1. DESIGN FLOOD FOR NATHPAA DAM

During July 1986, hydrological studies were carried out in consultation with Central Water Commission (CWC) to estimate the Probable Maximum Flood (PMF) based on snowmelt flood peak and the Probable Maximum Precipitation (PMP) in the catchment area of the Nathpa dam. A memo on the design flood for Nathpa Jhakri Project was jointly prepared by Central Water Commission (CWC) & HPSEB and presented to the Penal of Expert (POE) in their second meeting held during 29th Dec. to 1st Jan. 1986. As per the memo, only 350 sq m out of total catchment area of 49820 sq km up to dam site falls below El. 3000 m which contributes run-off from rain fall and contribution from the remaining catchment is on account of snow melt. A total PMF of 5495 cumec was thus obtained comprising 2740 cumec (as snowmelt contribution) which is the recorded discharge on 29.6.1979 (drought year) and 2755 cumec (as rainfall contribution) for a catchment area of 350 sq km below El. 3000 m taking PMP in the catchment equal to point rainfall (340 mm) of Kullu Station. The POE agreed with the view that the PMF of 5660 cumec taken for the design of spillway appears liberal. It was checked that the design flood can be passed through sluices and central spillway considering one sluice inoperative as per IS: 11223 - 1985.

In October 1994, further studies using annual flood frequency analysis based on Gumble's Method were carried out by SJVN with hydrological data of flood peaks w.e.f. 1963 to 1993. It was found that design flood of 5660 cumecs for the Project has a return period of 10000 years with a probability of 0.0001 each year.

However, an unprecedented flood of the order of 6500 Cumec occurred on 1st Aug., 2000. The flood emanated in river Satluj somewhere above the confluence of river Satluj and Spiti from the catchment area in Tibet. As per NRSA report, the cause of the flood was sudden breaching of temporary storage of river Satluj due to slides after a cloud burst in the catchment area in Tibet region. It is also mentioned that due to breach of temporary lake on Parechu, a tributary of Satluj , flood of the magnitude of 4500 cumecs passed the dam site on June 25, 2005. To pass this flood, flood routing studies were carried out and it was found that flood of this magnitude could be passed through flood routing by operating all the five sluices and central spillway of the dam. Accordingly all other engineering structures were also checked for the highest flood level observed in the river on account of this flood.

2. NATHPAA DAM - SEISMICITY

Nathpa Jhakri Hydroelectric Project lies in zone – IV of seismic map of India as per IS: 1893:1984. National Committee on Seismic Design Parameters (NCSDP) is the statutory body for approval of seismic design parameters for river valley projects in the country. The project specific studies were conducted through Department of Earthquake Engineering, University of Roorkee (DEQUOR), (now IIT Roorkee). For Nathpa dam, Acceleration Response Spectra for MCE (Maximum Credible Earthquake) and DBE (Design Basic Earthquake) was developed specifically for NJHEP site by DEQUOR, (now IIT, Roorkee). Spectral acceleration (g) was found out corresponding to the period found from the Acceleration Response Spectra. The value of DBE was obtained by using multiplying factor given in the spectra. A maximum value of 0.29g worked out as above has been used as design horizontal seismic coefficient ($\alpha_h$) at top of dam. This value has been reduced linearly to zero at base of the dam as per Clause 7.3.1 of IS: 1893 – 1984. Vertical seismic coefficient has been taken as 0.5 times the value of $\alpha_h$ at top of dam reducing the same linearly to zero at base of the dam.

As per DEQUOR Report, the DBE has been recommended for design purpose in replacement of seismic coefficient recommended in IS: 1893 -1984. Dynamic analysis of Nathpa dam was also carried out by DEQUOR using $\alpha_v = 0.23g$ , $\alpha_h = \frac{2}{3} \alpha_v$ for MCE condition and 50% values for DBE condition. The stresses were evaluated in various parts of the dam and foundations and found to be within permissible limits. All the seismic design parameters were approved by National Committee on Seismic Design Parameters (NCSDP), CWC, and New Delhi.

3. DAM AND SPILLWAY DESIGN

The diversion dam at Nathpa is a concrete gravity structure having a height of 62.5m above the deepest foundation level (Photo 1). The dam axis is orientated at an angle of N 9°47' 20.3" E. The reservoir has a live storage capacity of 303 ha m & gross storage of 343 ha m which can cater to 3 hours peaking during lean season. The layout plan & upstream elevation of the dam is as per Figs. 1&2 also
cross-section of the maximum sluice section and Non-overflow section is as shown in Figure 3&4. There are five number sluice blocks each having a width of 16 m for accommodating five sluices of the size 7.5 (wide) x 8.5 m (high) controlled by radial gates. There is also an auxiliary spillway in the central block for regulating the reservoir level & passing trash. This spillway arrangement is capable of passing the design flood of 5660 cusec by considering one of the sluices inoperative. There are six non-overflow blocks in the dam, giving a total length of dam as 185.5 m.

