DECIPHERING THE SHAPE OF THE VALLEY : GEOLOGICAL INVESTIGATIONS AT DAM SITE OF THE MANGDECHHU HE PROJECT

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ABSTRACT

Deciphering the shape of the river valley beneath the overburden at any dam site, has been a chal-lenging task for the geologists as well as designers as the choice of the dam and other associated components is dependent upon the depth of overburden and shape of the valley. The problem gets further compounded by the remoteness of the area and meandering rivers in the Bhutan Himalayas. The geologists' expertise in comprehending the shape of the valley based on his geomorphological understanding of the area becomes very valuable in developing a reliable model of the dam complex based on minimum geotechnical explorations. Successful execution of the 720 MW Mangdechhu HE project in the Bhutan Himalaya, rightly underscores this.

Mangdechhu HE Project consists of a 110m high concrete gravity dam across the river Mangdechhu in Bhutan. The dam complex consisted of two nos. coffer dams, one no. 682m long 7.5m finished diameter diversion tunnel, one intake structure and two nos. 340m x 14m x 17.7m high desilting chambers. Geotechnical investigations consisted of geological mapping, exploratory drilling, drifting and geophysical resistivity surveys. Exploratory drilling consisted of seven drill holes having cumulative length of 336 m carried out during the detailed investigation stage, eight drill holes totaling 559m completed during the pre-construction stage and fourteen. drill holes totaling 830 m during the execution stage. During the course of investigations at the downstream cofferdam, a buried paleochannel was very timely discovered, for which correc-tive measures were adopted to keep the seepage from the downstream side under control as well as to avoid unforeseen deep excavation in the dam pit. A very uneven valley was interpreted with reasonable accuracy based on above explorations. This has immensely helped in overcoming construction difficulties as well in detailed designs. The present paper describes how timely decisions about geological explorations can aid to the technical decision making process, thereby excluding potential chances of delay.

INTRODUCTION

The Mangdechhu HE Project is a run-of-river scheme over the Mangdechhu River near Trongsa town in the Central Bhutan. The project is designed to utilize a gross head of 733 m between the dam and the TRT by construction of a 114m high concrete-gravity dam near Trashidingkha Village and a 155m (L) x 23m (W) x 41m (H) Underground Powerhouse near Khame Village to house four Pelton turbines of 180MW each. The water conductor system comprises of two desilting chambers (340m x 14m x 17.7m), a 13.5km long 6.0m finished dia concrete-linedhead race tunnel, an open to air 152m deep 13.5m diameter concrete lined surge shaft, two 3.5m dia 1910m long steel lined pressureshafts and a 1.33 km long tail race tunnel. The project is designed to generate 2925.50 MU in a 90% de-pendable year. The construction of the project started in 2012 and has been commissioned in 2019.

The diversion structure comprises of a 105 m high concrete-gravity dam and upstream and down-stream coffer dams of 15m and 10m height above the river bed respectively. To facilitate construction, the river was diverted through a 682m long 8.5m dia horse-shoe shaped concrete lined diversion tunnel on the right bank. The dam consists of four spill ways in the centre and non-overflow blocks on either side.

REGIONAL GEOLOGICAL SETTING OF THE PROJECT

The project area lies in the Central Crystalline belt of the Himalayas and is surrounded by rocks belonging to Thimphu Gneissic Complex (TGC) and meta-sedimentaries of the Chekha Formation. A large body of Tertiary Leucogranite is emplaced in the otherwise Archeozoic to Proterozoic TGC &metasedimentaries. Overall the Trongsa area is covered by Greater Himalayan Sequence (GHS) as mentioned by Grujiic et al. (2002). The general stratigraphic sequence of the area is as follows:

