INITIAL PLAN, CHALLENGES AND DESIGN SOLUTION FOR COFFER DAM OF PUNATSANGCHHU-I H.E. PROJECT BHUTAN

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ABSTRACT

The nature and scope of design engineering are such that the problems and projects we deal with are a never-ending source of both challenge and excitement. In most cases we do very well in defining the problems and developing suitable solutions resulting in successful completion of projects. In a significant number of cases perhaps the unexpected or surprise outcome might have been anticipated and well tackled, Coffer dam of Punatsangchhu-I project (PHEP-I) is one such case. PHEP-I is a Run-of-River Scheme in Wangdue-Phodrang district of Bhutan. The Project contemplates construction of a 130m high Concrete Gravity Dam across Punatsangchhu River to divert 385.54 cumecs of water through a 9 km long, 10 m diameter Headrace Tunnel to an Underground Powerhouse for generating 1200 MW power under 357.68 m gross head.

In the DPR, the Upstream coffer dam was proposed as colcrete type dam of 21m height with design discharge of 1960 cumecs, adopted for 1 in 25 years monsoon return period, as per standards practices for the construction of concrete dam. The diversion arrangement consists of twin concrete lined 10m diameter tunnels of 2724m total length located on the left bank of the river. During tendering stage and after detailed investigation it was found that the bearing capacity is on the lower side to withhold the stresses and that the deepest rock is 60m deep, hence, the dam type was changed to rockfill type with clay core and jet grouting to avoid seepage through foundation. However, as soon the works were about to start, a cyclone named “AILA” hit the area in May’2009. Punatsangchhu River received maximum ever recorded discharge of 2430 cumecs due to cyclone AILA. This made designers to revisit the entire diversion arrangements and specially the upstream coffer dam. In the revised design, upstream coffer dam height was increased from 21m to 29m, type of dam was changed, and diameter of diversion tunnels increased from 10m to 11m. This led to other sets of associated problems like- schedule delay, stresses within safe bearing capacity of the foundation with increase in height, settlement and seepage issues, junction of cut off wall etc.

Considering the frequency, magnitude and severity of the problems, an integrated and innovative Coffer dam comprising of both colcrete & rockfill type dams with 100% deterministic solution to stop seepage was thought, designed, and implemented by the designers. Initial planning, nature’s surprise and associated challenges with design solutions are discussed in this paper.

***Keywords** : River diversion, Coffer Dam, Rockfill dam, planning.*

INTRODUCTION

The Punatsangchhu-I Hydroelectric Project (PHEP-I) in kingdom of Bhutan lies in the Eastern Himalayas between latitude 26.70° N and 28.40° N and longitudes 88.70° E and 92.20° E. Bhutan with geographical area of 38,394 km2 is strategically located between India and China. There are four major river systems in Bhutan namely Torsa, Wangchu (known as Raidak in India), Sankosh and Manas. All these rivers having large snow fed perennial flows, afford attractive possibilities of hydro-electric development. The demand for electricity in Bhutan is expected to be meager in the near foreseeable future as compared to the hydro-electric potential. Bhutan has a feasible hydro potential of 23,760 MW from 76 hydro schemes (> 10 MW capacity). The present hydro installed capacity in Bhutan is about 2326 MW (9.79%). Out of this 2136 MW has been developed with Indian technical and financial assistance. Further, 2820 MW (11.86%) is under construction and 6745 MW (28.39%) is under various stages of development with Indian technical and financial assistance (source, CEA).

Punatsangchhu I Hydroelectric Project is one of the major run-of-river schemes in Punatsangchhu river basin initiated under the Indo-Bhutan Friendship Programme. The PHEP-I contemplates construction of a 130 m high (from the deepest foundation level) Concrete Gravity Dam with its top at El 1205 m to divert 385.54 cumecs of water of Punatsangchhu River through a 9 km long, 10 m diameter Headrace Tunnel to an Underground Powerhouse for generation of 1200 MW power under 357.68 m gross head. The PHEP-I is located on Punatsangchhu River, 7 km downstream of Wangdue- Phodrang, the district headquarters. At this location the river flows in almost straight course from north to south with a moderately steep gradient and intermittent rapids. On the main Dam Axis at the deepest point bedrocks occur at about 65m depth below river bed level. Dam site is located about 70 km north of Thimpu, the Capital city of Bhutan (fig 1). The catchment area (up to dam site) 6000km2 extends between latitude 27º 15’ and 28º 30’ N and longitude 89º 15’ E and 90º 30’ E. It is completely mountainous, significant part of which is covered by snow. The river carries a minimum discharge of about 70 cumecs during January-February whereas the maximum recorded discharge is about 2400 cumecs (for the last 25 years). The catchment area of the drainage is 6390 km2 with elevation ranging from 1200m to 7500m above mean sea level.

