Geotechnical Problems in the Construction of the Contract Packages C-2 & C-3 of the Head Race Tunnel, Tala Hydroelectric Project, Bhutan

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Abstract

Tala Hydroelectric Project (Installed Capacity1020 MW), a joint venture between Government of India and Royal Government of Bhutan, has been successfully commissioned in 2006. It is a run-of-the-river scheme on river Wangchu, located downstream of Chukha power house (336 MW) in south west Bhutan.

The tunnel alignment passes through biotite gneiss, augen gneiss, gneiss with bands of quartzite, biotite schist, muscovite schist, quartz-mica schist, calc silicate, with subordinate chlorite schist and sericite schist with acid and basic bands representing Central Crystallines (Thimphu Group). The tunnel between Padechu d/s and Geduchu u/s has suffered frequent overbreak/loose falls (sagging and slabbing) from crown-springing area owing to the sub parallel to acute angle relationship of rock strike and tunnel alignment with gently dipping foliations. The inability to achieve appropriate thickness of SFRS (alkali free) on smooth and planar rock surfaces of micaceous schist at crown remained a continuous problem. Detachment of shotcrete layers and failure of schistose rock mass surrounding the face-plates of rock bolts, created unsafe conditions in the rear zones particularly in class-IV and class-V rock mass reaches. In order to ensure safety and stability in the late dilating rock mass, steel ribs provided at frequent intervals proved to be very useful along with optimum pre-tensioning/torquing of the rock bolts using hit and trial.

The actual observations and logical extra pollutions regarding squeezing and support pressure are in close conformity with the equations given Singh et. al (1992) and Grimstad & Barton (1993). For 'Q' values of ± 1 and less (i.e class-V and VI), steel ribs in suitable combination with rock bolt and SFRS, appear to be a reasonable support system.

Geduchu HRT (4430m) did not face any serious problem and was completed as per the schedule, whereas Padechu HRT (4996 m) got delayed mainly due to serious geological problems in the adit and its junction area with the main HRT. Besides, lack of proper exploration and related contractual implications in a ***Fast Track Project Model****, have also been discussed. The underground excavation in the project, in general, has been carried out in accordance with the* ***Norwegian Method of Tunneling*** *using conventional drill and blast technique.*

Introduction

Tala Hydroelectric Project (1020MW) is a joint venture between Royal Government of Bhutan and Government of India. It is a run-of-the-river scheme on river Wangchu, located immediately in the downstream of Chukha Power House (336MW) in southwest Bhutan. The project comprises a 92m high concrete gravity dam, three underground desilting chambers (250m x 13.9m x 18.5m) each, 23km long and, 6.8m finished diameter horse-shoe shaped head race tunnel, 15m diameter 184m deep surge shaft, two steel lined inclined pressure shafts (1.1km length) each trifurcating into three penstocks, an underground power house (206m x 20.4m x 44.5m), an underground transformer hall (190m x 16m x 26.5m) and a 3.1km long tail race tunnel (7.75m dia). The project was commissioned in the year 2006.

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Contract package C-2 (Padechu HRT) and C-3 (Geduchu HRT) were constructed by M/s Jai Prakash Industries (JIL, New Delhi) and M/s Larsen & Toubro (L&T, Chennai), respectively.

Geology along the tunnel alignment

The entire HRT has been excavated through medium to high grade metamorphic rocks of Central Crystalline Group (designated as Thimphu Formation) comprising variants of gneisses, schists and quartzites of Pre-Cambrian age in Eastern Himalayas. Rocks along the tunnel alignment are generally folded into open synforms and antiforms (Fig-1). A number of cross and foliation parallel shears were intercepted. Water seepage of the order of 30 to 500 lpm was associated with major shears.