Table 1 : General Stratigraphic Succession of Trongsa Area

Group/ Formation	Age	Litho logy
Leucogranite Thimphu Chukha Group (Chekha Formation)	Tertiary (10-30m.y) Palaeo-Proterozoic -----------Thrust --- ---	Leucogranite Tourmaline granite Garnetiferous Micaceous Quartzites, Mica schist, Granite, pegmatite and mafic intru-sions.
Thimphu Gneissic Complex	Proterozoic	Granite gneiss, Augen Gneiss, Hornblende Gneiss, Garnet- staurolite Mica schist, Gra-phitic schist, Calc.gneiss, Intrusions of granite

(With references drawn from Grujic et. al, 2002, Jangpangi B.S. and Department of Geology & Mines, Royal Government of Bhutan)

Photograph 1 : View of the dam site of the Mangdechhu from Trongsa Dzong.

The rocks of both the Thimpu Gneissic Complex and the Chekha Formation are the significant litho domains of Bhutan and cover large parts of the country. The rock mass in the area is dominantly gneissic with inter bedded biotite / muscovite schists in the Thimpu Gneissic complex while quartzites with inter-bedded schists are dominant in the Chekha formation.The dam area lies in the Central Crystalline belt and is surrounded by rocks belonging to Thimphu Gneissic Complex and meta-sedi-mentaries. Thimphu Gneissic Complex comprises of Granite Gneiss with subordinate bands of Schi-stand Granite intrusions.

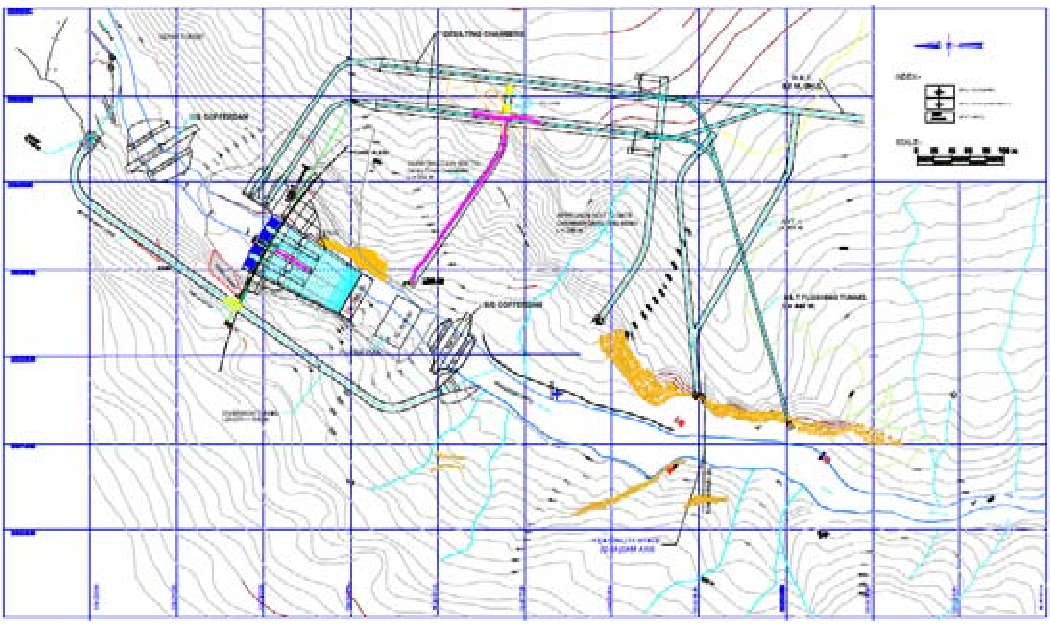

Figure 1 : Layout Plan of Dam site of Mangdechhu HE Project

Table 2 : Exploratory Drilling at Alternative Dam axes (Feasibility Stage- by Norconsult)

