Hydraulic Transient Studies for Restoration of Downstream Surge Gallery of Punatsangchhu-II Hydroelectric Project (1020 Mw), Bhutan.

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Abstract: Punatsangchhu-II (6 x 170=1020 MW) hydroelectric power project is a run-of-the-river scheme being implemented in Bhutan by Royal Govt. of Bhutan and Govt of India. The originally envisaged Downstream Surge Gallery (DSG) of this project consists of an underground cavern of size 314 m (Length) x 18 m (Width) x 58.5 m (Height) which has been provided for smooth functioning of the water conductor system under various hydraulic transient conditions. During excavation, a massive rock fall occurred in March 2016, between RD 135m to RD 200m at the crown level, puncturing the steel rib support system installed at the crown of the chamber and created a very large cavity (of about 91m high) above the crown of the DSG. It is estimated that the volume of fallen muck is of the order of 100000 cubic metres. Considering the large volume of muck and other site constraints, it was decided to abandon the portion of chamber which was filled with muck and utilize the remaining chambers on both sides for hydraulic stability. The lost volume needed to be compensated by providing adequate number of surge galleries/tunnels. This major incident has resulted in abandoning of about 155 m length of DSG from RD 107m to RD 262 m, which corresponds to a loss of 48% volume of the chamber. Detailed Hydraulic Transient studies have been carried out for restoring the hydraulic stability of DSG under different transient conditions arising due to various turbine operations. The details of Hydraulic Transient studies carried out are described in this paper.

Keywords: Transient pressure; Downstream Surge Chamber; Expansion Gallery; Upsurge; Downsurge

Abbreviations

DSG – Downstream Surge Gallery
TRT – Tail Race Tunnel
TWL – Tail Water Level
CEA – Central Electricity Authority
WHAMO - Water Hammer and Mass Oscillation

1. Introduction

Punatsangchhu-II HEP is a 1020 MW run-of-the river project located on Punatsangchhu river in Wangdue Phodrang Dzongkhag in Western Bhutan. The Downstream Surge Gallery (DSG), which consists of an underground cavern of size 314 m (Length) x 18 m (Width) x 58.50 m (Height) has been provided for smooth functioning of the system under various hydraulic transient conditions. The crown of the DSG is at EL. 623.50 m (from RD 0 to 210) and at EL. 613.50 (from RD 210 to 314), while the bottom is at El 565 m. Six numbers of draft tubes meet upstream of the DSG at the bottom and two tail race tunnels (length 323.70 m and 178.40 m) off-take from the downstream of the DSG. These branch TRTs meet at downstream of DSG and the common TRT has a length of 2.850 km up to the outfall location. The layout of Power House complex originally envisaged is shown in fig.(1)

A massive rock fall occurred in the Downstream Surge Gallery (DSG) on 3rd March, 2016 between RD 135m to RD 200m at the crown level, puncturing the steel ribs installed at the crown of the chamber and created a very large cavity (of about 91m height) above the crown of the DSG. It is estimated that the volume of muck is of the order of 100000 cubic metres. This has resulted in abandoning of about 151.50 m length of DSG from RD 107m to RD 258.50 m, which corresponds to a loss 48% volume of the chamber.

As a consequence of abandoning large portion of DSG, the draft tube tunnels need to be realigned and the hydraulic stability of DSG needs to be restored under different transient conditions by providing additional expansion chambers/ surge galleries. Hydraulic Transient studies have been carried out for various turbine operation conditions with the proposed revised layout of draft tube tunnels. The results are presented in this paper.

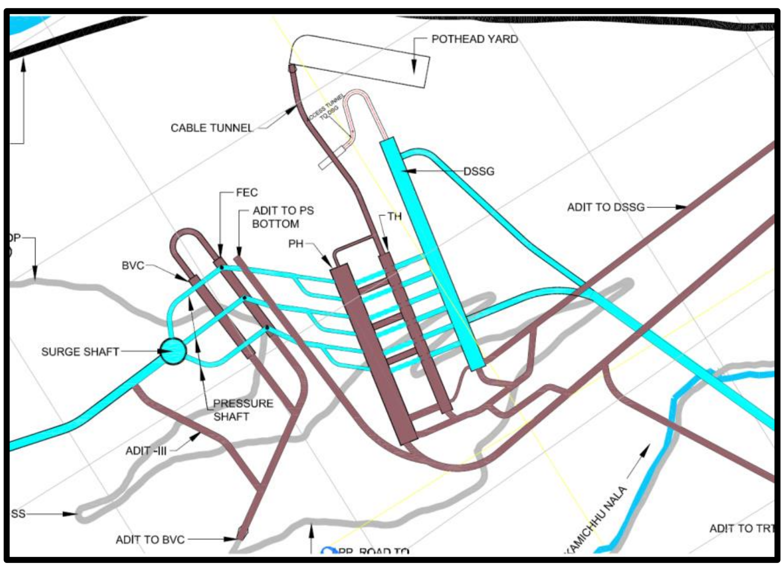

Fig (1)- Layout of PH complex originally envisaged

2. Hydraulic Transient Analysis Methodology

The transient analysis has been carried out by considering two separate surge tanks, on either side of the abandoned portion of the DSG. The Northern side surge tank (ST 1) will receive discharge from 2 units (Unit V & VI) and the Southern side surge tank (ST 2) will receive discharge from 4 units (Unit-I, II, III & IV). Additional surge gallery has been considered on

Northern and Southern end which are added to the existing surge gallery area. The schematic layout is shown in fig.(2) below:

