences of faults and verify in field during geological mapping to confirm their effect on underground structures.

Joints

Joint controls the stability of underground excavation and slope. More the number of closely spaced joint sets more likely that the quality of rock mass becomes poorer and increase instability. In addition, presence of ground water will reduce joint shear strength and facilitates failure condition. Therefore, collection and analysis of joint sets and their properties are not only important for designing of underground structures also for slope and foundation. Orientation, sets, aperture, filling, spacing, persistence, ground water are important joint properties. It is important to identify critical and persistence joint set which will cross underground structures.

Generally in Nepal Himalaya foliation and bedding planes are critical joints (Fig. 4).Careful registration and interpretation of strike and dip of joints is important for projection of rocks and structures down to tunnel level. Local variation of strike and dip due to local folding, drags folds, toppling, faulting etc. could mislead in interpretation. Hence, orientation of foliation to construct geological model shall be registered as many as possible and localise affect orientation shall be discarded.

Fig. 4: Critical foliation joint.

Ground water

Ground water is the one of major influencing factor for underground stability and construction. It is the most difficult regime to predict and is also most troublesome during construction. Water can change physical properties of the ground, can wash away filling material and can create void causing the matrix to become loose, resulting in tunnel instability. Hence, identification of ground water regime i.e. inrush and leakage area are very essential to estimate grouting volume and to control tunnel instability and speed up progress. Water flow is basically taking place along the faults and joints (secondary porosity). Ground water flow in discontinuities is a function of discontinuities density, aperture and persistence of discontinuities. Similarly fault zones normally constitutes a porous aquifer, with a hydraulic conductivity varying from highly permeable in Blocky brittle fault to impermeable in Clayey brittle fault (Sunuwar 2011). To estimate ground water ingress and water leakage through tunnel more focus shall be given to faults, shear zones, gully crossings, syncline fold, fractured zone, wide/open steep joints and depression area. Tunnel alignment needs to be divided into different ground water zones such as dry, wet, dripping and flow based on flow volume in 10m length.

Weathering

Weathering downgrades the quality of rock mass. Flatter the ground higher the degree of weathering. Degree of weathering depends on rock type, joint frequency, topography and climate. In the Himalayas saddle, flat topography, incompetent rock and faulted area undergoes high degree of weathering. Weathering creates problems like instability of tunnel and slope due to weak and heterogeneous nature of rock mass.

Karst

Karst features such as sinkholes, solution cavities and caves is generally present in limestone gypsum, anhydrite, and dolomite terrain. This topography creates problems like collapsing of foundation, loss or ingress of water and requires filling or shielding of voids for engineering structures which is expensive. Hence investigation of karst features in limestone, gypsum and dolomite terrains are necessary.

Tracing of contact

Tracing of contact and faults is very important for geological mapping to predict geological condition for underground structures. Horizontal beds have outcrops which follow the contours and never cross contour because they are at constant altitude whereas vertical beds have straight outcrops which ignore the contours. Similarly dipping beds have curved outcrops which cut across and respond to the contours because outcrops shit down dip as erosion lowers the surface. Hence, it is difficult to trace the contact of dipping beds in sloping terrain as compare to vertical and horizontal beds. Major effort and care has to be given to trace contact of dipping beds. Likewise, for accurate projection apparent dip should be used during preparation of geological section where tunnel direction is not perpendicular to the strike.

CASE STUDIES

Only very few hydro projects' underground structures especially located in Higher Himalaya were successfully minimised uncertainties by geological mapping due to presence of very strong metamorphic rocks with very few shear/weak zones and faults. On the other hand underground structures constructed in Lesser Himalaya and Siwaliks faced more uncertainties than predicted due to presence of more shear zones, weak zones and faults which were difficult to identify. Geological uncertainties faced in headrace tunnels of Khimti I and Chameliya hydro projects due to poor geological mapping were considered as case studies.