Sl. No.	Drill Hole No.	Location	Total Depth (m)	Ground EL (m)	Bedrock Depth & EL (m)
1	BH-1	Left bank of D-2axis	71.10	1690.8	54.60 (EL 1636.2)
2	BH-2	Left bank of D-2 axis (inclined 55 towards river)	102.25	1690.8	70.50 (inclined depth)
3	BH-3	Left bank of D-2 axis (inclined 60 towards hill)	74.55	1690.8	64.90 (inclined depth)
4	BH-4	Left bank of D-2 axis (inclined 57 towards hill)	25.7	1696.1	15.5 (inclined depth)
5	BH-5	Left bank D-2 axis	60.1	1754	5.5 (EL 1749.3)
6	BH-6	Left bank D-2A axis	52.1	1693.4	24.1(EL 1669.3)
7	BH-7	Right bank D-2A axis	45.7	1705.3	5.3 (EL 1700)
		Total Drilling (m)	431.5 m		

GEOLOGICAL INVESTIGATIONS IN THE DAM AREA

The feasibility studies of the Mangdechhu HE Project had been carried out by M/s Norconsult who investigated around 5km stretch starting from the confluence of the Mangdechhu & Tarkhachhu. Seven alternative locations had been studied by Norconsult before proposing the selected site. Nor-consult had explored the dam site with seven boreholes as detailed in table 2. When NHPC was en-trusted with detailed investigation and preparation of detailed project report by Government of India, it started with perusal of the feasibility stage investigations and problems associated therewith. The geological section based on investigation data along the dam axis showed overburden depth of about 25-26 m towards left bank terrace and 55m in the mid-stream portion, with even deeper overburden expected in the dam toe area. Actually the Norconsult termed the deep rock profile below the river bed as canyon. Accordingly, considering the potential instability on left bank and the deep bed rock in the river bed and abrupt curvature in the downstream of proposed dam toe, downstream dipping

foliation planes with more number of weak schist rock, design and geology team reviewed the feasibility stage dam site. Considering the geomorphology and other features it was anticipated that the bed rock would not be so deep in the upstream, one more location which was about 560m u/s of feasibility stage axis (christened as D2A axis), was identified and taken up for further investigations. During field traverse, both the banks at this alternate location were found to be consisting of strong to very strong gneissic rock with very few schist bands. The banks are also observed to be relatively stable compared to downstream site.

GEOLOGICAL INVESTIGATIONS AT THE PRESENT DAM AXIS

An array of geotechnical investigations were undertaken at the new site commencing from engineering geological mapping, exploratory drilling and galleries in adutments or test tunneling, geophysical surveys, groutability tests and rock mechanic tests. The geological mapping of the dam area was carried out on 1:1000 scale contour plan with 2 m contour interval by marking of rock outcrops and exposures, demarcation of RBM, terrace deposits and slope wash/talus areas in overburden, besides engineering classification of rockmass. The orientation and other characteristics of major discontinu-ities were collected and possible problematic areas identified. The dam site was finalized based on geological appraisal along with other technical considerations like positioning of ancillary structures and overflow section. The layout plan of the dam complex is given in Figure 1.

Table 3 : Exploratory Drilling in Dam Area (DPR stage)

Sl. No.	Drill Hole No.	Location	Total Depth (m)	Collar EL (m).	Bedrock Depth and El-evation (m)
1	DDH-1	Dam Axis (Alternative D-2A) Mid Stream hole	69.5	1687.115	55.5m (1661.615)
2	DDH-2	D-2A dam axis, L/B	45.50	1692.05	25.5m (1666.55)
3	DDH-3	DPR Dam Axis, Right Bank	59.0	1698.558	34.5m (1664.058)
4	DDH-4	DPR Dam Axis, Right Bank (In-clined hole, 720 from horizontal)	52.0	1697.909	33.2m (Inclined depth) (1666.0)
5	DDH-6	L/B, DPR Dam Axis (20m u/s of dam axis)	45.3	1697.936	39.5m (1658.436)
6	DDH-7	R/B, 25m u/s of dam toe	64.75	1700.164	51.0 m (1649.164)
		Total	336.05 m		