Because of extreme silt load in river Satluj, provision has been made for flushing of reservoir periodically during high flow season to preserve live & dead storage of the reservoir against siltation. Accordingly, sluices have been lined with abrasion resistant steel having Brinell hardness of 400 BHN.

4. RAISING NATHPA DAM HEIGHT IN TWO STAGES

As per original report (1986), a 60.5 m high gravity dam had been envisaged at Nathpa for diverting discharge of 465 cusecs (inclusive of 20% for flushing of silt particles). It was also contemplated that this project will take daily

![Photo 1 Nathpa dam](image)

![Plan 1 Layout plan of the dam](image)
NATHPA DAM - UPSTREAM ELEVATION

Fig 2 Upstream elevation of the dam

Fig 3 Maximum sluice section with central spillway
peaking load continuously for 3 hours for which pondage of 457 ha m had been envisaged corresponding to Full Reservoir Level at EL 1490.5 m.

The level of bench mark (BM) established (Wangtoo Bridge Check Post) by Survey of India at the time of planning of upstream 120 MW Sanjay Vidhyut Pariyojana (SVP) – Bhaba, owned by H.P. State Electricity Board (HPSEB) project was adopted by SJVNL (then NJPC) for designing of various components. While carrying out precision survey during construction stage of NJHEP in 1994, it was observed that there was discrepancy of 2.0581 m (correct level of BM being 1524.874 m instead of 1526.933 m) in the level of aforesaid Bench Mark. Hence, the elevation of tail race tunnel outfall (overt) of SVP – Bhaba Project was actually ± 1489.84 m (earlier taken as 1491.90 m) which was lower than Full Reservoir Level (FRL) of Nathpa reservoir, i.e., 1490.50 m. Since TRT of SVP – Bhaba operates as free flow tunnel, necessary correction became inevitable to prevent water of Nathpa reservoir entering into tail race tunnel (TRT) of SVP – Bhaba. Therefore to maintain the same free -board as envisaged in the Project Report, it was decided to keep the FRL of Nathpa reservoir at EL 1488.50 (Phase-1) m to avoid entry of water into TRT of Bhaba Power House.

The lowering of FRL of Nathpa dam by 2 m resulted in reduction of storage capacity of Nathpa reservoir. In addition to this due to heavy slide of the order of 1.0 million cum. on the right bank in July 1993 and further flash flood of July 1997, there was more reduction in the storage capacity. The cumulative effect was that the gross storage capacity of Nathpa reservoir came down to 165.07 hm corresponding to EL 1488.50 m, which would have provided only 1.5 hours of peaking power in place of 3 hours continuous peaking envisaged in the original project report.

To bring the continuous peaking power duration close to as originally envisaged, it was decided to raise the Phase-I FRL from EL 1488.5 m to Phase-II FRL at EL 1495.5 m by increasing the height of the dam by 5 m in order to increase the pondage to 343.39 ha m. With this increase, water level in the reservoir is increased by about 7 m. In view of increase in the FRL of Nathpa Reservoir, the TRT outfall of Bhaba Project was getting submerged and consequently it would have adversely affected the operation of Bhaba Power House which has Pelton turbines.

Accordingly the matter was taken up with Ministry of Power, Govt. of India and Govt. of H.P. to increase the height of Nathpa dam and divert tail water of Bhaba Power House to downstream of Nathpa dam. It was approved by Ministry of Power, G.O.I. in June 1998 to design Nathpa dam for raised height of the dam. A comprehensive scheme was drawn to divert the Bhaba Tail water through a new tunnel.
(plugging the original tunnel) to downstream of Nathpa dam. The scheme also included a small underground reservoir from where the tail water of SVP-Bhaba Project was to be pumped into Nathpa reservoir during lean period for which about 8.0 MU of energy is required annually.

An expert committee was appointed by SJVNL to study the proposal of diverting Bhaba Tail Race to downstream of dam and for suggesting measures for safeguarding Bhaba PH. HPSEB was convinced for diverting Bhaba tail race to downstream of Nathpa dam on the basis of the measures suggested by the experts and the same were incorporated in the Bhaba Tail Race Diversion Arrangement works.

5. BHABA TAIL RACE DIVERSION WORKS

Nathpa dam reservoir extends up to a length of ± 2.5 km upstream corresponding to the full reservoir level (FRL) at El. 1495.5 m. About 800 m & 1 km upstream of the dam on the right bank are located respectively the Tail Race Tunnel (TRT) Outfall & Main Access Tunnel of the existing Power House of Sanjay Vidhyut Pariyojana (SVP-Bhaba) owned by Himachal Pradesh State Electricity Board. Before raising the Nathpa dam height by 5 m, the water from Bhaba TRT Outfall used to discharge directly into Nathpa reservoir which was being maintained at a lower level because Bhaba Power House has Pelton turbines and maximum water in the tail race tunnel was kept lower than El. 1488.5 m. After all the works related to Bhaba Tail Race Diversion Arrangement (BTRDA) were complete, tail race tunnel outfall of SVP-Bhaba was plugged and then water level in Nathpa reservoir was raised to El. 1495.5 m during March, 2008 to restore peaking of NJHEP close to three hours. An underground small reservoir has been constructed in the BTRDA and water is pumped into Nathpa reservoir during lean flow season for more than nine months (Sept. to June) when discharge in the Satluj river is less than the design discharge.