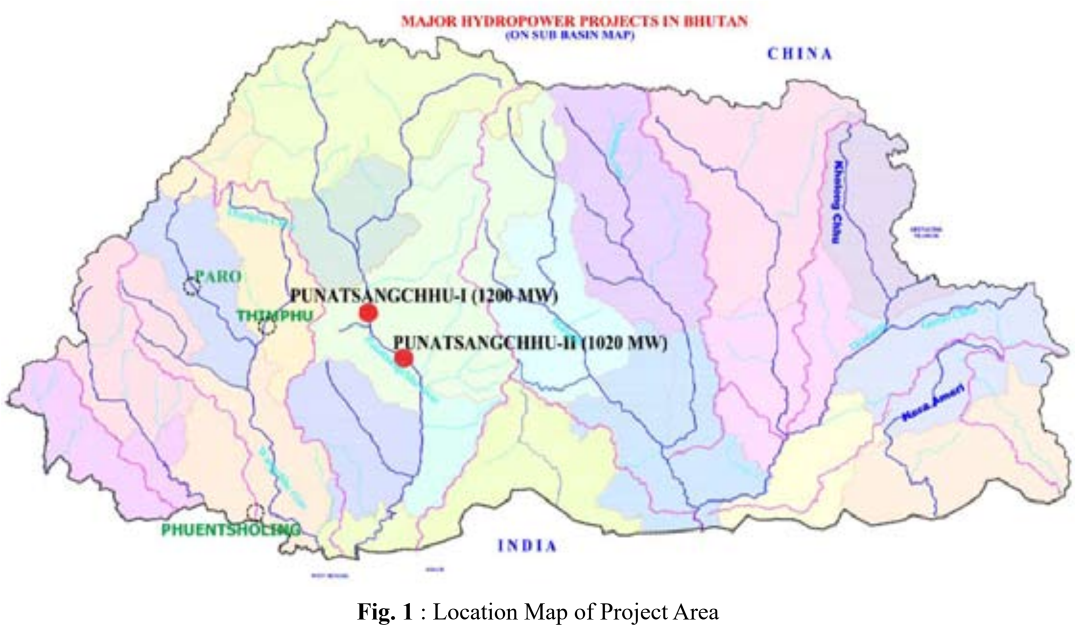

Fig. 1 : Location Map of Project Area

GEOLOGICAL SETTINGS

Regional Geology and Geomorphology

Bhutan is divided into several geomorphic regions by ravines created by major southerly flowing rivers, like Amochhu, Wangchhu, Punatsangchhu, Mangdechuu and Manaschhu, within its Lesser and Central Himalaya tract. These rivers owe their origin to glacier and glacial lakes located to the north, near the Tibetan Plateau having a general elevation of 4000m from MSL. Mochu and Phochu, the two major rivers joining to form river Punatsangchhu originate in two glacial lakes viz., Lunana and Rephsbeng in the northern Bhutan. These rivers flow southerly and meet at Punakha from where it is named as Punatsangchhu. Towards further downstream of PHEP-I in the southernmost region of Bhutan, this river is also named as Sankosh, which flows towards plains of India and finally joins the river Brahmaputra.

Regionally the PHEP-I area is located within the Tethyan Belt of Bhutan Himalayas and at the proposed dam site; rocks of Sure/ Shumar Formation of Thimphu Group of Precambrian age are exposed. The rocks of Thimphu Group in general are characterized by coarse – grained quartzo-feldspathic biotite-muscovite gneiss with bands of mica schist, quartzite and concordant veins of foliated leucogranitoid, migmatites with minor bands of amphibolites and marbles. Garnet porphyroblasts are also seen within these gneisses.