Table 4 : Exploratory Drilling in Dam Area (Pre-Construction stage)

Sl. No.	Drill Hole No.	Location	Total Depth (m)	Collar EL (m)	Bedrock Depth and Elevation (m)
1	DDH - 8	Dam Axis R/B	60m	1697.978 M	32.70m/El 1665.278 M
2	DDH - 9	Dam Toe, Right Bank	75m	1692.862M	57.40m/El 1635.462 M
3	DDH -10	Diversion Tunnel Outlet	50m	1705.580M	19.50m/El 1686.08 M
4	DDH -11	Upstream Coffer dam L/B	54m	1705.09M	38.75m/El 1666.815 M
5	DDH- 12	Groutability Holes	80m	1696.835 M	48.5m/El 1648.335 M
6	DDH- 13		80m	1695.523 M	25.2m/El 1670.323 M
7	DDH -14		80m	1696.419 M	39.25m/El 1657.169 M
8	DDH-15	Groutability –Central Check Hole	80m	1695.277 M	42.45m /El 1652.827 M
		Total	559 m		

During the DPR stage NHPC limited explored the river bed profile in the dam area with six nos. drill holes totaling 336 m (table 3). This was followed by drilling of eight drill holes (table 4) totaling 559m during the Pre-construction stage. The supplementary investigations in the pre-construction stage enabled NHPC to firm up the expected bedrock levels in the dam foundation area. The exploratory drill holes were augmented by geophysical surveys. To investigate the quality of the abutments, one exploratory drift (gallery) each were excavated on the both banks at the dam axis. The bedrock at the dam site was known with considerable accuracy with the exploratory drilling undertaken during the DPR and Pre-construction cycle of investigation.

On the basis of the drill hole data (DDH 7, DDH 9) it was prognosticated that the bedrock might be deeper towards the left bank side in the dam toe area and it was proven correct after excavation. Similarly, in the intake area upstream of dam axis based on results mainly from DDH-6 , it was predicted that the bedrock will be deep and accordingly the concreting for intake structure would have to be founded at depth. However, during excavation, as the intake excavation commenced towards the left bank a natural rock pedestal was found instead of the deeper curved bed rock profile which enabled placement of intake concreting from a higher level than anticipated. This was utilized by modifying the intake structure, which resulted in saving considerable quantity of concrete. After com-pletion of pre-construction stage investigations, a conservative bed rock profile was generated con-sidering the deeper bed rock depth in some of the drill holes as seen in tables 3 and 4 wherein buried channel was interpreted. It was later proved to be a meandering channel which was towards left bank near intake location and moving quickly towards centre of the river and towards right bank at dam toe. As explained in subsequent paragraphs by the time downstream coffer dam was reached the deep channel once again moved towards left bank. This was hardly appreciable from the surface expression of the river valley. However, confirmatory explorations undertaken during the construction stage at the coffer dams, proved to fill the gaps in understanding and a better prediction of the bedrock profile could be achieved. Thus, the encountered and expected rock profiles were in good agreement (Figure 2). This has resulted in avoiding any major delay in construction of the dam.