The following works were associated with raising the Nathpa dam height by 5 m and Bhaba Tail Race Diversion Arrangement:

(i) Raising of Nathpa dam height by 5 m i.e., from El.1493.50 m to El. 1498.50 m including raising of central spillway crest/gate and bridge over the spillway in block 6. A total area of 23.45 ha is anticipated to be submerged by the reservoir with FRL at El.1495.5 m (Phase-II) as against an area of 16.5 ha submerged with FRL at El. 1488.50 m (Phase-I). Reservoir would extend upto a distance of about 2.52 km upstream of Nathpa dam by raising dam height as against 1.7 km previously.

(ii) Constructing Bhaba Tail Race Diversion Tunnel (BTRDT), 3.1 m × 3.1 m, D-shaped, concrete lined 256 m long (upstream of reservoir) and 2.8 m × 2.8 m, D-shaped, concrete lined, 997 m long (downstream of reservoir) including RC.C. Portal.

(iii) Constructing outfall structure from BTRDT outlet to river Satluj including bridge etc.

(iv) Constructing underground reservoir of size 120 m (long) × 8 m (wide) × 8.00 m (max. height) and pump house of size 46 m (long) × 8 m (wide) × 15.3 m (high).

(v) Realigned Bhaba Main Access Tunnel (MAT) of size 6.3 m D-shaped, concrete lined, length 100 m having invert level of its portal at El. 1504 ± including R.C. Portal and suitable raising of road in the vicinity.

(vi) Constructing 150 m long, 4 m × 4 m, D-shaped access tunnel to pump house including R.C.C.-portal.

(vii) Constructing 9.0 m (wide) × 4.5 m (high), 22 m long tunnel for taking out delivery pipes from pump house and 4.5 m × 4.5 m, D-shaped tunnel, 62 m long along-with outfall structure into Nathpa reservoir for conveying discharge from delivery pipes to Nathpa reservoir.

(viii) Constructing concrete plug of size 9.0 m (wide) × 4.5 m (high) × 4 m (long) near the exit of delivery pipes.

(ix) Plugging of existing Bhaba Tail Race Tunnel of size 4.1 m × 3.95 m, D-shaped (plug length 6.0 m).

(x) Plugging of existing main access tunnel of Bhaba Power House of size 6.3 m, D-shaped (plug length 4.0 m).

(xi) 5 Number pumps of capacity HP each have been installed in the pump house cavern located above the small reservoir.

(xii) Electric supply

A plan showing Bhaba Tail Race Diversion Arrangement Works is shown in Fig.5.

Energy of about 8 MU is consumed in pumping Bhaba water into Nathpa reservoir. By operating the project at FRL of 1495.5 m, energy of the project increased by 33 MU after deducting the energy consumed in pumping Bhaba water. Annual design energy of 6951 MU at FRL of 1488.5 m was approved by CEA during October 2002. During the high flow season, when discharge in the Satluj river is more than the design discharge of NJHEP (383.88 cumecs), water from Bhaba power House would be
discharged directly into the river Satluj from the outfall of Bhaba Tail Race Diversion Tunnel located downstream of Nathpa dam.

Financial Benefits From Increased Height of Nathpa Dam

(i) With increased dam height in phase - II (dam top at 1498.5 m & FRL at El. 1495.5 m) total annual energy generation works out to 6992 MU in place of 6951 MU in phase-I (dam top at El. 1493.5 m and FRL at El. 1488.5 m). Thus, there is an increase of 41 MU with increased dam height.

(ii) There is a direct gain of about Rs. 13 crore due to additional energy.

(iii) Due to increase in live storage, peaking duration increases to about 3 hours in place of 1.46 hours.

(iv) Extra units generated during peaking are about 741 MU.

6. STABILITY OF DAM

Nathpa dam is solid concrete gravity dam consisting of five number sluice blocks, one sluice block with control spillway & five non overflow blocks. The deepest foundation level for sluice section with central spillway (Block No .6) and maximum sluice section at El. 1436.00 and for maximum non overflow section (Block No.3) at El. 1437.00 m.

Stability of Nathpa dam has been checked for raised height of the dam. Base width of the dam has been provided as 65.013 m for raised height of the dam in Phase-II (i.e. 1498.50 m)

Stability of the Nathpa dam has been checked as per IS: 6512-1984 "Criteria for Design of Solid Gravity Dam".