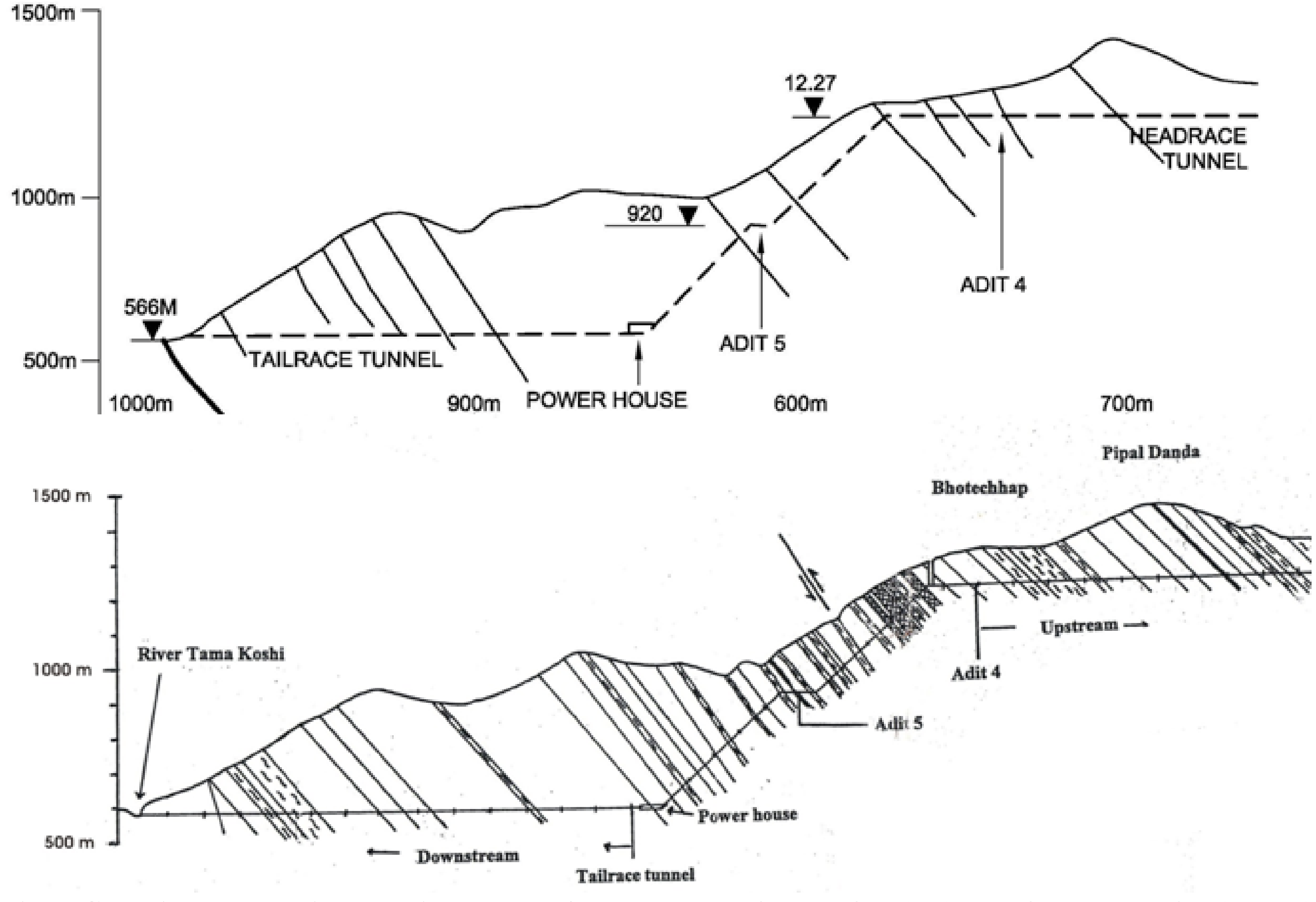

Fig. 5: Geological cross sections showing the shear/weak zones and faults before (top) and after construction (bottom).

Khimti I Hydropower Project (60 MW)

The Khimti Hydropower Project is a 'run-of-the-river' project located in approximately 175 km due east of Kathmandu, Nepal. Major components are diversion weir, surface settling basin, 7.9 km long headrace tunnel (4 m span), 58.4 m high surge shaft (5 m diameter), 913 m long inclined penstock tunnel (2.6 m diameter), an underground powerhouse and 1.3 km long tailrace tunnel. The country rocks are augen gneiss with weak tectonized schist bands belonging to the Lesser Himalaya.