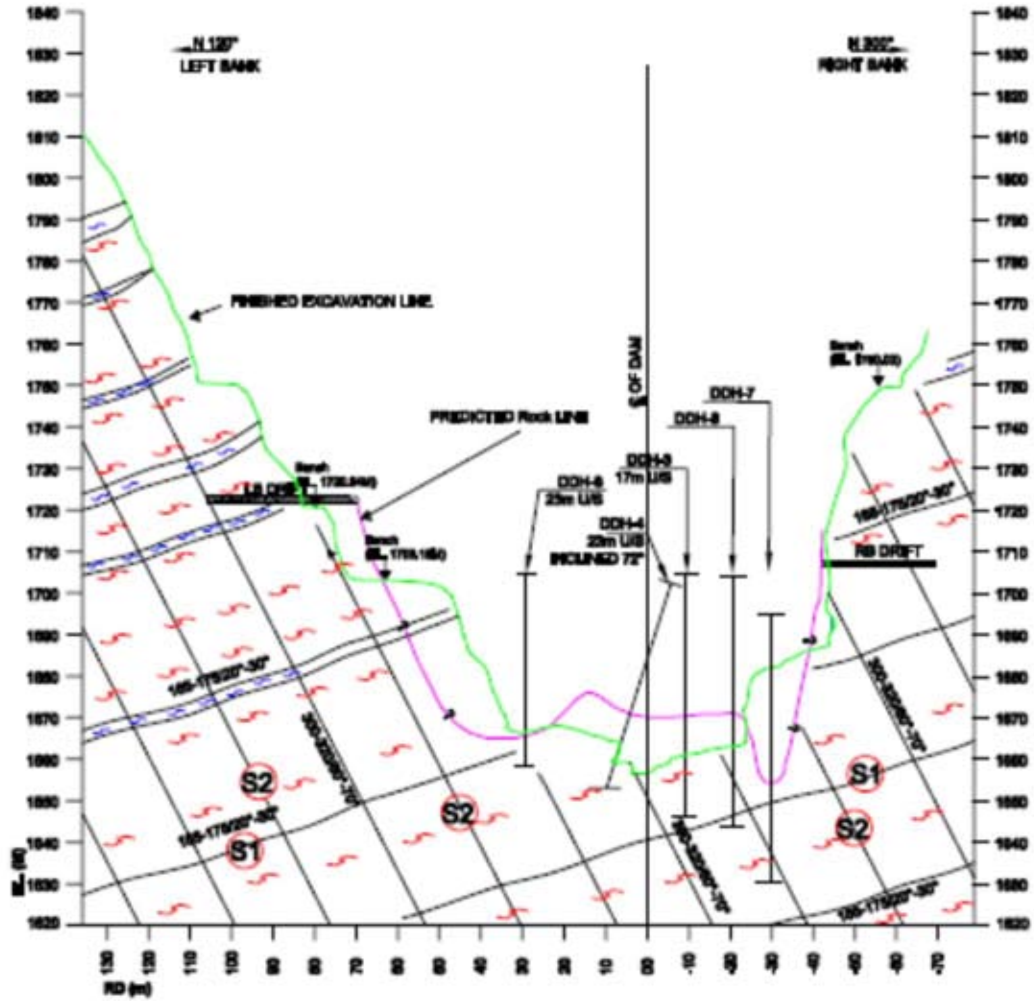

Figure 2 : Geological Section at Dam Axis.

SUB-SURFACE INVESTIGATIONS AT THE COFFER DAMS:

To facilitate construction of the dam, upstream and downstream coffer dams were proposed at 115m u/s and 242m d/s of the dam axis. At the upstream coffer dam the expected overburden was of the order of 55m. However, owing to logistics constraints envisaged at the time of the DPR, the seepage control was planned through permeation grouting at both the upstream and downstream coffer dams.

Further study of the data from the exploratory drillings during DPR, Pre-construction and construc-tion stages suggested that the river channel was underlain by riverine debris material constituted by boulders cobbles, pebbles and gravels of Granitic Gneiss and Gneissose Granite, Pegmatite's and Quartzite's within a medium to fine grained sandy matrix. Boulder of several metre sizes were inter-cepted during dam foundation excavation. The exploratory drilling too revealed the presence of a prominent sand horizon of undulating width; spanning the river channel and extending from upstream to downstream coffer dam locations, interpreted to be of thickness ranging between 4.5m to 12m.