The following forces have been considered for the design for load combination A,B, C, D, E, F & G as per IS. 6512 -1984:

- Dead load
- Reservoir tail water loads
- Uplift pressure
- Earthquake forces
- Earth and silt pressures

Earthquake forces have been computed as per IS: 1893-1984 using Response spectrum method. Maximum value of \( \alpha_s \) used in stability computations is 0.29 g. Maximum value of \( \alpha_s \) has been taken at top of the dam and reduced linearly to zero at the base the dam.
Permissible stresses on upstream and downstream faces of the dam have been taken as per IS: 6512-1984. The factors of safety against overturning have been taken as the ratio of stability movements and destabilizing movements.

Factors of safety against sliding have been calculated as per IS: 6512-1984. The value of cohesion (C) & coefficient of internal friction (\( \phi \)) between concrete to rock interface has been taken as per in-situ shear tests carried out by Central Soil & Minerals Research Station (CSMRS), New Delhi. The cohesion and angle of internal friction were found out to be 6.11 kg/\( \text{cm}^2 \) and 66° for peak values and 5.6 kg/\( \text{cm}^2 \) and 56.8° respectively for residual values for concrete/rock interface.

Results of stability analysis carried out for maximum sluice section, sluice section with central spillway and maximum non overflow section show that stresses are well within permissible limits. Tensile stress values upto 0.01f, & 0.04 f, are allowed for Load Combination E (Normal operating condition with earthquake) & Load Combination G (Load Combination E with extreme uplift) as per IS : 6512-1984 where \( f_c \) is cube compressive strength of dam concrete. In case of Nathpa dam, tensile stress value of 11.4 t/m² for Load Combination E & 45.3 t/m² for Load Combination G were computed in the Static Stability Analysis which are less than permissible values of 30 t/m² & 80 t/m² respectively for M20 grade of concrete used for upstream face of the dam.

6.1 Dynamic Analysis

Dynamic analysis studies considering two dimensional finite element modelling have been carried out for maximum non overflow section, sluice section with central spillway & sluice section without central spillway at DEQUOR Roorkee (Now IIT Roorkee). Dam foundation interaction has been considered by taking a part of the foundation contributing to the stiffness of the dam. Foundation width of 250.0 m has been taken which is approximately five times the base width of the dam. The depth of the foundation (60.0 m) is taken approximately equal to the height of the dam.

The results of the analysis show that total tensile stresses generated in static conditions are within permissible limits as per IS: 6512-1984. For dynamic conditions, the computed stresses are less than apparent seismic tensile strength of dam mass concrete.

7. SPILLWAY ARRANGEMENT

7.1 Sluices Spillway

7.1.1 Number and Size of Dam Sluices

Design flood for Nathpa dam is 5660 cumec which has a probability of 1 in 10,000 years. In order to pass this flood five no. sluice openings of size 7.5 m (wide) x 8.5 m (height) each and a central spillway having two bays of size 5 m (wide) x 3 m (high) each have been provided in the dam. These sluices have been provide as per IS: 11485:1985 as trajectory type with their crest at El. 1458.00 m. When the reservoir is at El. 1495.50 m (FRL Phase-II), the discharging capacity of the sluices has been worked out on the basis of model studies carried out at Central Water & Power Research Station (CWPRS), Pune using the following formula:

\[
Q = C_d A \sqrt{2gH}
\]

where

- \( Q \) = discharge through submerged portion of the gate opening
- \( A \) = area of the submerged portion of the sluice
- \( H \) = head up-to centre line of the sluice opening
- \( C_d \) = coeff. of discharge for submerged orifice
- \( = 0.9 \) for max. head on the sluice for FRL at 1495.5 m

(C_d for silted water during floods has been recommended as 0.85 as per CWPRS, Pune)

Discharging capacity of each sluice by the above formula works out to 1440 & 1384 cumec for \( C_d \) of 0.9 & 0.85 respectively with FRL at 1495.50 m.

Further as per IS: 11223-1985, one gate has been considered to be inoperative in the event of occurrence of design flood. Thus a flood of 5536 cumec can be passed through four sluices & about 130 cumec through central spillway with FRL at 1495.50m.

7.1.2 Sluice Steel Liner

River Satluj carries heavy suspended as well as bed load. Nathpa dam has five sluice openings of size 7.5 m (wide) x 8.5 m (high) each. These sluices are designed to pass design flood of 5660 cumec when river water would contain high concentration of silt and small boulders etc. The sluices are also to be used for flushing river sediments including small boulders each year to restore storage capacity of reservoir. To withstand abrasive forces on account of high velocity silt laden water flowing through the sluices and to counter impact loads, these have been provided with high strength steel lining. The Photo 2 is showing sluice steel liner.

As per specification drawings /bid drawings 25 mm thick steel lining in the sluices was proposed to be fixed to the surrounding concrete using 16 mm diameter bolts, 1000 mm long and 400 x 10 MS Plates @ 500 c/c staggered
placed in between the boles. The design of steel liner and its fixity with the surrounding concrete was further reviewed with retainer consultants M/s Electrowatt Engineering (EWI), Switzerland. According to the studies carried out by EWI, the sluice liner consists of 20 mm thick steel plates forming the walls of the sluice opening with stiffeners comprising of 700 mm high and 20 mm thick outer flange. Between these main transverse stiffeners longitudinal stiffeners 250 mm high & 20 mm thick were provided for further stabilization of the sluice liner.