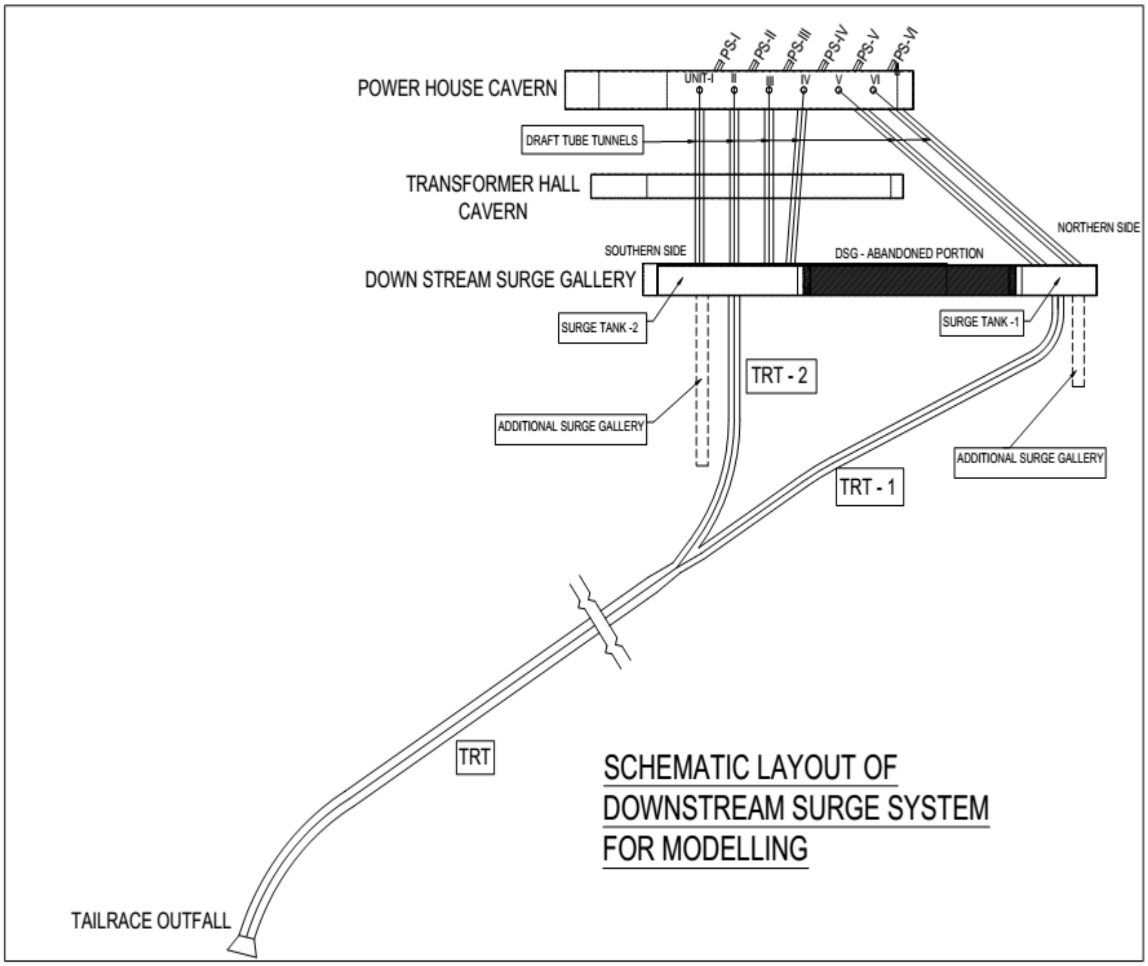

Fig. (2): Schematic Layout of Power House Complex showing Additional Expansion Galleries

The transient analysis for Downstream Surge Gallery has been carried out to determine the following parameters:

a. Maximum and minimum surge levels in the two sections (Northern & Southern end) of the DSG for various load combinations. The existing DSG has been divided into two parts due to abandoning of the middle portion of DSG. Draft Tubes from Unit-I, II, III & IV join the southern part of the DSG (ST 2 in the model) and Draft Tubes from Unit-V& VI join the Northern part of the DSG (ST 1 in the model).
b. Exploring the requirement of additional area of surge gallery required for meeting the extreme surge levels.

2.1 Basic Input Data for Transient Analysis

Following basic data has been adopted for transient study analysis:

Table 1: Salient Features

Parameter	Value
Minimum Tail Water Level(1 Unit Operating)	576.80 metres
Normal Tail Water Level(6 Units Operating)	579.50 meters
Normal Tail Water Level(6 Units Operating with 10% overload)	579.60 meters
PMF Tail Water Level	595.90 meters
Turbine	
Type	Francis
Nos.	6
Turbine Centre Line	569.00 meters
Installed Capacity	1020 MW (170x6)
Tail Race Tunnel (Concrete Lined)	
Nos.	1
Diameter & Shape	TRT1 – 7.80 meters, Circular TRT2 – 7.80 meters, Circular TRT – 11.00 meters, Circular
Length	TRT1 – 323.678 meters TRT2 – 178.418 meters TRT – 2850.27 meters
Design Discharge (Q) (*total for 6 units*)	466.0 cumec
Design Discharge (Q)-With 10% Overload	528.00 cumec

2.1.1 Load Acceptance

As per the specifications provided by the turbine manufacturer (BHEL), the Gate valve opening time is **12 seconds**.

2.1.2 Load Rejection

The time taken for full load rejection is based on the specifications supplied by turbine manufacturer , which are as follows:-

100% to 10% - 6.50 Seconds
10% to 0% - 8.00 Seconds
Total Time 14.5 Seconds

2.1.3 Load Combinations

a. The load scenarios to be considered for the transient analysis have been from Indian Standard IS: 7396 (Part 2). They all include combinations of full load acceptance or specified load acceptance and/or full load rejection. The CEA guidelines have also been kept in view.
b. When load combinations are involved, the time of application of the load change is to be adjusted so as to generate extreme surge levels.
c. Transient analysis has been conducted for normal operating condition for 1020 MW (6X170 MW) plant capacity and also with 10% overloading.

2.2 Conditions For Upsurge In Downstream Surge Gallery

As per IS: 7396 (Part 2) Clause 5.1.1, the maximum upsurge level in the downstream surge tank shall be worked out corresponding to:

a. The full load acceptance at the highest downstream tail water level; and
b. Where considered necessary, load rejection followed by specified load acceptance at the instant of maximum negative velocity in the tail race tunnel, the downstream tail water level being at its highest and higher of the two shall be adopted.

For the case (a) as indicated above, Instead of Full Load acceptance, the load acceptance by only two units simultaneously has been considered in the analysis as per CEA guidelines.

Maximum upsurge level in the downstream surge gallery with minimum friction in water conductor is computed for following cases at Normal Tail Water Level (NTWL):

2.2.1 Normal Operation

- Specified load acceptance after full load rejection (100-0-33)
- Full load acceptance after specified load acceptance (66-100-100)

2.2.2 Overload Operation

- Specified load acceptance after full load rejection (110-0-33)
- Full load acceptance after specified load acceptance (66-110-110)

Specified load acceptance after full load rejection shall be considered at the instant of maximum negative velocity in the tail race tunnel (from Surge gallery to Turbine).