To confirm the extension and behavior of these sand horizons additional investigation was done in the construction stage. Also, to study the possibility of providing a cut-off wall, it was desired to have proper rock line along the coffer dams. Therefore, five nos. drill holes at the upstream coffer dam and 4 nos. drill holes (Table 5) at the downstream coffer dam were done. Data from these new drill holes and earlier holes done during the DPR and Pre-construction stages, depicted the shape of the under-lying bedrock profile with sufficient confidence (Figure 3) and confirmed the longitudinal as well as lateral extension of the sand horizons throughout the dam foundation. These facts alongwith nature of sand horizons formed the basis for replacement of the permeation grout curtain at the upstream coffer dam with a diaphragm wall and adoption of suitable grouting measures at the downstream coffer dam to achieve sufficient water tightness. The progressive explorations during the construction stage ensured that that the construction of the upstream coffer dam is completed without surprises and proper prognoses are made. However it is also brought out that with two holes at upstream coffer dam and one hole near downstream coffer dam a complex valley profile was deciphered for these ancillary structures also.

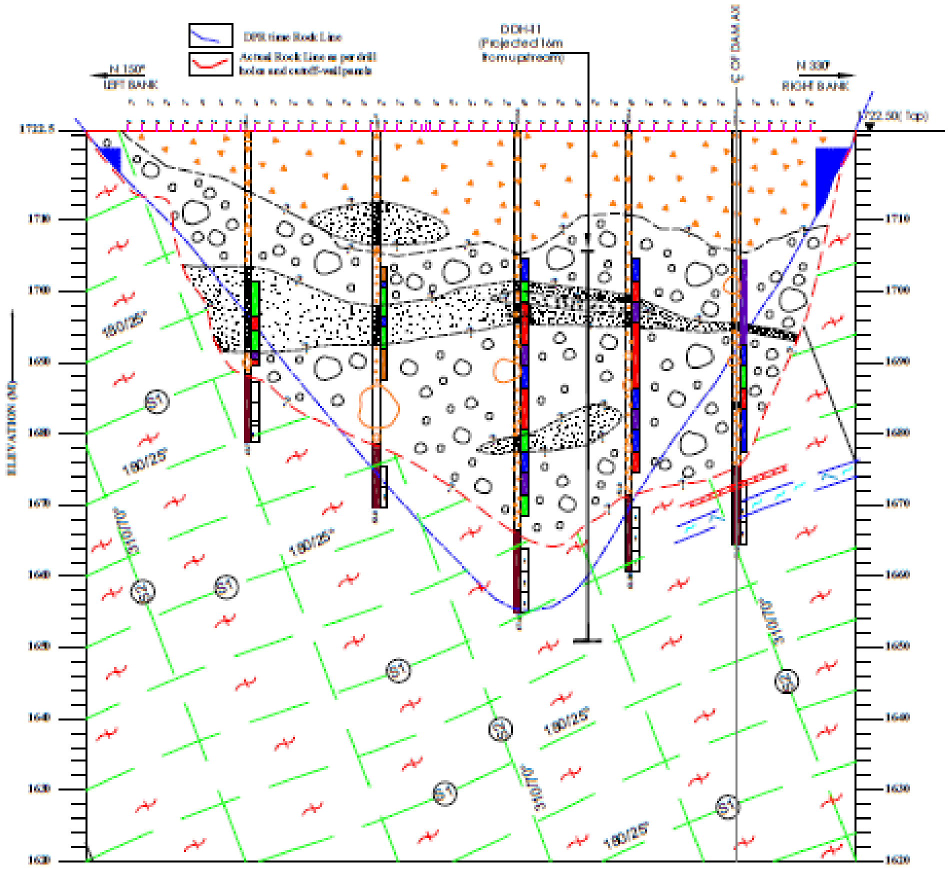

Figure 3 : Geological section of the upstream coffer dam.