The sluice liner has been designed for the following load cases:

- **Water Load** - Under the full reservoir level of 1495.50 m, water pressure at the base of the sluice liner (elevation 1456.00 m) is 375 KN/m². The sluice liner is designed for water pressure of 375 KN/m² all around.

- **Concreting on Top** - The loading due to weight of 1 m of concrete i.e. 25 KN/ m² on top of the sluice liner.

- **Concreting at Sides** - The concreting on sides of the sluice opening causes a lateral pressure on the side walls of the sluice liner. Provided that concreting progresses at a slow speed, this loading amount to about 25 KN/ m² over the whole height of the side walls.

Out of these three load cases, maximum effective stresses occur under the water load case in the mid span regions of sluice liner. These stresses are smaller than 250 MPa which is less than the allowable stress of 287 MPa for steel having yield stress of 460 MPa, using a factor of safety of 1.6.

7.2 Central Spillway

A small gravity spillway had been envisaged for Nathpa dam on the right bank as per proposal contained in the specification drawings besides sluices. Central Water and Power Research Station (CWPRS), Pune, while conducting model studies for Nathpa Dam observed in their technical report No. 3143 in May, 1994 entitled Hydraulic Model Studies for Bank Protection, that due to the pit provided in front of the gravity spillway, hydraulic performance of Ski- jump bucket downstream of sluices is impaired as strong return flow is generated in front of spillway leading of boosting up of tail water levels. In order to overcome this problem, CWPRS, Pune, proposed a chute spillway in place of gravity spillway. It was suggested that the above proposal may be considered in the light of geological conditions and techno-economic feasibility before taking a final decision.

The panel of experts during their 13th meeting had observed that the proposal of CWPRS, Pune to convert the right bank gravity spillway of 15m length into a chute spillway was acceptable as this spillway would involve least disturbance to the right bank hill slope. Considering suggestions of the CWPRS, Pune, the chute spillway proposal was studied in the light of observations of the POE and following are the major findings:

(i) A comparison of the quantities of excavation and concreting for gravity spillway proposal and chute spillway proposal reveals that there is no significant saving in concreting and excavation in case of chute spillway vis-a-vis gravity spillway.

(ii) In case of chute spillway proposal, deep cuts varying from 6 m to 16 m have to be made on the slope of the right bank to a relatively longer distance of about 95 m downstream of dam axis.

In order to avoid cutting of the right bank along length of the chute and also considering CWPRS recommendations, alternative arrangement for providing the central spillway over one of the sluice blocks was considered. This proposal consists of provision of central overflow spillway in block no. 6 over the sluice section which was discussed with retainer consultants of M/s Electrowatt Engineering, Switzerland and was approved by the Panel of Experts. The bucket of this spillway lies vertically above the bucket of the sluice in block no. 6. Both the buckets discharge without inter-mixing of water jets at full reservoir level. The central spillway has a discharging capacity of about 130 cumec which is sufficient to pass lean period discharges in case of sudden shut down of generating units. Throw distance from the lip of the bucket in case of central spillway would be about 47 m as against 38 m for the sluice bucket. The central spillway proposal had the following three major advantages vis-a-vis chute spillway proposal:
(i) Significant saving of the order of 30,000 cum. in the quantity of excavation and 20,000 cum quantity of concrete.

(ii) Excavation of the right bank completely avoided for locating the chute on the right bank. Hence disturbance to the right bank slope downstream of dam was avoided.

The water jet of central spillway discharges freely into the centre of the river, hence the plunge pool formation near the right bank was avoided.

8. ENERGY DISSIPATION ARRANGEMENT

Nathpa dam has five sluice openings of size 7.5 m (width) \times 8.5 m (height) which are capable of passing a flood discharge of 5660 cumec with Full Reservoir Level at EL 1488.5 m. In phase –II with dam top at EL 1498.50 m, & FRL at EL 1495.5 m, four sluices and a central spillway over sluice block no. 6 are capable of passing the flood discharge. The sluices are provided with trajectory type buckets (Photo 3) for dissipating the energy generated due to high velocity water flows downstream of sluice radial gates. These buckets have been designed as per IS: 7365 – 1985, to encounter water moving with a velocity of the order of 23m/sec.

The principal features of hydraulic design of the trajectory bucket consists of bucket invert elevation, radius of the bucket, lip angle of the end sill and estimation of scour downstream of spillway. Hydraulic forces acting on a trajectory bucket are of interest in the structural design of the bucket. Bottom pressures change continuously throughout the bucket and are a function of the entering velocity and depth of flow, radius of curvature and angle of deflection of the flow. Radius of the bucket for Nathpa dam has been worked out as 24 m. The bucket lip angle affects the horizontal throw distance. The factors affecting the horizontal throw distance also include the initial velocity of the jet and difference in elevation between the lip and the tail water. Normally the lip angle is between 30° & 40°, the final choice depending upon the minimum throw permissible under the local rock conditions. The lip angle of the buckets has been selected as 27° so as to avoid any return flows. The horizontal throw distance of the water jet emanating from the bucket lip works out to about 38 m which is at a safe distance from the dam foundation into the river bed which mainly comprises of gneisses type of rock.