The valley is significantly wide as observed all along and is mostly modified U-shaped (glacier valley) with gentle abutment slopes on both the sides. This part of the river valley is characterized by rock cliffs, mostly on the left bank and gentle abutment slope covered with colluviums on the right bank. Owing to gentle foliation dips of the gneisses the dip slope of the right bank is much gentler whereas the left bank slope is cliffy. The right bank slopes are covered with colluvium consisting of large boulders/ rock blocks set in sandy to clayey matrix.

Site Geology

The river valley at dam site is characterized by steep rocky cliffs on the left bank and gentle abutments on the right bank with alternate ridge and geomorphic depressions. Both the banks and riverbed comprise thick and wide colluvium/hill wash material with some zones of river borne material (RBM). The exploratory drill holes and open excavation has revealed that the foundation of the coffer dam in riverbed comprises colluvium/hill wash material consisting of rocky boulders, cobbles and gravels set in overburden soil (Silty and sandy matrix).

The rocky boulders are of medium to coarse grained quartzo-feldspathic gneiss, quartzite and leucogranite. Most of the boulders/cobbles are of quartzo-feldspathicgneiss, which ranges from very small to maximum up to 12m size, whereas the boulders of quartzite and leucogranite are of small to medium size. The overburden soil is light yellowish to light brownish colored, granular from very fine to medium grained. It is the matrix of silt, sand and fine gravels but a major part of the soil is silty. The borehole data also revealed that, the riverbed area comprises ≈ 20 - 25m wide zone of river borne material (RBM) at certain depths below El 1125m, comprising of sandy layers and well-polished pebbles of gneiss, quartzite and leucogranite. The encountered colluvium material is assorted and not well graded due to varying size and shapes of boulders, but it is observed that this material is compact, cohesive, and moderately denser in majority of the places, which has been witnessed by its angle of repose acquired during excavation on either abutment.

Fig. 2 : Exposed rock at left bank (left) & overburden at dam rite (right)

The bedrock exposed in the project area (reservoir and dam), is represented by garnetiferous quartzo-feldspathic gneiss. The left bank slope rises steeply from riverbed for about 20 m followed by sub-horizontal slope up to the upper rocky scarp. The Right Bank Slope of the Dam Complex is entirely covered with landside/ slope wash debris from 350 m in the upstream to 400m in the downstream. The rock shows minor warping and small-scale tight folding along foliation joint due to which rolling of dip is noticed at many places.

GEOLOGICAL & GEOTECHNICAL INVESTIGATION:

Detailed site investigations comprising geological mapping of dam complex, drilling, drifting, hydro-fracture and in-situ stress tests, including detailed geotechnical investigations in in-let and outlet portals of the diversion tunnel sections have been accomplished by various top agencies of India. Subsurface investigations in the proposed site of dam complex carried out during 2008 with the drilling at various locations of dam body and along the alignments of diversion tunnels. About 1799 m of drilling was completed in 22 drill holes and over 275 m of drifting in main dam complex during pre-construction phase. The drill holes ranging between 60 m and 150 m depth were planned to intersect the inferred bedrock contact and geological features such as fault/ shears and provide geological information along section of dam complex as well as tunnel alignment. Permeability test was conducted in most of the drill holes. The mechanical properties of rock core samples were determined by laboratory tests and field test were performed to determine the in-situ stresses and deformation characteristics of the rock surrounding the exploratory drifts. Based on detailed investigations the planning and detailed design of the coffer dam was done.