Table 5 : Exploratory Drilling in Coffer Dam Area (During Construction stage):

SI. No.	Drill Hole No.	Location	Total Depth (m)	Collar EL (M).	Bedrock Depth and Elevation (m)
1	DDH-16	Upstream coffer dam right bank (Inclined @ 65⁰ (N103°))	65m	1713.358	49.50m /El 1668.50 M
2	DDH-17	Downstream coffer dam right bank (Inclined @ 75⁰ (N164°))	65m	1696.145	38.60m/El. 1658.86 M
3	UCD-1	U/s Coffer dam L/bank	43.7m	1722.61	34.0m/El 1688.41 M
4.	UCD-2	U/s Coffer dam L/bank	53.0m	1722.55	43.8m/El 1678.55 M
5.	UCD-3	U/s Coffer dam Centre	67.65m	1722.71	56.0m/El 1666.51M
6.	UCD-4	U/s Coffer Dam R/Bank	61.8m	1722.71	51.0m/El 1671.56M
7.	UCD-5	U/s Coffer Dam R/Bank	58m	1722.58	46.5m/El 1675.98M
8.	DCD-1	D/s Coffer dam middle of river bed of river	54m	1697.923	43.5m/El 1654.35M
9.	DCD-2	D/s Coffer dam L/bank	82.5m	1698.463	71.5m/El 1626.963M
10.	DCD-3	D/s Coffer dam R/bank	45m	1698.072	34.5m/El1663.57 M
11.	DCD-4	D/s Coffer Dam L/bank	50.0m	1710.802	50m/El 1672.80M
		Total	645.65m		

The downstream cofferdam was investigated with help of one drill hole (DDH-17) during the pre-construction stage. This hole encountered bedrock at 38.60m depth. As the drill hole (DDH-7) in the dam toe area and one of the drill holes (DDH-12) done for the groutability tests had encountered bedrock at 51m and 48.5m depth respectively, it was anticipated that a deeper channel should be present at the downstream cofferdam site too. Therefore, to decide how to arrest seepage from the downstream direction, it was thought prudent to investigate the bedrock further. Accordingly, 4 nos. drill holes were done during the construction stage. Of these, drill hole no. DCD-2 intercepted bedrock at 71.5m depth corresponding to El 1626.963M. This proved the apprehension of a deeper channel on the left side (Figure 4). This information along with other analyses done with nature of the sand horizons in the overburden was utilized in designing proper permeation grouting solution for the downstream coffer dam.