Padechu HRT (contract package c-2)

The Padechu upstream HRT is aligned in N15°E-S15°W direction along its 2915m of total length. The pace of excavation/progress for about 580m (from adit junction towards u/s) length remained extremely slow on account of poor to extremely poor rockmass conditions and profuse water seepage. The rockmass in this reach consists of slightly to moderately weathered, highly sheared, folded, jointed, wet and thinly foliated quartz-biotite-schist with occasional bands of quartzite and thinly to moderately foliated biotite-gneiss. The foliation dips 15°-40°/N305 to 345 along with overall three sets of joints dipping 40°-70°/N100 to N105 (J1), 45°-75°/N060-N085 (J2) and 50°-85°/N200 to N240 (J3), respectively.

From Ch 580m onwards the rockmass conditions registered slight improvement, though shears, water seepage and overbreak in the crown continued up to Ch ±610m. However, the rate of progress started picking up. It may be important to mention here that the geological conditions in this reach (from adit junction towards u/s) were predicted to be poor to extremely poor till the crossing of Padechu Nala (vertical rock cover ±102m. The improvement in the rockmass strength remained more or less consistent throughout

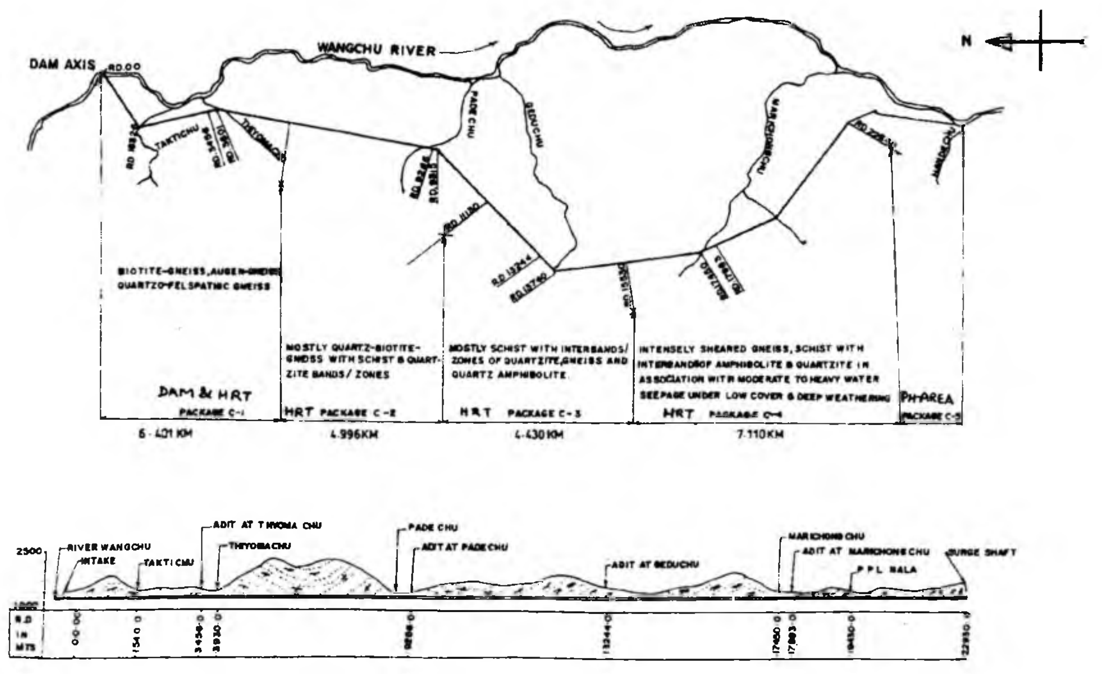

Fig.1: Layout of the HRT and general topographic profile along the alignment (tala hep, Bhutan)

the u/s length except some intermittent patches affected by minor shears and water seepage requiring steel rib support. The average monthly progress after Padechu nala crossing significantly improved to over 100m (mostly without ribs).

The down stream HRT, after a minor kink (at Ch.30m) from adit junction, progressed in S50°W direction for its total length of 2081m. In the initial reach of about 350m length (from adit junction) the tunnel has encountered mostly thinly foliated quartz-biotite-gneiss and quartz-biotite-schist affected by weathering, intensive shearing, jointing and water seepage. The rockmass has been classified mostly under class IV, V & VI necessitating the rib supports, thereby hampering the progress significantly. The dip of foliations varies from 15°-35°/N265 -N300. This may be attributed to frequent folding & warping. The rockmass has been dissected by a number of shears (parallel and across the foliations) and mainly three sets of joints (with variable spacing and continuity) dipping 65°-75°/N045-N065, 40°-80°/N125-N160 and 50°-60°/N285-N330.