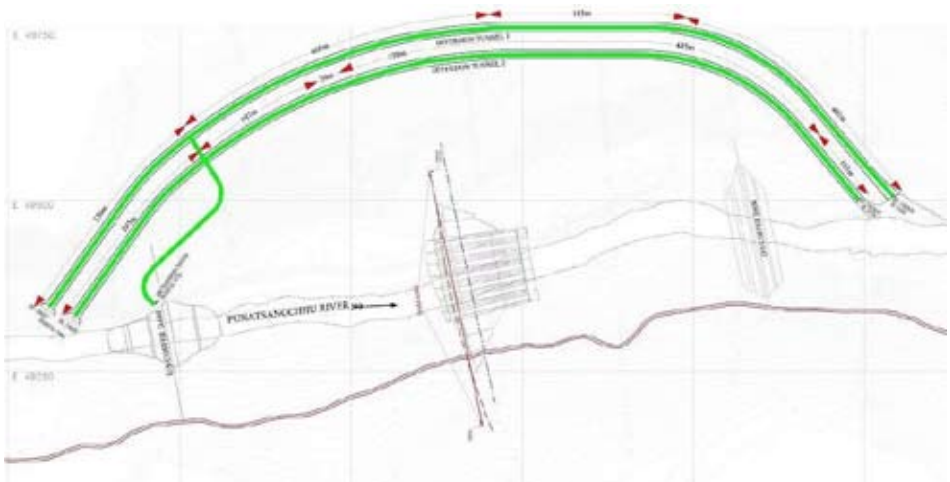

Fig. 3 : Diversion arrangement plan

COFFER DAM: A BRIEF HISTORY

At DPR

At DPR Stage the upstream coffer dam of Punatsagchhu-I project was proposed of colcrete dam type. The height of the coffer dam was 21m from the riverbed level with provision of jet grout below it to stop the seepage, length to be decided based on the detailed site investigation. A typical section is shown in the figure below :

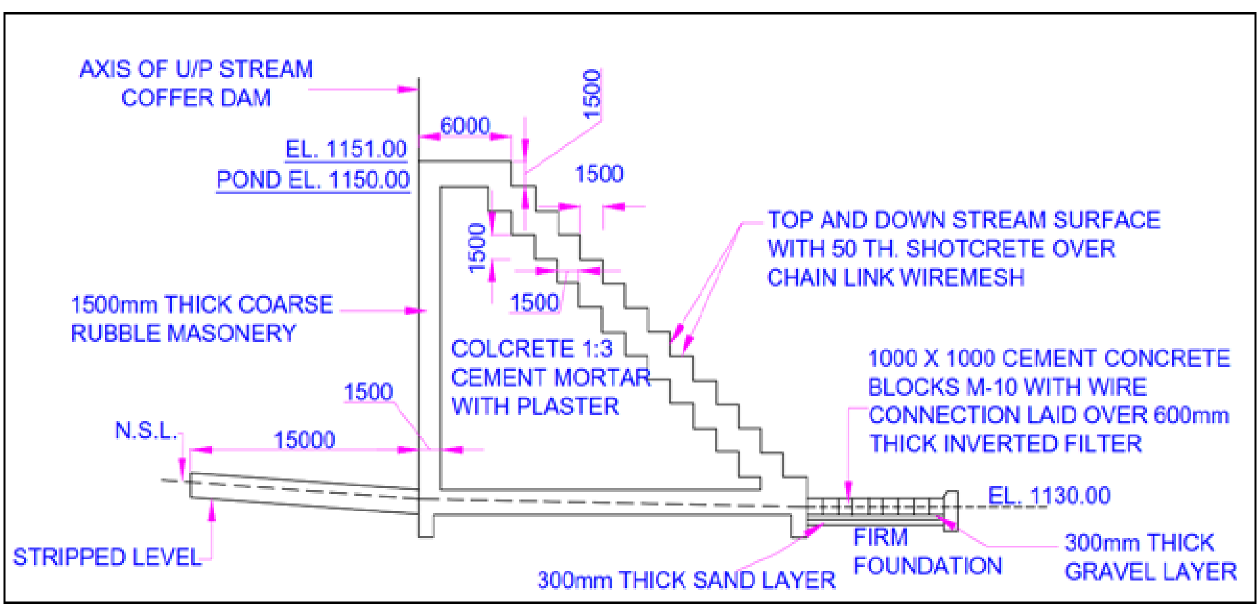

Fig. 4 : Maximum section of Upstream Coffer Dam (Colcrete)

At start of project works:

During detailed investigation to ascertain the riverbed rock 05 drill holes along the axis of the upstream at various locations. At upstream coffer dam three vertical holes on right bank and one inclined at 300 angle and one vertical hole drilled at left bank were made to establish the bed rock/ rock line. All holes terminated after 30-40 m in fresh bedrock, the deepest bedrock encountered was at 60 m below the riverbed at upstream coffer. It becomes pertinent to mention here that the location of dam axis was changed from the DPR stage hence, the detailed investigations showed varied findings for the present coffer dam location. During the test excavation of coffer dam foundation, the colluvium material was cut at almost >55° angle for a height of 8-10m in most of the places and it remained standing without any temporary support in dry condition. The results of plate load test conducted on left bank of u/s coffer dam axis indicated that maximum settlement is of the order of 19.24mm at 93.72 T/m^2 load intensity on soil. Accordingly safe bearing capacity of the ground has been taken as ≈37 T/m^2 considering the factor of safety 2.50.

After the geological/geotechnical investigation of the site for coffer dam it was found that the bed rock encountered was at larger depth than envisaged, considering the bed rock profile and the overburden matrix, which is highly susceptible to uneven settlement, the upstream coffer dam was proposed to be of rock fill with combination of clay core and jet grouting wall to stop seepage. The upstream coffer dam is composite of earthen rock fill with clay core allowing the overtopping of discharge during monsoon. A concrete diaphragm wall/ Jet grout curtain 75m deep will be provided touching the bed rock for controlling seepage of water during the construction of dam. In a revised hydrological study, the diversion scheme was designed for discharge of 1960 cumecs i.e 1 in 25 monsoon return period as per the relevant Indian standards for concrete dams. A typical geological and maximum coffer dam section is shown in the figure no. 5 and 6 respectively.