2.3 Conditions For Down-Surge In The Downstream Surge Gallery

As per IS: 7396 (Part 2) Clause 5.1.1, the minimum Down-surge level in the downstream surge tank has been worked out corresponding to:

a. the full load rejection at the lowest downstream tail water level; -and
b. Where considered necessary specified load acceptance followed by full load rejection at the instant of maximum positive velocity in the tail race tunnel the downstream tail water level being at its lowest and the lower of the two shall be adopted.

Minimum surge level due to down surge in the downstream surge gallery with maximum friction in water conductor is computed for following cases at Normal Tail Water Level (NTWL):

2.3.1 Normal Operation

- Full Load rejection (100-0-0)
- Full load rejection after specified load acceptance (66-100-0)

2.3.2 Overload Operation

- Full Load rejection (110-0-0)
- Full load rejection after specified load acceptance (66-110-0)

Full load rejection after specified load acceptance shall be considered at the instant of maximum positive velocity in the tail race tunnel (from Turbine to Surge gallery)

2.4 Method of Analysis

Transient studies have been carried out both for maximum and minimum friction conditions separately. The basic data used in transient study are listed in Table shown above. During the transient state, the profile of water surface oscillation in the Surge Tank has been studied and the maximum and minimum water levels are recorded for different loading conditions. All the cases of transient analysis with 10% overload conditions have been analysed with normal tail water level when all the six turbines are running, in consultation with CEA.

2.5 Modelling Tools

The transient study has been done using WHAMO (Water Hammer and Mass Oscillation), developed by US army Corps of Engineers. WHAMO uses the finite difference technique to solve the partial differential equations of continuity and momentum. The program WHAMO has been used to determine the maximum and minimum surge levels in the surge tank and also to determine the water hammer pressure for various scenarios of load changes.

The following figure depicts schematic layout of modelling of downstream surge system. The modelling of this layout is done in WHAMO, in the form of nodes and links. The system comprises of downstream reservoir, Equivalent Tail Race tunnel representing TRT, TRT1 & TRT2, 2 Nos. Surge Tanks, Draft Tubes and Turbines (as a flow boundary).

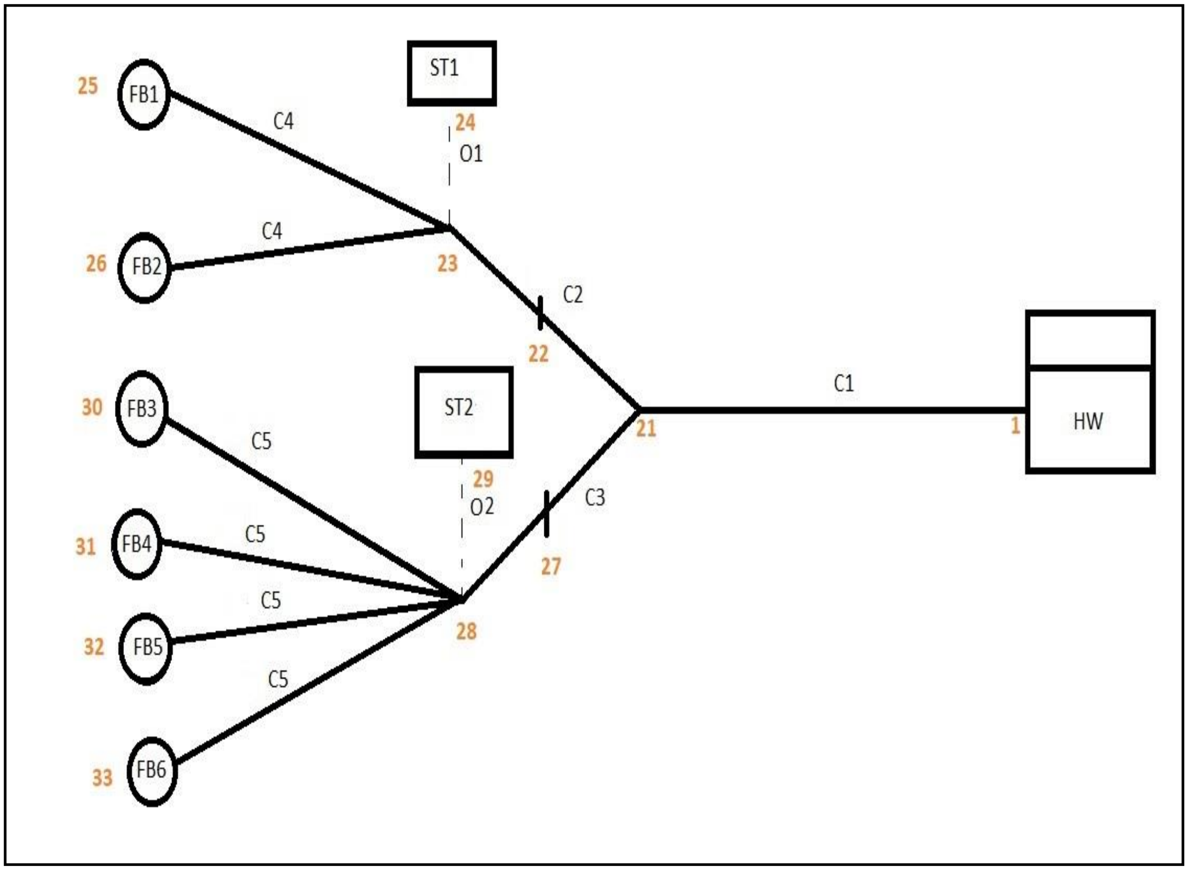

Fig. (3): WHAMO network for analysis

2. Different Options Considered

As already indicated about 48% of the volume of DSG has been lost due to the cavity formation and hence the restoration of hydraulic stability of the system requires various alternative considerations. The solution which meets the optimum performance needs to be adopted.

The following alternatives have been considered:

Alternative 1: Expansion Chambers/Surge Gallery on **both sides** with different area/length of the surge tunnels at different elevations.

Alternative 2: Expansion Chambers/Surge Gallery on **one side** with different area/length of the surge tunnels at different elevations.

Alternative 3: Expansion Chambers/Surge Gallery on both sides with **Restricted Orifice** on both tanks with different area/length of the surge tunnels at different elevations.