From Ch 350m onwards the rockmass condition improved and the excavation progressed satisfactorily through thinly to moderately foliated quartzo-felspathic gneiss with intermittent bands of quartzitic gneiss and quartzite up to Ch. 2081m, except at Ch. 835-841m where it took about two months to cross a shear zone (Goyal D.P, Khazanchi R.N. 2002). Slabbing related failures from the crown were checked by providing steel ribs (4-6 sets with concrete backfill) at an interval of 10-15m based on geological assessment and advice.

Geduchu HRT (Contract package C-3)

Geduchu adit (967m) was more or less smoothly driven through class III and IV rockmass comprising gneisses and schists with a few patches of class II and class V.

The total length of Geduchu HRT is 4430 m including upstream (1905m) and downstream (2525m) portions. The u/s tunnel (from adit junction) is aligned in N50°E direction and the d/s tunnel (from adit junction) in S50°W up to Geduchu nala crossing/bend, and then it swings towards S10°E direction.

Geduchu up stream HRT has been excavated mainly through folded and warped quartz-biotite-schist, biotite-schist with frequent interbands of biotite-gneiss, quartzitic-gneiss and quartzite. The rocks are further dissected by shears and joints. The dip of the foliations varies from 20° to 30°/N350- N040 along with four sets of joints with varying dips of 45°-70°/ N280-N340, 50°-65°/N210-N260, 50°-80°/ N100-N165, 45°-70°/N060-N080 having variable spacing, continuity and alteration characteristics.

The portion of HRT d/s of adit junction was negotiated through folded & thinly foliated, jointed, gneiss and schists with frequent interbands of quartzite and quartzitic gneiss with foliations dipping 10°-25°/ N350-N060 (wide variation due to folding) along with four prominent joint sets dipping 60°-80°/ N260-N340, 45°-80°/ N100-N170, 50°-70°/N240-N260, and 50°-75°/N040-N080.

Support System

During the HRT excavation, behavior of rockmass & performance of support system was studied in detail. The CWC, based on geological input and recommendations given by GSI, has designed support system for different classes of rockmass as given in Table 1: Support system designed for HRT

- The reaches in immensely poor tunneling medium, where supports as per specification of class VI failed, were redesignated/reclassified as 'Beyond Class-VI'. Here excavation methodology & support system have been adopted as per site requirements which include:
- Providing perforated pipe forepoles, extensive pre-excavation high pressure grouting and advance drainage.
- Multi-phase excavation, entirely by chipping (without blasting) and

Rockmass class	Designed support	Alternative support
Class-I (Very good rockmass with Q=>40),	Spot rockbolting (25 Ø, 3500 long) or local application of 50mm SFRS (as required)	-
Class II (Good rockmass with Q=10-40)	Rockbolt (25 Ø, 3500 long) @ 1750 c/c both way staggered or 50mm SFRS from haunch to haunch plus spot rockbolting (25 Ø, 3500 long).	-
Class III (Fair rockmass with Q=4-10)	Pattern rockbolting (25 Ø, 3500 long) 1750 c/c both way staggered along with 50mm thick SFRS up to spring level.	-
Class IV (Poor rockmass with Q= 1-4)	Pattern rockbolting (25 Ø, 4000 long) 1500 c/c both way staggered along with 100mm thick SFRS up to invert.	Steel ribs ISMB-250 @ 750 c/c, 50mm SFRS & backfill Concrete.
Class V (Very poor rockmass with Q=0.1-1)	Pattern rock bolting (25Ø, 4000 long). 1250 c/c both way staggered along with 150mm thick SFRS up to invert.	Steel ribs ISMB-250 @ 600 c/c, 75mm SFRS & backfill Concrete.
Class VI (Extremely poor rockmass with Q=0.01-0.1)	-	Steel ribs ISMB-250 @ 500mm c/c 100mm SFRS & backfill concrete.

immediate rib support of the excavated part using rib segments and back fill by SFRS.