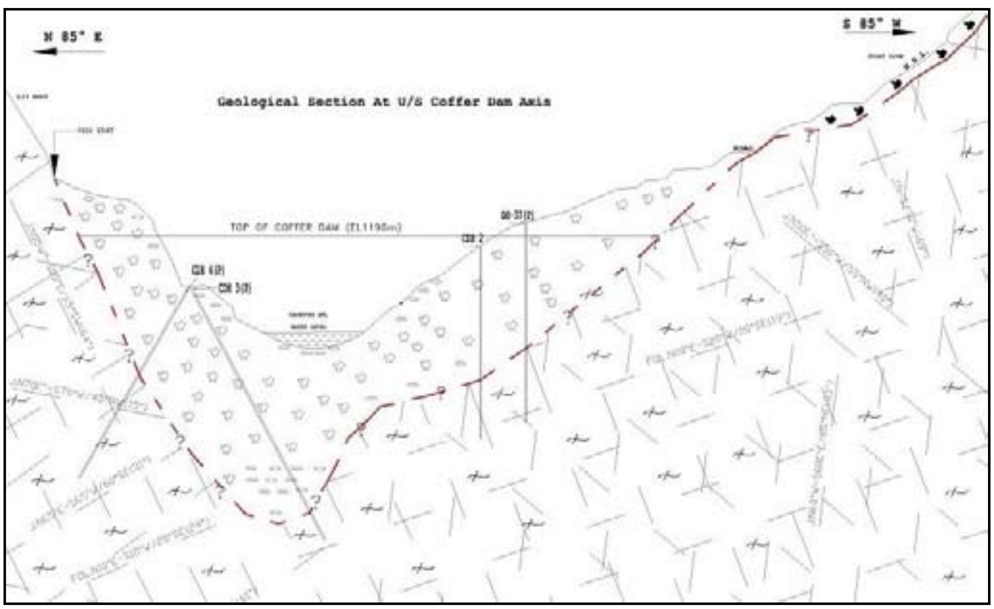

Fig. 5 : Typical Geological Section at Upstream Coffer Dam

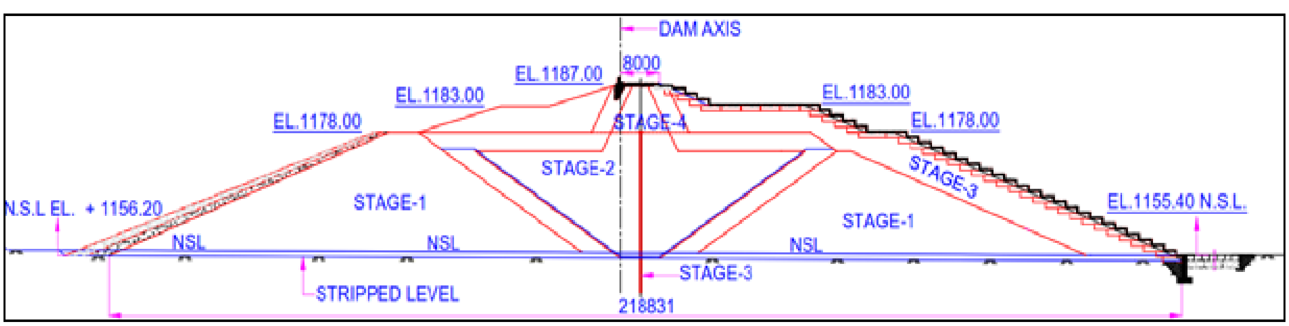

Fig. 6 : Maximum section of Upstream Coffer Dam (rockfill) at Tender Stage

After AILA Cyclone:

On the verge of start of execution, on 26 May 2009, Punatsangchhu River received maximum ever recorded discharge of 2430 cumecs due to cyclone AILA. This cyclone brought many design realizations and changes which were revision of design discharge from 1960 cumecs to 2430 cumecs, change in coffer dam height from 21.0m to 29.0m, revision of diameter of diversion tunnels to 11.0m, to achieve construction of Coffer dam to a safe height before monsoon, rockfill type was changed to colcrete-cum-rockfill type. The change in dam type also benefitted for speedy construction and better reliability in case of overflow. Apart from these, it was also decided that additional protection works in form of steps of wire crates, steel reinforcement, and M20 grade concrete cladding was provided on the downstream face.

Design Challenges: Increase in height brought associated challenges

- Higher safe bearing capacity requirement of the foundation soil as otherwise settlement cracks would be developed in the structure.
- Energy dissipation of spilling water in the event of overflow would be difficult to manage.
- The stiff junction between the jet grout curtain and colcrete dam would crack resulting in heavy seepage.

Design Solutions

To achieve such height before monsoon, the coffer dam was conceptualized to be made in parts- two colcrete dams of each 18m height sandwiching central portion of rockfill type with lined compacted clay. An 8m to 9m pedestal of larger base width was proposed so that an 18m Colcrete Dam of normal dimension can leave a sufficient wide Colcrete berm downstream of the 18m height portion of the dam and settlement can be taken care of appropriately. This served two purposes- first, the construction of dam could be achieved at a desirable height before the first monsoon and secondly the work was done at faster rate.

Considering the unprecedented event of Aila cyclone, designers decided to provide an energy dissipation arrangement in the downstream slope of the coffer dam by providing the steps along with a provision of 5x1x1m blocks of gabion boxes covered by 150mm thick concrete of M20 grade with expansion joints and PVC seal provision at 6.0m c/c.

Regarding the junction between the grout curtain and the Colcrete Dam, the problem of possible cracking is eliminated as the curtain below the Coffer Dam has been revised from “jet grouting” to “plastic concrete cutoff wall” to accommodate for the deformations. Plastic concrete cutoff wall was started from a platform 20m above the deepest foundation level and was completed within 2 months of time.

The upstream coffer dam is a composite of dumped rock fill, compacted rock fill material with downstream face of gabions in 1:2.5 slopes. The material properties to be used to design the coffer dam where the permeability should not exceed more than 1*10-6 cm/sec for impervious core material. The size of rock fill material to be used in coffer dam for compacted rock fill and the dumped rock fill is shown in table below-

Table 1 : Material Properties for Upstream Coffer Dam

S. No.	Part of Structure	Moist Density (t/m3)	Saturated Density (t/m3)	Submerged Density (t/m3)	C (eff) (t/m2)	Ø (eff) (Degree)
1.	Impervious Core	1.99	2.20	1.20	1.0	23
2.	Rockfill	2.15	2.28	1.28	0	38
3.	Transition Material	2.10	2.28	1.28	0	30
4.	Foundation	2.15	2.28	1.28	0	28
SIZE OF ROCKFILL						
Item			**Compacted Rockfill**		**Dumped Rockfill**	
Max. Particle Size (mm)			300		600	
Min. Particle Size (mm)			75		75	