Main reason for facing uncertainties in tunnels of the Khimti project is due to not identifying weak tectonized schist bands embedded in augen gneiss along the foliation plane during geological mapping. The tectonized schist bands were crenulated, sheared, chlorite-sericite-talcose schist with clay gouge and thickness varying from a few centimetres to a maximum of 60m. It is gently dipping and difficult to spot. Rock mass quality prediction along the tunnel alignment was completely based on the surface geological mapping. Tunnels excavations were difficult and problematic due to soft and weak nature of tectonized schist bands with gently dipping. Tunnel collapses at 13 places, rock squeezing in 270m tunnels length and water inflow problems were encountered in the tectonized schist bands during construction (Sunuwar, 2005). Tunnel construction work was delayed by more than one year in upper pressure shaft due to 3 catastrophic tunnel collapses. Similarly delay time of each major tunnel collapse in horizontal tunnels was almost 4 weeks. Heavy rock support with pre-treatment was provided in squeezing section leading to increase of construction time and costs. The presence of the tectonized schist bands and sheared zones downgraded the rock mass quality as a result estimated rock mass quality became just reverse i.e. worse rock mass quality was about 30% higher (Sunuwar 2005). Finally rock support cost was very high. If we compared geological map before construction and after construction about 20% shear/weak zones and faults were not identified (Fig. 5) and which the main cause of uncertainties was.

Chameliya Hydroelectric Project (30 MW)

The Chameliya Hydroelectric Project is a 'peaking-run-of-the-river' project located in approximately 960 km due west of Kathmandu, Nepal. Major components are 54 m high concrete dam, underground settling basin, 4 km long headrace tunnel (4.2-5.2 m span), 48 m high surge shaft (8m diameter), 72 m high drop shaft (3.9 m diameter), 384 m long horizontal penstock tunnel (3.7 m diameter), surface powerhouse and 703 m long tailrace box culvert. The rock types are dolomite, phyllite, slate, meta-sandstone and limestone of the Lesser Himalaya.

Rock mass quality prediction along the tunnel alignment was completely relied on the surface geological mapping. Several large shear zones and faults created major georisks were mostly unpredicted (Shah 2014) (Fig. 6). Rock mass was found substantially weaker, especially in lower half of project area. Consequences during tunnel construction (Shah 2014) due to not identifying problematic shear/weak zones were:

* Higher levels of supports installed,
* Frequent collapses and debris flows,
* Large water inflows,
* Rock squeezing,
* Frequent stoppages,
* Reduced rate of advancement from planned 2-2.5 m/day to 0.37-1.4 m/day,
* Delays and claims.

Severe to extremely severe squeezing (20 to 40%) was experienced about 843m length of headrace tunnel (Shah 2014) when tunnelling through shear zones. Shear zone was saturated highly crushed rock mass of grey to white talcosic dolomite with phyllite intercalation. The tunnel squeezing was noticed by deformation of steel ribs and cracking of shotcrete. Maximum deformation measured was 1.32 to 1.9 m (Shah 2014). Hence reshaping of 842 m headrace tunnel sections was supported by yielding steel sets with 60 cm thick shotcrete in severe active squeezing section and 35-40 cm thick bar (25 mm diameter) reinforced shotcrete support in extreme but stable section (Shah 2014). A 1.88 MUSD (NRs. 2.05 billions) additional cost was spent for reshaping of the tunnel (Shah, 2014). In addition mud flows in several places especially in saturated shear zones were encountered and as a results work halted for over 9 months due to monsoon and mud flow clearance.