Alternative 4: Additional surge tank at the junction of TRT-1 & TRT-2 with main TRT (Multiple Surge Tanks)

Detailed analyses of various alternatives as indicated above have been carried out and satisfactory results for safe operation of the system could be obtained only for **Alternative 1:** (Expansion Chambers/Surge Gallery on both sides with different area/length of the surge tunnels at different elevations.). Hence this case has been further fine-tuned and adopted for implementation.

II.1. Alternative sizes of Additional Surge Galleries considered

Various trials have been carried out by adopting different sizes of additional surge galleries for achieving safe extreme surge levels.

The following cases have been examined for **additional surge gallery on both sides:**

Table 2: Various Cases Analysed

Sr. No.	Additional Surge gallery		
	Northern End (in m^2)	**Southern End (in m^2)**	**Elevation (in m)**
1	3200	10000	EL 573 to EL 581
2	3240	9600	EL 573 to EL 581.50
3	2500	10000	EL 573 to EL 581
3	2500	10000	EL 574 to EL 582
4	5000	10000	EL 573 to EL 581
6	5000	10000	EL 574 to EL 582

All the above cases have been studied for different operation conditions. Based on the detailed analysis as indicated above, the option with additional surge gallery on both sides (Northern and Southern End) is found to satisfy the extreme transient conditions. **The total required length of additional tunnels (8m x 8.5m) in the Northern and Southern End of DSG is respectively 405m and 1210m. This implies, that the area of additional surge galleries required is 3240 m^2 (Plan Area) on Northern end and 9600 m^2 (Plan Area) on Southern End.** The result for this option, which has been finally adopted, is given in the following section.

3. RESULTS

II.2. Maximum Upsurge Level (Normal TWL: El 579.60 M)

II.2.1. Specified load acceptance after full load rejection at Overload - 110-0-33 (2 units in Southern end started after full load rejection)

In this case the maximum up surge in the DSG is computed when 2 units are simultaneously opened at a critical time (at the instant of maximum negative velocity in the TRT) after the full load rejection. The discharge corresponding to overload operation of the turbine is considered.

This is a combination load case and hence the analysis has been done in two stages: 110-0-0 & 110-0-33. As there are two surge tanks (Northern side joining 2 DTs and Southern side joining 4DTs), the critical time for opening of the two units is different for each tank. From the first case 110-0-0, approximate critical time has been determined and the final case 110-0-33 has been run by taking different timings (400s to 900s) for finding the maximum up surge level in both Surge Tanks.

In this case 2 Units in Southern end are started after full load rejection. The maximum upsurge in Northern ST (2DTs) is **EL 597.50 m** when the 2units opened at 750s and the maximum upsurge Southern ST (4DTs) is **EL 595.51m** when the 2units opened at 650s**.**

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (4)** below:

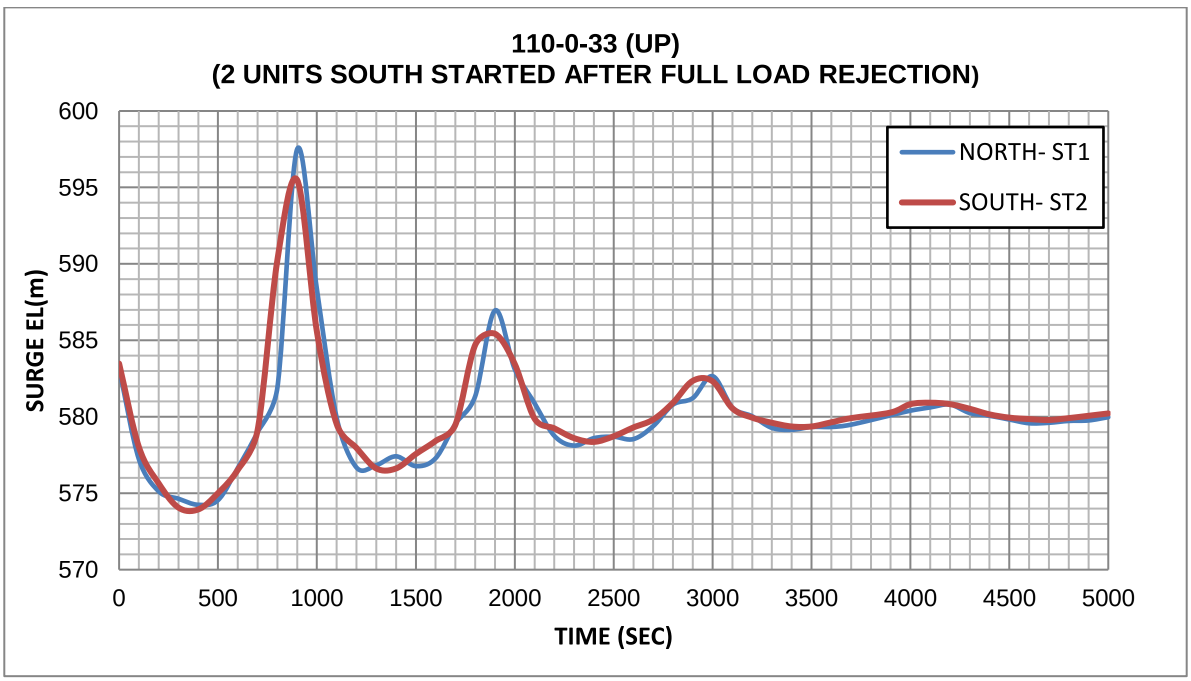

Fig.(4): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) when 2 units in Southern End started after full load rejection

II.2.2. Specified load acceptance after full load rejection at Overload - 110-0-33 (2 units in Northern end started after full load rejection)

In this case 2 Units in Northern end are started after full load rejection. The maximum upsurge in Northern ST (2DTs) is **EL 599.63m** when the 2units opened at 600s and the maximum upsurge Southern ST (4DTs) is **EL 595.65m** when the 2units opened at 800s, after the full load rejection.