- Provision of horizontal runners/struts at different spacing and
- Provision of bottom struts once full phase excavation completed.

Geotechnical Assessment

The HRT in general and few specific and critical reaches in particular, experiencing wedge failures and squeezing conditions were studied in detail. The empirical relations between depth of squeezing, 'Q' values and support pressure have been discussed in accordance with following equations.

Tunnelling Index Q = RQD/Jn x Jr/Ja x Jw/SRF (Barton 1974)

Depth of squeezing H > 350 Q 1/3 (Proposed by Singh et.al 1992)

Support pressure P arch = 2/Jr.Q1/3 (Proposed by Grimstad & Barton 1993)

The tunneling in the project has being carried out in accordance with the Norwegian Tunneling Method, using conventional drill & blast. Rock support is mainly with rock bolts and plain/steel fibre reinforced shotcrete (SFRS). In case of extremely poor rock mass condition, positive supports were also provided in form of structural steel ribs. To check late dilation of rock and sagging tendency, excavation followed by concurrent rockbolting and SFRS support over a length of 7-10m followed by 3m length of steel rib support, alternately, checked this situation. SFRS thickness upto 150mm in a single application by using alkali free accelerator, (Meyco SA160 of MBT), was also achieved in some geologically favourable reaches of the HRT.

Barton's Rock Quality Index 'Q' (1974) was used for providing the support system in Norwegian Tunneling Method, as per equation given below:

Q = RQD/Jn x Jr/Ja x Jw/SRF

Padechu HRT (Contract package C-2)

The support pressures for 'Q' values of 7, 1.16, 0.33 and 0.044 is estimated to be of the order of 10.5, 19, 28 and 57 tones respectively. Accordingly, the tunnel reaches having 'Q' values less than 1.16, preferably be supported with steel ribs, in some practicable combinations of rockbolt and SFRS as per site specific requirements. However, for class V and VI reaches, continuous rib supports would be more favorable.

Instances of squeezing indicated by twisting of steel ribs and cracking of laggings were observed between Ch ±580m u/s and ±350m d/s (including the adit junction) at irregular intervals on account of weak schistose rocks affected by weathering, shearing, and water seepage. The overburden thickness in this reach has been of the order of approx.100m to 170m. Similarly, in the d/s HRT (with respect of adit junction), due to a major shear zone (Ch 835-841m) the signatures of squeezing were observed. In this reach the vertical rock cover was of the order of ± 415m. It could not be possible to ascertain the degree of squeezing or percentage-closure of tunnel on specific chainages, as the instrumentation plan was taken up at a later stage. Therefore, the data collected, exhibited stabilizing trend of squeezing.

Collapse in Padechu Adit

In the Padechu adit, from Ch. 118-132m the construction schedule was seriously affected, due to extremely poor tunneling conditions. At chainage 118m of Padechu adit, the crown collapsed at 13.00hrs on 7th May' 1999 along with heavy ingress of water (40-50 ltr/min).

The loose and unstable rock mass above spring level was continuing, repeat procedure of making bulk head, driving forepoles of heavier steel section was carried out in stretches and steel ribs were erected in parts, and placed on the muck. About half a meter space was cleared for accommodating steel rib and further bulkhead was made for each advancement. Due care was always taken to channelise gushing water coming from the face. Any attempt made to open a space of more than 0.5m, led to increase in the flow of rock mass along with water.

Full face was opened at Ch. 132m and, only after some improvement in the rock strata, the face could sustain full blast. It took four months with conventional method to negotiate the situation encountered between Ch.118m and Ch.132m.

Cavity formation in padechu HRT D/S

A major shear zone associated with along with seepage was encountered between Ch.838m and Ch.841m. The shear had a dip of 750-800/N210-220 and was arcuately disposed within this reach. It had an effective width of ±1.75m with crushed and fractured gneiss having multiple thin clayey gouge seams. Due to its steep faceward dip, it suddenly appeared leading to flowing condition in the tunnel.