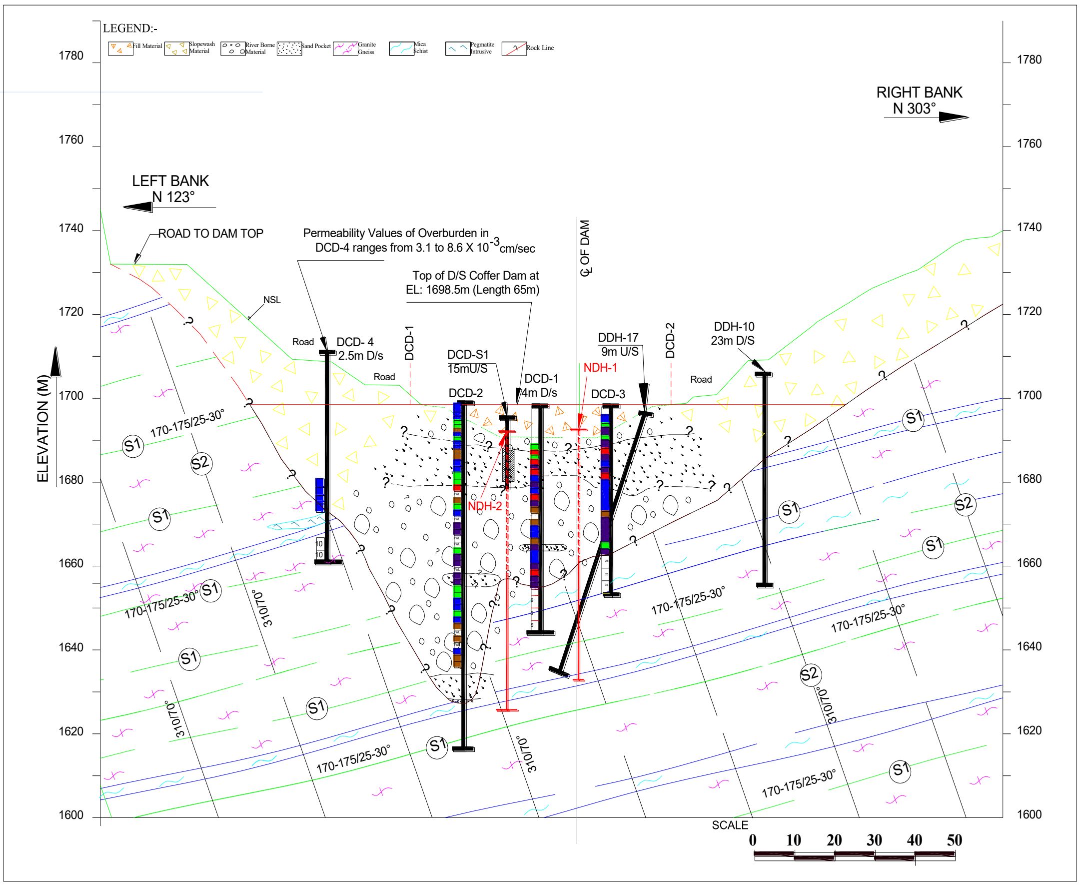

Figure 4 : Geological Cross section at the downstream coffer dam

DISCUSSIONS AND CONCLUSIONS

The above instances has been discussed to undersocre the importance of progressive explorations in deciphering the shape of the valley at the bedrock level. Taking a cue from the Norconsult explorations regarding existance of a canyon even though the dam site was shifted in the upstream the deep channel was brought out by prossive explorations. At the present dam site it was not so pronounced as at feasibility stage axis in the downstream. Thus modification in dam site not only avoided possibl;e hiccups during construction but by careful investigation even smaller impediments were smoothened out which facilitated in overall commissioning of the project with minimal cost and time overrun.

Tight schedules and limited budgetary provisions often result in insufficient explorations during the DPR stage. This coupled with inaccessibility of sites in the initial stages (Photograph 1), compel the geologist to prepare the geological sections for preliminary designs conservatively on the basis of limited information with understanding of geomorphology and other surface features only. In the absence of sub-surface investigations such interpretation cannot be relied upon for detailed design of dam structures. Lessons have to be invariably learnt from past expereinces and documentation. In the present case, after submission of the DPR and before start of the actual construction, a detailed programme of confirmatory investigations was executed which provided valuable information for issuance of construction drawings. This practice continued during the construction stage too and wherever necessary further explorations were done progressively to arrive at optimum treatments. The deepest bedrock at dam foundation and the highly complex burried channel was as per prognosis during the DPR. However, the deepest channel was quite narrow at the new site as already explaned above.

The Mangdechhu Project has since been commissioned (Photograph 2) and is an example of perfect coordination between geologists, designers and construction team in well planned execution. The challenges faced during the excavation were handled by timely interventions. The proactive role played by the Mangdechhu Hydroelectric Project Authority is also highly praiseworthy which did not hesitate in taking prompt technical decisions, whenever, the need arose. This has also proved how comparatively smaller expenditures on getechnical explorations can save huge cost and time overruns.

Photograph 2 : View of the dam site of Mangdechhu after commissioning.

ACKNOWLEDGEMENTS

V. Pandey expresess sincere gratitude to the NHPC Management for providing opportunity to attend the ICOLD -2020 and present this manuscript. The help received form Mr. K. Lahkar and Mr. Deepak Joshi, geologists working with MHPA, in preparing the figures is duly acknowledged. The assistance provided by Mr. Sushil K Almadi, NHPC is also thankfully acknowledged.

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