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (5)** below:

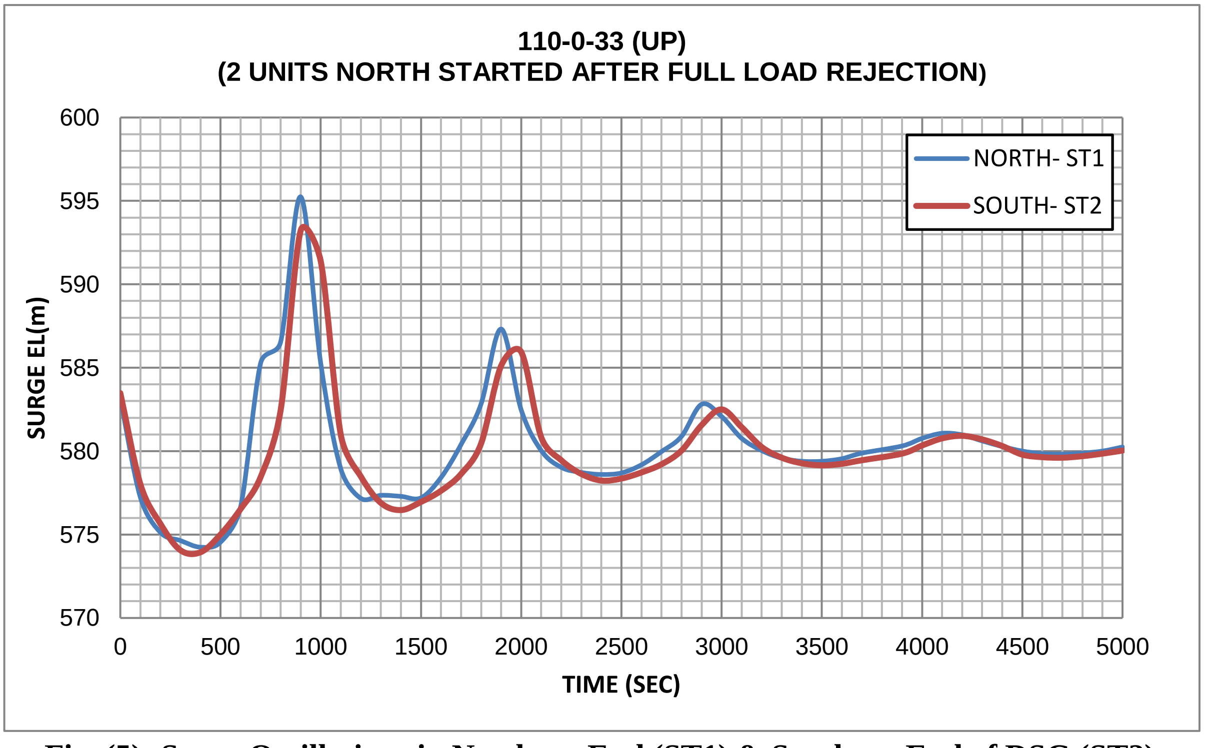

Fig. (5): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) when 2 units in Northern End started after full load rejection

II.2.3. Full load acceptance after specified load acceptance at Overload - 66-110-110 (2 Units in Southern end closed initially which are opened)

In this case 2 Units in Southern end which were closed initially are opened simultaneously. The maximum upsurge in Northern ST (2DTs) is **EL 588.56m** and the maximum upsurge Southern ST (4DTs) is **EL 588.23m**.

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (6)** below:

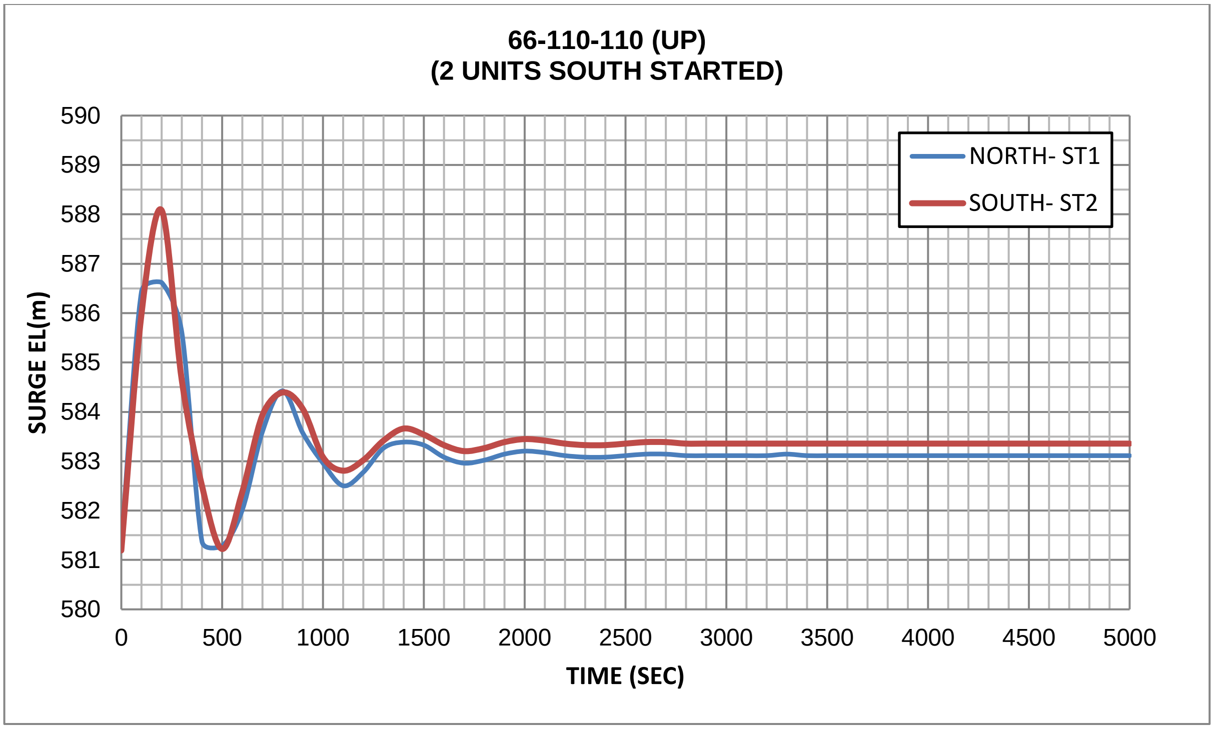

Fig. (6): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) for Case 66-110-110 (UP) when 2 units in Southern End Started

II.2.4. Full load acceptance after specified load acceptance at Overload - 66-110-110 (2 Units in Northern end closed initially which are opened)

In this case 2 Units in Northern end which closed initially are opened simultaneously. The maximum upsurge in Northern ST (2DTs) is **EL 588.84m** and the maximum upsurge Southern ST (4DTs) is **EL 588.84m**.