9. DAM GALLERIES

9.1 Foundation Gallery

Foundation gallery has been provided along the length of dam near and parallel to dam axis. It has been provided near the sound rock profile of dam foundation. In steep slopes on the banks the foundation gallery has been provided with steps running in parallel & transverse direction with respect to dam axis. The purpose of this gallery is to provide access to the interior mass of the dam in order to inspect the structure and study the structural behaviour of dam after completion. Apart from this, holes have been drilled and grouted for the main grout curtain and drainage holes are drilled for draining water seeping through the foundation in order to provide relief in uplift pressures.

Sump well of size 4 m \times 4.0 \times 3.5 m has also been provided in block No.5 with access from foundation gallery at EL 1441.0 m. The size has been decided based on anticipated max. seepage of 50 ltt/sec. The depletion time works out to be 18.67 min.

The size of the pump chamber has been proposed as 4.0 m \times 4.0 m \times 3.0 m. This has been placed exactly above sump well at higher elevation.

As per IS: 12966 (Part I): 1992, tread of size 250 mm & rise of size 200 mm should be provided and max. 25 steps in one flight. In our case two type of arrangement have been provided. In 1st type tread has been taken as 250 mm & rise as 200 mm. In 2nd type tread has been taken as 250 mm & rise as 250 mm. In steep portions 2nd type of arrangement has been proposed.

The above arrangement was decided at CWC, New Delhi. The two meter width of gallery has been distributed in the following manner:
Ramp = 70 cm wide
Step = 100 cm wide
Drain = 30 cm wide

Apart from this it was decided to keep minimum 1.0 m as horizontal distance from contraction joint in the stair portion i.e., no steps are provided in this portion. 1m wide path for access to operation of gates at E1. 1472 m has been provided.

Three nos. grouting & drainage galleries (R1, R2 & R3 at E1. 1441.0, 1459.0 & 1481.0 respectively) on right bank and three nos. galleries (L1, L2 & L3 at E1. 1441.0, 1459.0 & 1481.0 respectively) on left bank have been provided. Size of each gallery has been kept as 2.0 m x 3.0 m (h) D-shaped having a length of about 20-30 meters. These galleries have been provided to facilitate drainage of abutment mainly. Curtain grouting has also been performed through these galleries.

Seepage water collected in the dam gallery flows through the drain provided in the gallery to the sump well from where this water is pumped to the downstream side of the dam by discharging it at a level higher than the maximum tail water level.

9.1.1 Design Criteria for Foundation Gallery

As per IS: 12966:1992 (Part-I), the foundation gallery should be located at a distance of 3.0 meters or 5 percent of the reservoir head (measured from FRL to the foundation level) from the upstream face of the dam, whichever is greater. In the case of Nathpa dam, this distance works out to be 3.425m based on foundation level at E1. 1431. Therefore minimum distance from upstream face of dam to u/s face of gallery has been kept as 3.5 m. The size of foundation gallery has been kept as 2.0 m (width) x 2.5 m (ht) as per the IS: 12966:1992. Also minimum cover of 4.25 m has been proposed at floor level of gallery, where upstream face is sloping. There should be minimum 1.5 m. concrete cover between the floor of the gallery and foundation grade profile. The concept of 1.5m cover has been followed in the situations where gallery routing is within the dam body. Sometimes another situation arises where gallery has been desired to route through trenches i.e., where normal concreting could not be provided due to site constraints, in that cases minimum cover of about 2.0 meter around the gallery is essential. In some situations the cover of 2 m has been followed.

9.2 Inspection Gallery

This gallery of size 1.5 m (wide) x 2.5 m (high) has been provided at E1. 1475.00 and runs parallel to dam Axis. Main purpose of this gallery is to provide access to the interior mass of the dam in order to inspect the structure and study the structural behaviour of the dam after completion. This gallery is also connected with foundation gallery at both banks.

9.3 Transverse Gallery

In block No.5 which is at deepest level, one transverse gallery of size 2.0 m x 2.5 m has been provided. This is basically for the instrumentation purpose. Also different approaches have been provided from this gallery e.g. for reading room for plumb line shaft.

10. FOUNDATION TREATMENT

10.1 Treatment of Shear Seams

Mica Schist bands 2-3 m wide were encountered in the dam foundation. Carrying out excavation upto 2 m depth carried out dental treatment of the seams. To avoid any eventuality of seepage through these seams, upstream & downstream cut-offs were provided to a depth of 12 m & 6 m respectively.

Reinforcement was provided in the dental concrete & also grouting of these seams was carried out through holes at specified points.