Head Race Tunnel in the d/s from adit at Padechu at Ch. 835m was progressing in class III by providing design-supports (rock bolt and shotcrete). Blast at Ch.835m was taken to reach the face at Ch. 838m. While mucking was in progress, rock mass started flowing from the crown forming a cavity extending backwards. Flow of rock mass continued along with the flow of water. The flowing muck covered full tunnel face forming a heap and was allowed to accumulate to check further flow from the cavity. While flow of rock mass at Ch. 838m was forming a cavity extending backwards, cracks were seen in shotcrete in crown portion behind Ch. 838m. In order to check any possible roof collapse in the areas where cracks had formed, steel supports were provided in reaches Ch.817m – 820m and Ch. 824m – 827m ensuring safety of the HRT in rear portion.

The fallen muck was pushed towards the face and the face was closed by providing a plug comprising steel plates in the bottom portion and gunny bags filled with muck in the upper portion. After sealing the face, GI pipes in lengths of about 6m-9m were pushed into the cavity from the face at different locations for grouting. Cement: sand grout (1:1) was injected to consolidate the flowing mass. This was attempted so that rock mass above the crown in the cavity could be consolidated enabling advance by providing rib supports below it.

Water seepage of 100-150 ltrs/min was observed in an around the crown. By cement grouting, the seepage water was brought towards the rear zone to facilitate further advance otherwise it would further lubricate flowing mass and accentuate the cavity. With cement: sand grout (1:1) and strengthening of the crown by providing four poles using ISMBs, pipes, angles, channels etc. it was possible to progress in heading by providing steel ribs in segments.

It was experienced that every time after grouting when an advance was made by installing a segmental rib, at a distance of 0.5m or less, muck in the heading in cavity portion would slide down making water flow through the cavity portion unless rock mass was grouted again. The cavity which finally extended from Ch. 835m – Ch. 841m could be overcome by sealing the face, grouting with cement sand mix, supporting with steel four poles, channelising the water, proceeding in heading, providing segmental rib 2m-3m long at a time and back packing with concrete. The size of cavity could be appreciated from the fact that 2700m3 of loose rock was removed from the tunnel. It took two months to advance through the blind shear and the affected zone from chainage 835-841m.

Geduchu HRT (Contract package C-3)

The crown has suffered frequent overbreaks mainly on account of gently/sub horizontally dipping schistose rocks striking parallel-sub parallel to tunnel alignment. Due to the rather smooth foliation planes of schist, the SFRS was not adhering in requisite thickness on the arch/crown in spite of repeated application, and its cracking/detachment remained a recurring problem in the rear zones preceding 20-25m from the face.

The problem of inadequate thickness of SFRS was further compounded by frequent slabbing/sagging tendency of schistose rocks from the intervening space (on the arch) between the rockbolts, resulting in the failure of rockbolts with their end-anchorage intact. The schists usually yielded from around the face plates, resulting in overbreak and unsafe working conditions in the rear zone. This phenomenon has been attributed to late dilation tendency, particularly in gently dipping schistose rocks. To cope-up with this problem, various economical combinations of SFRS, rock/bolting and steel ribs were experimented, and 4-6 sets (1m spacing) of steel ribs (with concrete backfill) at 1-1.5 D interval were found appropriate to break the sagging span of the tunnel through schistose rockmass and ensure safety and stability of the rear zone, along with safe advance at the face. This support-procedure was not adopted where hard and compact gneisses, quartzites & quartz- amphibolites were disposed on the arch. No evidence of rib twisting was noticed even in class V (4.29% of total length of Geduchu HRT) and class VI (0.19% of total length of Geduchu HRT) rockmass in this tunnel. The curved portion of HRT, under Geduchu nala (Ch 567-606m) was supported with steel ribs (ISMB 250 @ 1000 c/c) due to the occurrence of mainly schists, affected by a sub-vertical shear and a number of minor cross shears and low rock cover (46.5m) above the nala span.