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (7)** below:

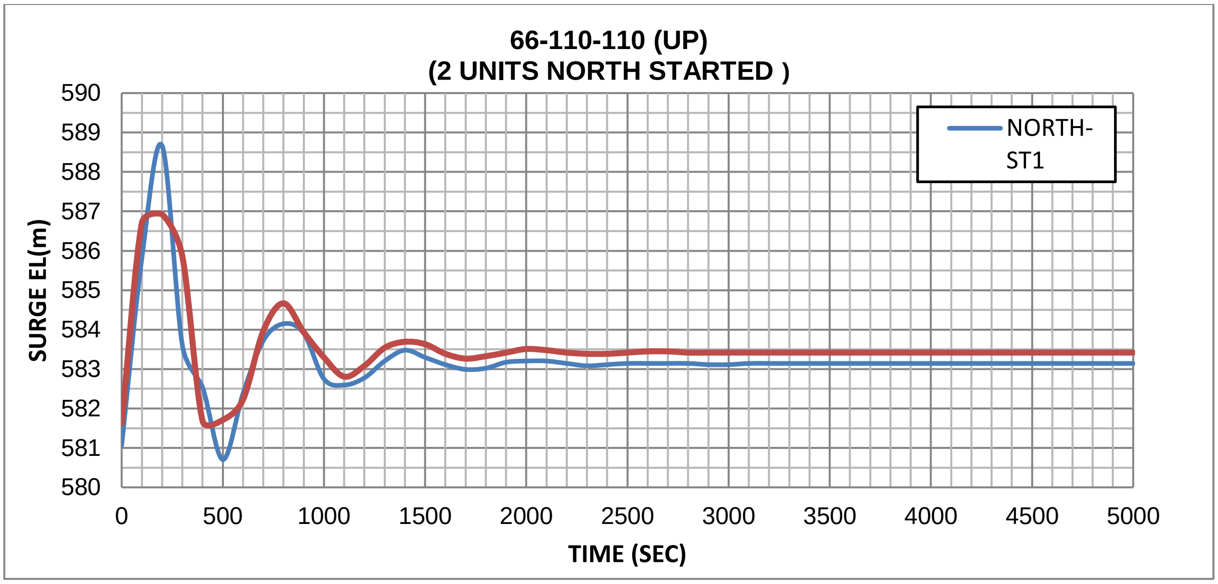

Fig. (7): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) for Case 66-110-110 (UP) when 2 units in Northern End Started

II.2.5. Summary of Upsurge Cases

Sr. No.	LOAD CASE	MAXIMUM UP SURGE LEVEL		REMARKS
		NORTHERN - ST-1 (With 2 D/Tubes)	SOUTHERN - ST-2 (With 4 D/Tubes)	
1.	**110-0-33 (UP)** *(2 units in Southern end started after full load rejection)*	**EL. 597.50m**	**EL. 595.51m**	***The critical time for load acceptance is 750 sec for ST1 &650 sec for ST2 after load rejection.***
2.	**110-0-33 (UP)** *(2 units in Northern end started after full load rejection)*	**EL. 599.63m**	**EL. 595.65m**	***The critical time for load acceptance is 600 sec for ST1 & 800 sec for ST2 after load rejection.***
3.	**66-110-110 (UP)** *(2 units in Southern end started)*	**EL. 588.56m**	**EL. 588.23m**	
4.	**66-110-110 (UP)** *(2 units in Northern*	**EL. 588.84m**	**EL. 588.84m**	

	end started)			

Table 3: Summary of Results for Upsurge Case

II.3. Minimum Down surge Level (Normal TWL: El 579.60 M)

II.3.1. Full Load rejection at Overload - 110-0-0

In this case the minimum down surge in the DSG is computed due to the full load rejection (with 10% Overload). The discharge corresponding to overload operation of the turbine is considered.

The minimum down surge in Northern ST (2DTs) is **EL 574.18m** and the minimum down surge in Southern ST (4DTs) is **EL 573.69m**.

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (8)** below:

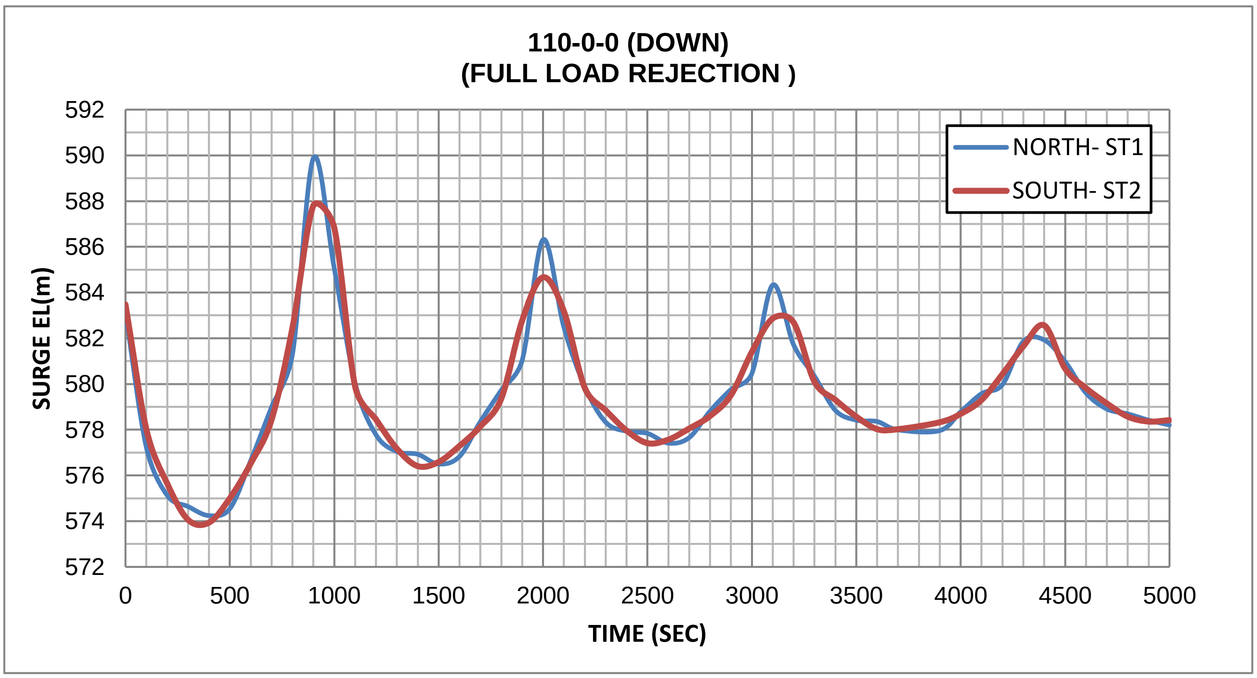

Fig. (8): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) for full load rejection