Details of the Final Coffer dam design

Final most Integrated Coffer dam design consisted of basically three parts- two colcrete dams of each 18m height sandwiching central portion of rockfill material lined with compacted clay. The compacted clay portion encapsulates the 90m deep plastic concrete cutoff wall. The working bench for plastic wall was created at a height of 20.0m from the deepest foundation level in central portion of compacted clay part. Considering the deep excavation of the main dam pit, designers wanted to be doubly sure of any sort of seepage on the dam pit, therefore a 100% deterministic option of plastic cut off wall was chosen. The colcrete dams were founded on 3.0mm thick RCC raft of M20 grade which took care of differential settlement and the bearing capacity. There was no provision of raft below the central portion that had rockfill material lined with clay as the bearing requirements was not much. The total area of the coffer dam foundation and addition of 20m length on the downstream & upstream side was grouted for 20m depth. Though, the dam was not designed to over top still considering the unprecedented event of Aila cyclone, it was decided to provide an energy dissipation arrangement. Steps were provided in the downstream slope of the coffer dam with dimension of 5x1x1m blocks of gabion boxes covered by 150mm thick concrete of M20 grade with expansion joints and PVC seal provision at 6.0m c/c. To deal with the stiffness of the junction and deformation, jet grouting was changed to plastic concrete wall.

Sequence of construction was that first the foundation rafts of 3.0m thickness for the two colcrete dams were constructed followed by construction of both colcrete dams up to height of 18.0m. for the central portion of the dam a compacted layer of clay along with rockfill were laid upto 29.0m. A bench at 20.0m height from the bottom was created in the centra portion of the dam from where the plastic concrete cutoff wall was executed. Typical sections at center and at abutments are shown in the figure no. 7 and 8 respectively.

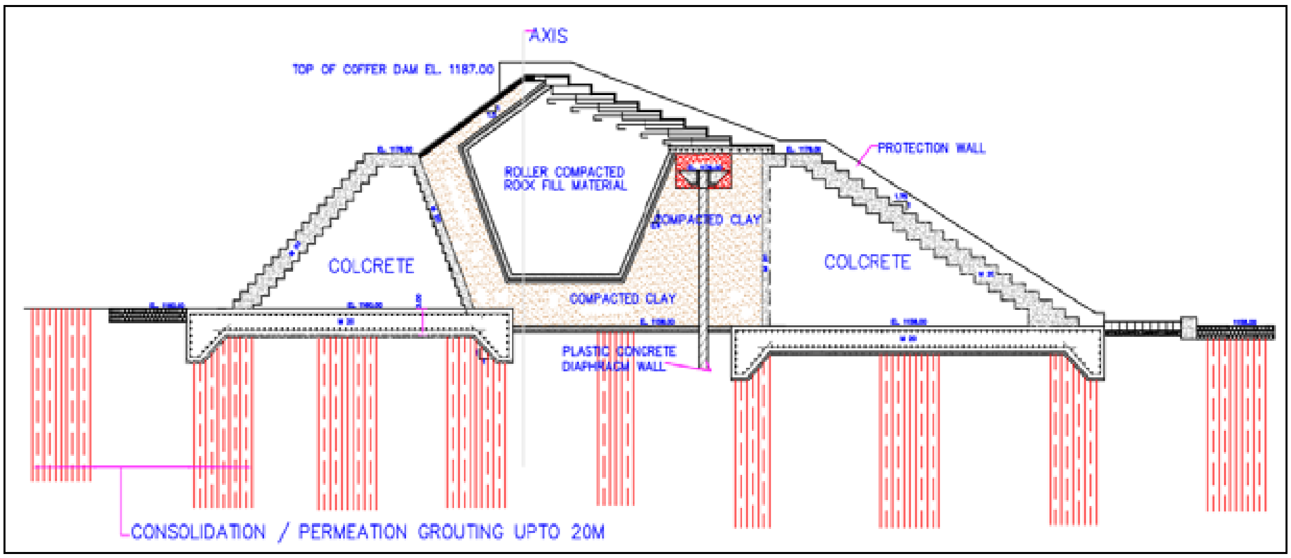

Fig. 7 : Maximum Section of Upstream Coffer Dam at centre (colcrete type) with clay and plastic cut off wall