10.2 Consolidation Grouting

10.2.1 Design Criteria

The principal objectives of grouting in a rock foundation are to establish an effective barrier to seepage under the dam and to consolidate the foundation. Spacing, length and orientation of grout holes and the procedure to be followed in grouting a dam foundation are dependent on the height of the structure and the geologic characteristics of the foundation. Grouting operations may be performed from the surface of the excavated foundation, from upstream fillet of the dam, from the top of concrete placements for the dam, from galleries within the dam or any combination of these locations.

The main purpose of consolidation grouting is to reduce the deformability of jointed or shattered rock. The aim covers to consolidate the bed rock so as to improve its strength & bearing capacity and create effective barrier to reduce seepage through the foundation by filling grout in the underground voids/cavities.

In case of Nathpa dam, extensive geological studies have been carried out to evaluate suitable direction & orientation of grout holes. Jointing patterns in every block alongwith dip & orientation of joints have been considered.

10.2.2 Inclination of Grouting Holes

For grouting in block Nos.1 to 3 following has been considered:

(1) Angle of 125 degree from North in clockwise direction in horizontal plane has been adopted.
(2) Angle of 70 degree w.r.t horizontal line in a vertical plane in the grid of 125 degree angle in plan has been adopted. Use of stereograph net has been made for consolidation grouting in Block Nos. 9 & 10.

(3) For block Nos. 11, whole circle bearing of 125 degree has been adopted as suggested by Geologist of GSI department.

(4) The drilling has been proposed at an angle of 70 degree w.r.t horizontal to cut max. no. of bedding planes and for effective grouting.

10.2.3 Spacing of Holes & Sequence of Grouting

In the 1st phase, holes have been drilled & grouted at a spacing of about 13 m. After the completion of grouting in 1st phase, split spacing procedure has been adopted further. The final spacing of holes are not more than 6 m c/c. In some areas, i.e., Geological weak pockets spacing of 3 m or less has been provided.

10.2.4 Grout Pressures

Grout pressures as high as practicable but which are safe against rock displacement have been first established by carrying out tests at site. In starting, low initial pressures of range say 0.10 to 0.25 kg/cm² per meter depth of rock have been applied. The pressures have been raised gradually. The pressures upto 3.5-50 kg/cm² were applied for the consolidation grouting.

10.2.5 Grout Mix

Grouting mixture of range 5:1 to 0.8:1 (water : cement by weight) has been used. Initial grout mix has been proposed as 5:1 and mixture has been gradually thickened to get optimum results w.r.t consistency of grout pressures.

Effectiveness of the consolidation grouting was checked by performing permeability tests so as to check that the permeability value is not more than 3.0 Lugeons.

10.3 Curtain Grouting

10.3.1 Design Criteria

Curtain grouting is mainly done to safeguard the foundation against erodibility hazard and to reduce quantity of seepage.

The pressure grouting of rock foundation is normally carried out to fill discontinuities in cavities or voids in rock mass by suitable materials.

The following formula has been adopted for plotting the profile of grout curtains:

\[ D = \frac{2}{3}H + 8 \]

\[ D = \text{Depth of the grout curtain in m} \]

\[ H = \text{Height of reservoir water in m} \]

Based on above formula total depth of curtain grout holes works out to be 3742.4 m.

10.3.2 Inclination of Grouting Holes

For design, the inclination of holes was proposed at 10 degree w.r.t vertical. In cases where lower gallery is coming above the gallery from where grouting is being done, the inclination was changed to get minimum cover of 2-3 meters.

10.3.3 Spacing of Grout Holes

In the 1st phase, spacing of about 6.0 m c/c was proposed for drilling & grouting of holes. After the completion of grouting in 1st phase, holes for the 2nd phase were drilled and grouted with spacing reduced to 3 m c/c.

10.3.4 Grout Mix

Grouting mixture in the of range 5:1 to 0.8:1 (water: cement by weight) has been used starting mixture of 5:1 is recommended. Thereafter mixture is thickened gradually and consistency checked w.r. t grout pressure.

10.3.5 Grout Pressures

In the initial stage grouting has been done with low pressures i.e. 0.1 kg/cm to 0.25 kg/cm per meter depth of rock. The pressure has been increased gradually. Pressures have been raised only when the intake rate falls below 5 litres/minute. The limiting values of pressures have been kept lower than two third of hydraulic fracture test results. For the pressure computations at different zones and depths curves as mentioned in IS: 6066 have been followed. Max. Pressure of about 30 kg/cm² has been applied for the deepest hole having depth of about 51.8 m.

Effectiveness of the curtain grouting performing permeability tests so as to check that the permeability value is not more than 1.0 Lugeon.