II.3.2. Full load rejection after specified load acceptance – 66-110-0 (Full load rejection after 2 Units in Southern end opened)

In this case the minimum down surge in the DSG is computed when full load rejection occurs at a critical time (at the instant of maximum positive velocity in the TRT) after 2 units are simultaneously opened. This is a combination load case and hence the analysis has been done in two stages: 66-110-110 & 66-110-0.

In this case 2 Units in Southern end which were closed initially are opened simultaneously (66-110-110). Then Total Load rejection occurs at a critical time (66-110-0). The minimum down surge in Northern ST (2DTs) is **EL 573.38m** and the minimum down surge Southern ST (4DTs) is **EL 572.93m.**

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (9)** below:

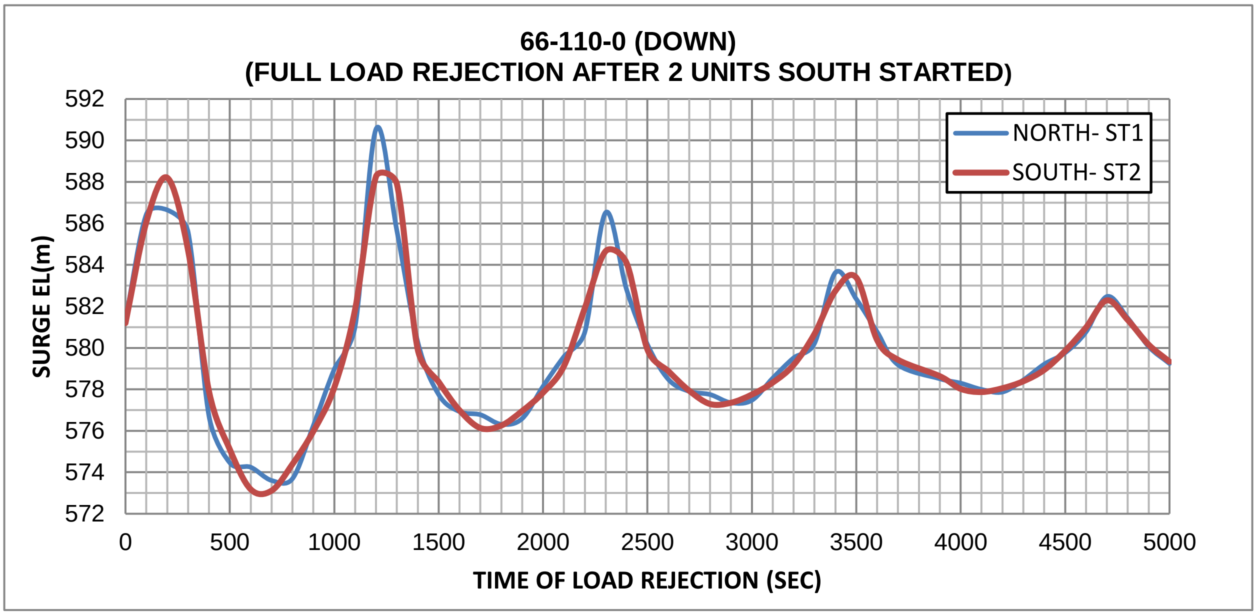

Fig (9): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) for full load rejection after 2 units in Southern End started

II.3.3. Full load rejection after specified load acceptance – 66-110-0 (Full load rejection after 2 Units in Northern end opened)

In this case 2 Units in Northern end which were closed initially are opened simultaneously (66-110-110). Then Total Load rejection occurs at a critical time (66-110-0). The minimum down surge in Northern ST (2DTs) is **EL 573.23m** and the minimum down surge Southern ST (4DTs) is **EL 572.99 m**.

The surge oscillations in Northern and Southern surge galleries for this case are shown in **Fig. (10)** below:

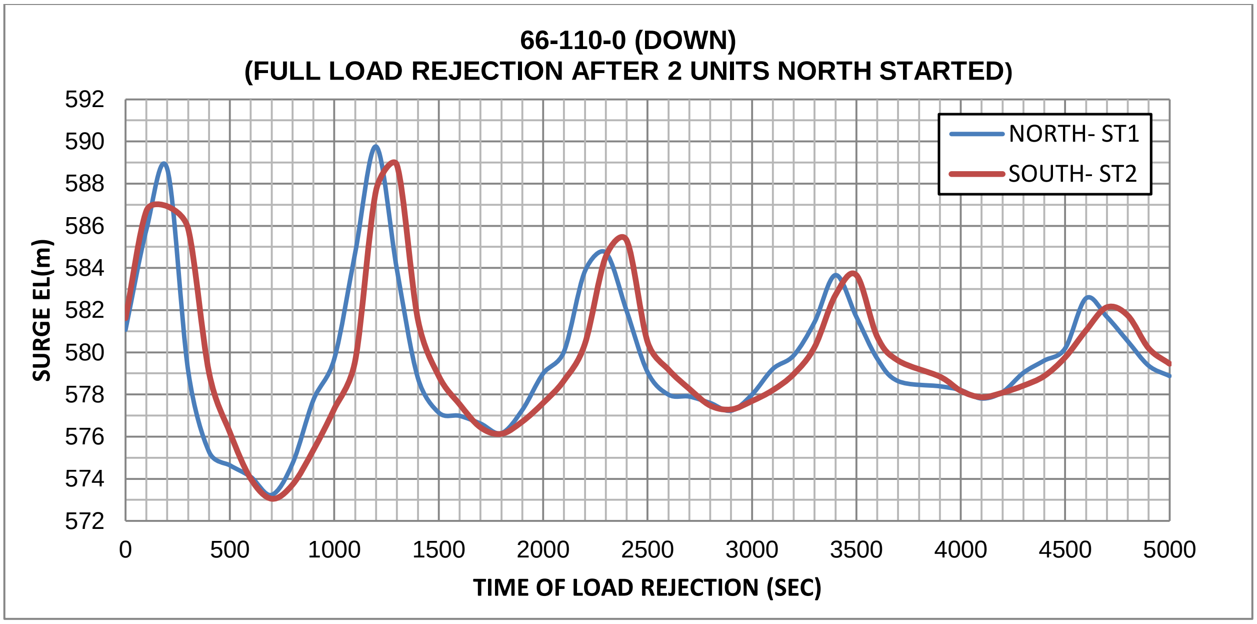

Figure (10): Surge Oscillations in Northern End (ST1) & Southern End of DSG (ST2) for full load rejection after 2 units in Northern End started