The support pressures as per empirical calculations were of the order of 11-19 tons for 'Q' values of 6 and 1.16, respectively, whereas the designed capacity of rockbolt was of the order of 12 tones. Therefore, the 'poor' reaches having 'Q' values close to 1.0 should preferably be supported with steel ribs at suitable spacing.

Similarly, the support pressure was of the order of 27-44 tons for 'Q' value of 0.4 and 0.097, far exceeding the rock bolt capacity (12 tones). Therefore, rib supports were more appropriate as per empirical/broader assessment of very poor (Class .V) and extremely poor (Class. VI) zones. The vertical cover above the tunnel-grade varied between 160m and 665m (except under Geduchu nala where the vertical cover was $\pm$46.5m) over the total 4.43km of tunnel length. No instance of squeezing was noticed.

The NIRM (Sengupta et.al. 2002A) has carried out deformability tests in the HRT which is given in Table 2.

Table 2: Deformability values in HRT

Test location	Rockmass class (Barton' 1974)	Deformation modulus Ed (GPa)	Elastic modulus Ee (GPa)	Ee/Ed
Padechu u/s	V	3.2042	4.2987	1.34
Geduchu u/s	IV	4.7344	7.0016	1.47

Variation in Projected and Actual Geology

Out of total 4996 m length of Padechu HRT (C-2), 27.29% Cl-III (fair), 53.13% Cl-IV (poor), 15.21% Cl.-V (very poor) and 4.37% Cl-VI (extremely poor) rock mass were encountered (Fig.2). However, during DPR stage, geologically projected figures for different rock mass classes were of the order of 4.68% Cl-I 25.39% Cl-II, 43.91% Cl-III, 15.84% Cl-IV and 10.18% Cl.-V. Total ribbed length is 1020.6m, which is about 20.42% of total length of Padechu HRT.

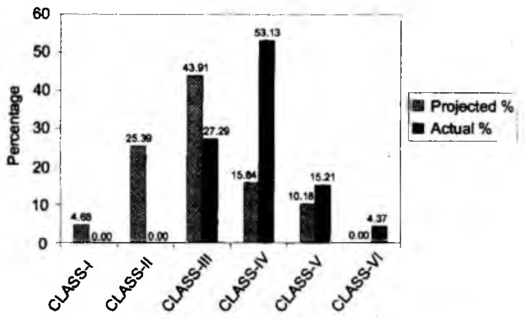

Fig. 2 : Projected Vs Actual geology along Padechu HTR (C-2)

Out of total 4430 m length of Geduchu HRT (C-3), 0.14% Cl-II (good), 13.99% Cl-III (fair), 81.4% Cl.-IV (poor) and 4.29% Cl-V (very poor) rock mass were encountered (Fig.3). However, during DPR stage, geologically projected figures for different rock mass classes were of the order of 34.30% Cl-II 45.71% Cl-III, 11.42% Cl-IV, and 8.57% Cl.-V. Total ribbed length is 1279.42m, which is about 28.88% of total length of Geduchu HRT.

Such variations may be attributed to a number of constraints faced by the geologist working in DPR stage of the project. Some of the most important factors influencing the geological prediction/projection consist of non

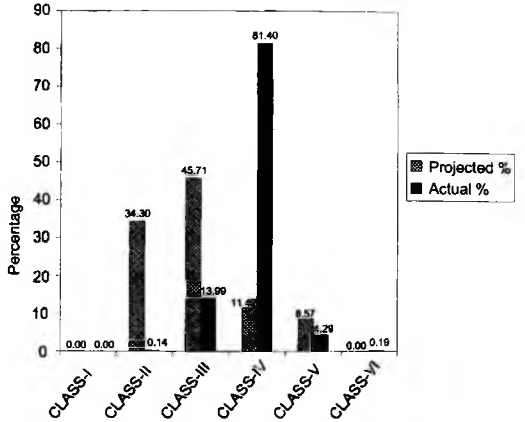

Fig. 3: Projected Vs Actual geology along Geduchu HTR (C-3)

availability of rock outcrops, thick soil and vegetation cover, inaccessibility along HRT alignment, inadequate geological/ geotechnical explorations and, eventually, slopeward shifting of the HRT layout causing deterioration in the joint characteristics leading to the deterioration in the rockmass classes as well. In fact, the geological assessment for the long and sinuous HRT carried out during feasibility and DPR stage, in any project, is quite conjectural and vague, particularly in the absence of proper and adequate exploration. In all probability, the construction agencies have a strong tendency to capitalize on this loophole.