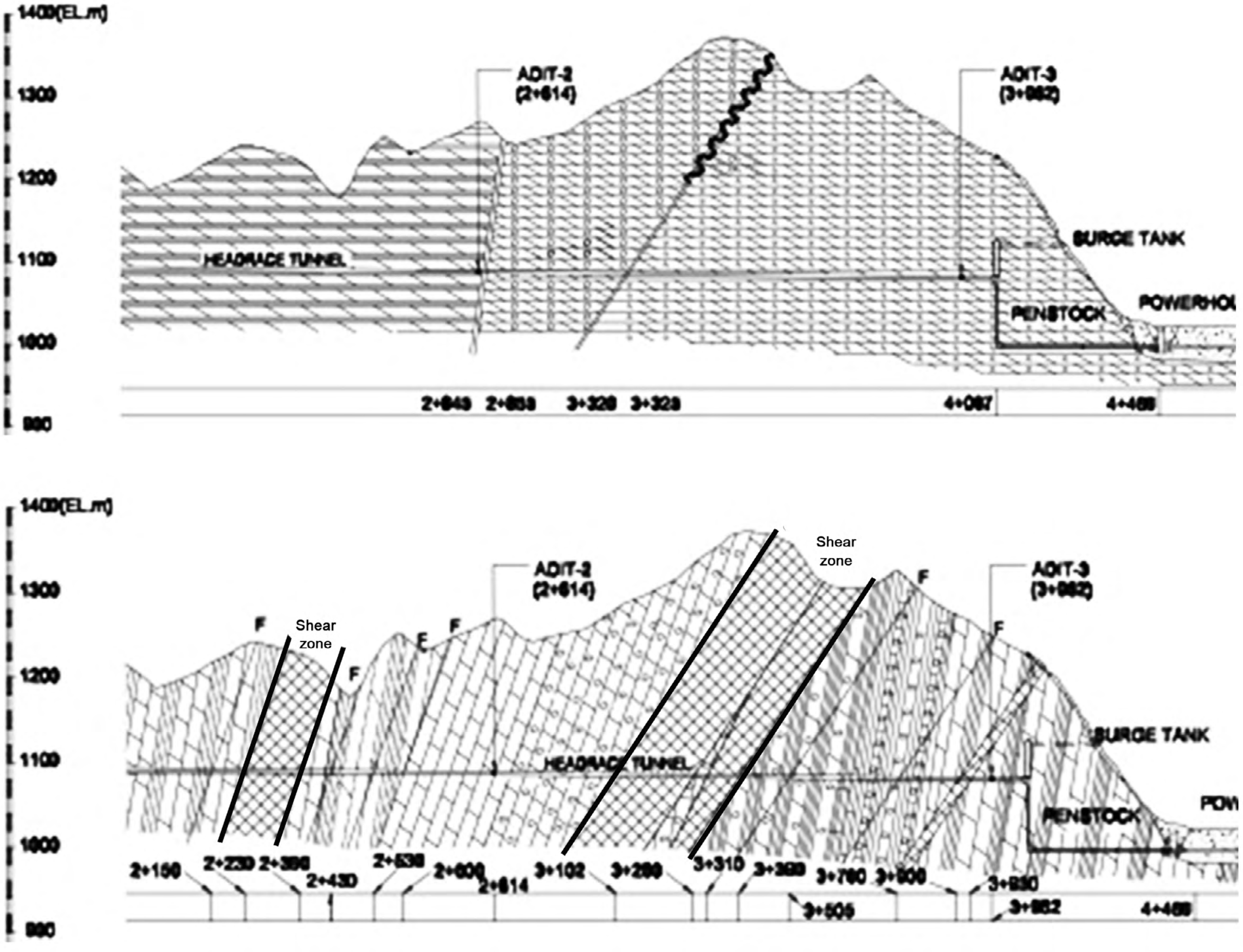

Fig. 6: Geological cross sections showing shear zones before (top) and after construction (bottom) (after Shah 2014).

CONCLUSIONS

Precise delineation of faults and shear/weak zones is important part of the geological mapping to predict uncertainties. On the other hand geological mapping to predict geological condition for underground structures is a challenge in the tectonically active Nepal Himalaya due to thrusting, faulting, folding and reverse metamorphism nature of rocks with difficult terrain and high overburden. Under high rock cover (> 500m), steep topography and difficult access conditions, geological prediction of underground structures is more rely on geological mapping. Only very few hydro projects' underground structures especially located in Higher Himalaya were successfully minimised uncertainties by geological mapping whereas most of underground structures constructed in Lesser Himalaya and Siwaliks faced more uncertainties than predicted.

REFERENCES

Rawlings, G. E. and Eastaff, D. J., 1974, Site investigation for tunnels –the consultant's view. An unpublished report presented to the Engineering Group, Geological Society, regional meeting, Liverpool.

Shah, S, 2014, Underground excavation at Chameliya Hydroelectri Project: Case study. An unpublished report presented in the Nepal Tunnelling Conference 2014, 19-20 December 2014.

Sunuwar, S. C., 2005, Geological problems in the hydropower development of Nepal: case studies. Proceeding of the 6th International Conference on Development of Hydropower: a major source of renewable energy, June 7-9, 2005, Kathmandu, organised by Irrigation Board of India and Nepal Electricity Authority, pp. 130-141.

Sunuwar, S. C., 2011, Faults and shear zones: A geological challenges in hydropower development of Nepal, Proceedings of the World Tunnelling Congress, Helsinki, Finland, 2011, pp. 406.