11. STABILITY OF SLOPES IN THE DAM COMPLEX

PROVISION OF 200T CAPACITY CABLE ANCHORS

11.1 Design Criteria

On left bank, slopes rise for a height of more than 140 m from the river bed at El. 1445 m to National Highway No.22 at El. 1585 m. It is covered by overburden from road at El.
WATER & ENERGY INTERNATIONAL

1585 m to El. 1524 m. Below El.1524 m, the rock comprises of gneisses with pegmatite intrusions, bands of quartz mica schist, biotite schist, amphibolites etc. The bank slopes in the dam area and vicinity of dam varies from 40° to 50°. The dip of the foliation planes of gneisses varies from 40° to 55° towards river side having strike almost parallel to the river flow. The dam site is located mainly in the area underlain by a gneiss group named Jeori-Wangtoo complex aged Pre-Cambrian. The foundation rocks in the dam complex are comprised of gneiss with bands of quartz mica schist, biotite schist on the left bank and of augen-gneisses with the same bands on the right bank.

Any rock cutting on left bank abutment was expected to disturb the rock slope stability and could have resulted into a planar failure i.e., failure along the foliation planes. As such detailed analysis of problem was necessary. Dam area on the left bank was analyzed for stabilization from 15 m u/s to 105 m d/s of dam axis. The angle of potential failure plane taken as 45° from 15 m u/s to 60 m d/s of dam axis and further 40° from 60 m d/s to 105 m d/s based on observed foliation angle. The location of failure plane has been marked on each section based on deepest cut i.e., the location w.r.t. exposed surface. In some sections, road cut is governing the deepest cut and in some sections dam foundation cut is governing the deepest cut. The sliding mass based on failure plane was analyzed considering the effect of resisting forces, disturbing forces, earthquake forces, uplift pressure, angle of internal friction and cohesion along the failure plane. The anchorages forces at different sections were computed for a factor of safety of 1.1 for non-seismic case and 1.0 for seismic case. The critical of two cases were finally adopted in the design and capacity, number of rows and spacing of anchors was decided accordingly.

For purpose of design the values of angle of internal friction & cohesion for rock and overburden were adopted as 41.9° & 1 t/m² and 41° & 0 t/m² respectively on the basis of investigations and back analysis of stable slopes. The value of horizontal seismic co-efficient adopted was 0.08 (site is located at Zone IV of seismic map specified in IS: 1893) and vertical component was assumed to be 50% of the horizontal component. Unit weights of rock and overburden were taken as 2.7 t/m³ and 2.3 t/m³ respectively based on test results in the dam area. The uplift force was assumed to be 25% of the average depth of sliding mass acting on total area. The angle of installation of the cable anchor was fixed as 15 degree downwards w.r.t horizontal from the consideration of effectiveness of grouting operations in the hole. For transferring the load from anchor head to the rock a continuous RCC wall (about 7cm thick) was provided in view of large capacity of anchors necessitated at a closer spacing.

On the above criteria about 170 nos. of prestressed cable anchors of 200 tonnes capacity have been provided in left bank dam area. These have been installed at a minimum horizontal spacing of 3 meters in maximum of five rows above road to top of dam. The installation has been carried out by constructing benches from top and moving downwards. From each bench 2 rows have been put at 2 meters vertical spacing. Photo 4 showing the view of 200T cable anchors.

Photo 4 200 T Cable Anchors

12. HIGHLIGHTS OF NATHPA DAM

- Diversion dam with diurnal storage of 303 ha m capable of providing 3 hours peaking of 1500 MW
- Low level sluice spillway provides facility of complete flushing of reservoir for preventing siltation of live & dead storage. Original flushing was planned once or twice a year. However, during operation of the project, weekly/fortnightly flushing introduced during high flow season depending upon silt content in the river, for enhanced efficiency of desilting chambers.
- During early stage of construction in 1993 a major landslide occurred with debris of about 1.0 million Cum. Blocking the river & consequently slope stabilization was reviewed and cable anchors were provided as shown in the Table 1.
- Because of heavy silt load & boulders, sluices have been lined with abrasion resistant steel with hardness on Brinell Scale as 400 BHN. Five number steel liners with 1650 Tonne of steel placed and concrete in one working season.
Table 1: Cable anchors in dam complex

<table>
<thead>
<tr>
<th>Location</th>
<th>River Bank</th>
<th>Capacity</th>
<th>Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam Area</td>
<td>Left Bank</td>
<td>200 T</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>Right Bank</td>
<td>40 T</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 T</td>
<td>33</td>
</tr>
<tr>
<td>Intake</td>
<td>Left Bank</td>
<td>200 T</td>
<td>274</td>
</tr>
<tr>
<td>Plunge Pool Area</td>
<td>Right Bank</td>
<td>200 T</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Left Bank</td>
<td>200 T</td>
<td>76</td>
</tr>
</tbody>
</table>

- Nathpa dam location being in a narrow valley, placement of concrete and erection of steel liners done with 5T capacity cable way.
- Two major floods encountered during construction in 1997 and 2000.
- During operation flood due to Parechu breach was encountered in June 2005 and passed safely taking advantage of flood warning arrangement.
- Because of submergence problem of upstream Bhaba Power House (120 MW), the Nathpa dam has been raised in two phases to increase the storage capacity. The height of dam was increased by 5 m after diverting Bhaba Tail Race downstream of the dam. Provision has also been made for pumping back Bhaba water during lean season.