Impact of acceleration scheme for HRT excavation

A comparative study of progress achieved in HRT before and after implementation of "acceleration scheme" indicates that there has been a significant increase in the average monthly progress in all packages, which enabled in retrieving most of the delays in the execution of 23km long HRT. Average monthly progress in all packages before implementation of acceleration scheme was of the order of 70m which increased to 91.27m after implementation of the scheme from April 2001.

From the above study it is observed that without acceleration scheme if the contractors would have continued with contracted average monthly progress then overall completion of HRT could have been delayed abnormally. Hence, instead of retrieving the lost time there could have been further delays in excavation of HRT thus seriously affecting the overall completion of the project. The increase in average monthly progress after implementation of acceleration scheme helped in retrieving about 14 months, out of 19 months delay in the excavation of HRT from Padechu adit.

However, in retrospect, the experience shows that the geological adversities are sometimes unexpected and may cause serious problems in other components of the project, thereby undermining the success of such acceleration schemes in totality. Moreover, in order to take maximum advantage of such incentive schemes, construction agencies may like to reduce the excavation cycle either by skipping the supports or compromising with the concurrency of the support system.

Conclusion

1. The tunnel between Padechu downstream and Geduchu upstream has suffered frequent overbreak/loose falls from crown on account of sub parallel to acute angle relationship of rock strike/ tunnel axis and gently dipping foliations (of interbanded sequence of schists, quartzites and thinly foliated gneisses) unable to counter the sagging/slabbing tendency at the crown. The inability to achieve appropriate thickness of SFRS (alkali free) on smooth & planar rock surfaces of micaceous schists at crown and optimization of pre tensioning/ torquing limit of the rockbolts remained a constant problem which manifested in cracking/detachment of shotcrete, and yielding of schistose rockmass around the face plates of rockbolts creating dangerous conditions in the rear zones particularly in Cl-IV and Cl-V rockmass stretches. To ensure the safety and stability in the late dilating rockmass, steel rib supports provided at frequent intervals (1.5D to 2D) proved to be very useful.
2. In general, the variation between projected and actually encountered percentages of different rockmass classes along such long HRT's will always be a point of debate. The geological projections at DPR stage are done on the basis of limited rock exposures, insufficient explorations, thick vertical/lateral overburden and inaccessibility along the alignment. Therefore, actually encountered geology during excavation may appear significantly different, particularly when viewed without due consideration of excavation methodology and concurrency of support system. Moreover, when alignments are shifted towards hill slopes to reduce the length of approach-adits (to save construction time and cost), the joint characteristics deteriorate and so do the rockmass classes. Therefore, the experts involved in the formulation of contract documents should incorporate checks / restrictions, so that any major financial implication on account of such normal geological variations may be avoided, unless any major shear zone / geological surprise disrupts the construction schedule significantly.
3. The observations/approximations regarding squeezing and support pressure are in close conformity with the equations given by Singh et al (1992) and Grimstad & Barton (1993). For 'Q' values of ± 1 and less (i.e., class V and VI), steel ribs in suitable combination with rock bolt and SFRS appear a reasonable support system.

4. Detailed and timely instrumentation plan is essential to understand the behaviour of rockmass strength parameters and visualize/anticipate the severity of convergence/closure, particularly for the poor zones of the HRT, which will help to plan the construction methodology and suitable support system in advance. The experience shows that the timing is of essence in tackling a poor zone. Any delay, either due to lack of experience or absence of advance preparedness at site, may convert a small geological problem into a serious hazard in the tunnel leading to protracted litigation and related contractual and financial implications in the project. Probe holes at regular intervals in presence of site geologists, should be made mandatory while excavating tunnels (HRT/TRT) so that sudden occurrence of weak geological features could be handled more effectively.

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