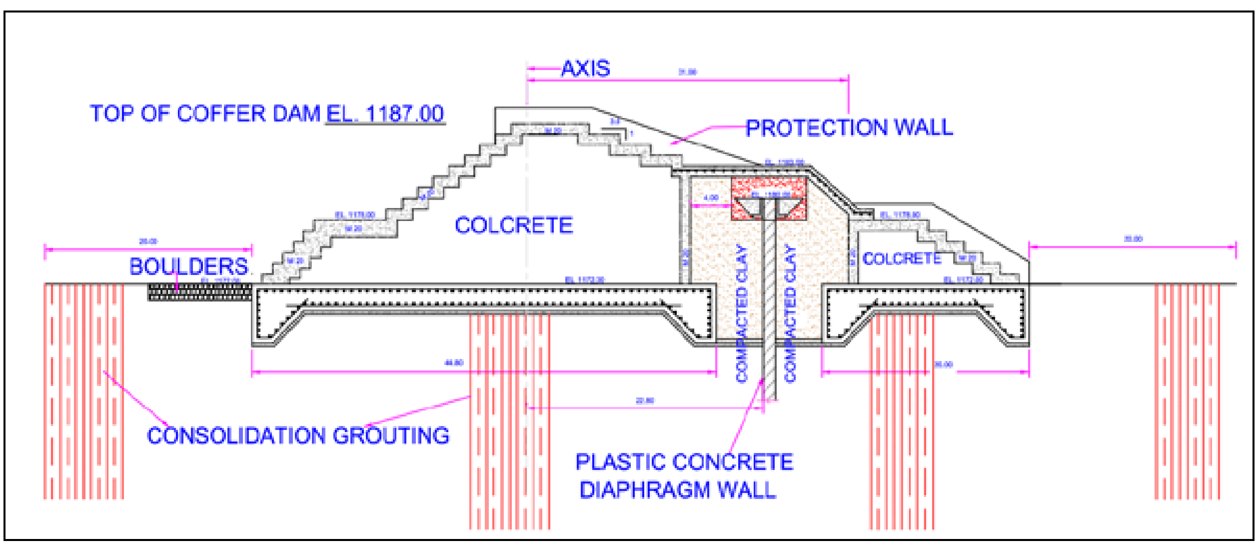

Fig. 8 : Section of Upstream Coffer Dam at abutments (colcrete type) with clay and plastic cut off wall

Fig. 9 : Constructed coffer dam, top view from right bank

CONCLUSION

Geological and Geotechnical investigation of the area, during tendering process, revealed that the anticipated rock line is at larger depth and that the bearing capacity is low to withstand the stresses. Therefore, the change in dam type from colcrete to rockfill was proposed. However due a natural calamity just before the start of the construction, the entire diversion arrangements were changed. This was a timely realization of the magnitude of uncertainties that if not anticipated well would have led to havoc. The temporary arrangement to divert the river discharged was then decided to revise based on the recent activities and anticipation of the problems. The height of upstream coffer dam was redesigned based on the total discharged capacity of 2430 m3/ sec. The overall design discharge was changed based on the recent cyclone, the twin diversion tunnels diameter was also increased. On the consideration of overburden matrix and the permeability test done in drill hole at coffer dam it was decided that a concrete plastic wall of 90m deep touching the bed rock will be provided just downstream of coffer dam to arrest the seepage water through the overburden material for construction of main dam. To tackle the seepage and safe bearing capacity an integrated model of coffer dam comprising of colcrete, clay core and concrete plastic wall was used.

This situation brings to light the importance of undertaking a geotechnical investigation of the ground conditions irrespective of the size and cost of the structure to be constructed and rationally anticipating the overall implications of the results & changes. Overall, this case study demonstrates that despite the natural challenges, geological surprises and complex ground conditions, designers were able to anticipate and tackle the very challenging condition via well thought and pristine designed solution.

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