IV.2.4 *Summary of Down surge Cases*

Table 4: Summary of Results for Down surge Case

Sr. No.	LOAD CASE	MINIMUM DOWN SURGE LEVEL		REMARKS
		NORTHERN - ST-1 (With 2 D/Tubes)	SOUTHERN - ST-2 (With 4 D/Tubes)	
1.	**110-0-0 (DOWN)** *(Full load rejection)*	**EL. 574.18m**	**EL. 573.69m**	
2.	**66-110-0 (DOWN)** *(Full load rejection after 2 units in Southern end opened)*	**EL. 573.38m**	**EL. 572.93m**	***The critical time for load rejection is 300 sec for ST1 & ST2 after load acceptance by 2units.***
4.	**66-110-0 (DOWN)** *(Full load rejection after 2*	**EL. 573.23m**	**EL. 572.99m**	***The critical time for load rejection is 250 sec for ST1& 300sec for ST2 after load***

	units in Northern end opened)			***acceptance by 2units***

III. SOLUTION

In order to compensate for the lost volume, additional surge galleries have been provided on both sides.

In the Southern side (where 4 DTs are joining), the additional gallery area required is 9600 sq.m (plan area). Therefore total D-Shaped Additional Surge Tunnel of total length 1210 m has been provided as shown in Fig. 11below:

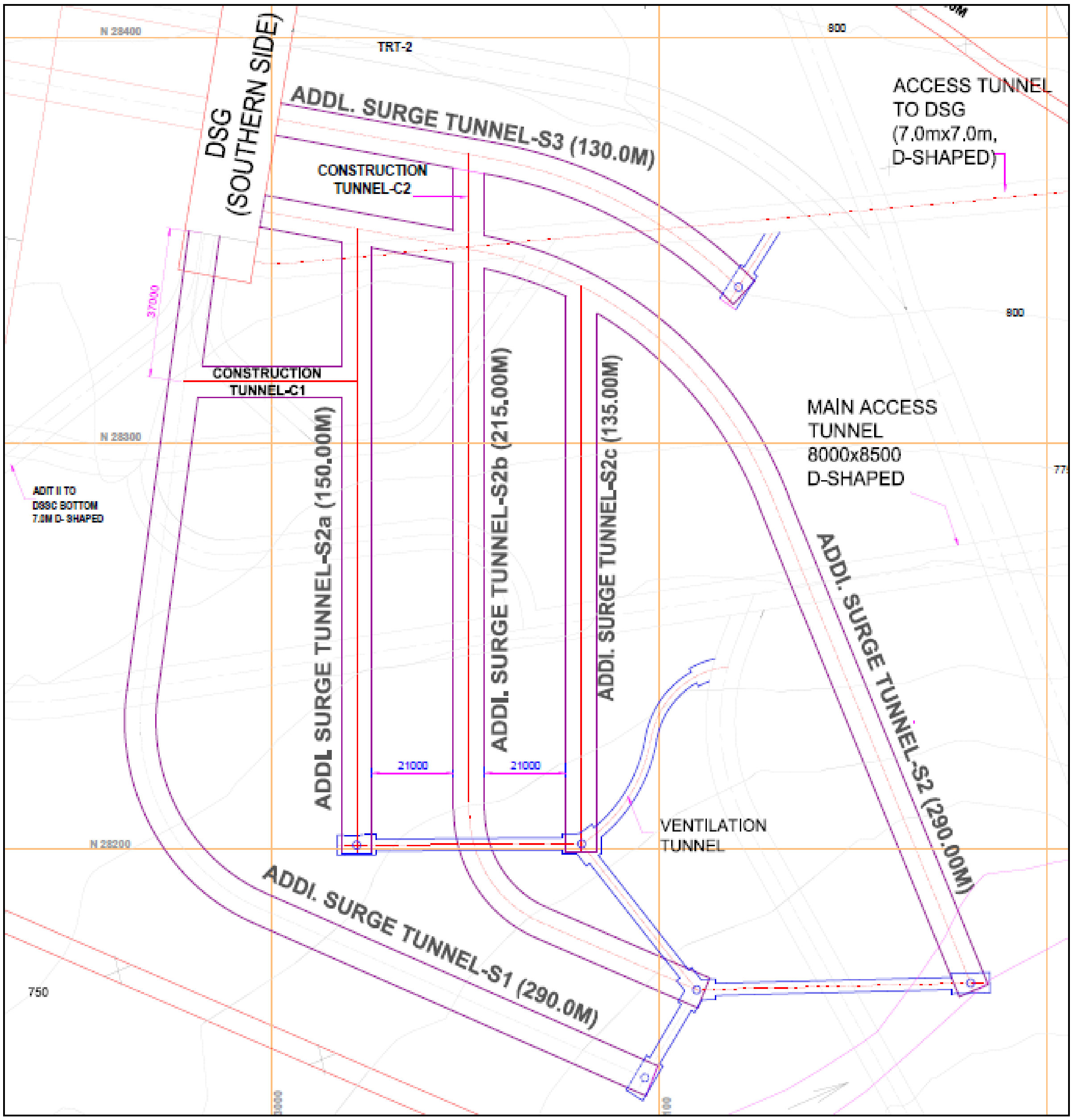

Fig. 11: Additional Surge Tunnel Layout Plan AT DSG Southern End

In the Northern side (where 2 DTs are joining), the additional gallery area required is 3240 sq.m (plan area). Therefore total D-Shaped Additional Surge Tunnel of total length 405 m has been provided as shown in Fig. 12 below:

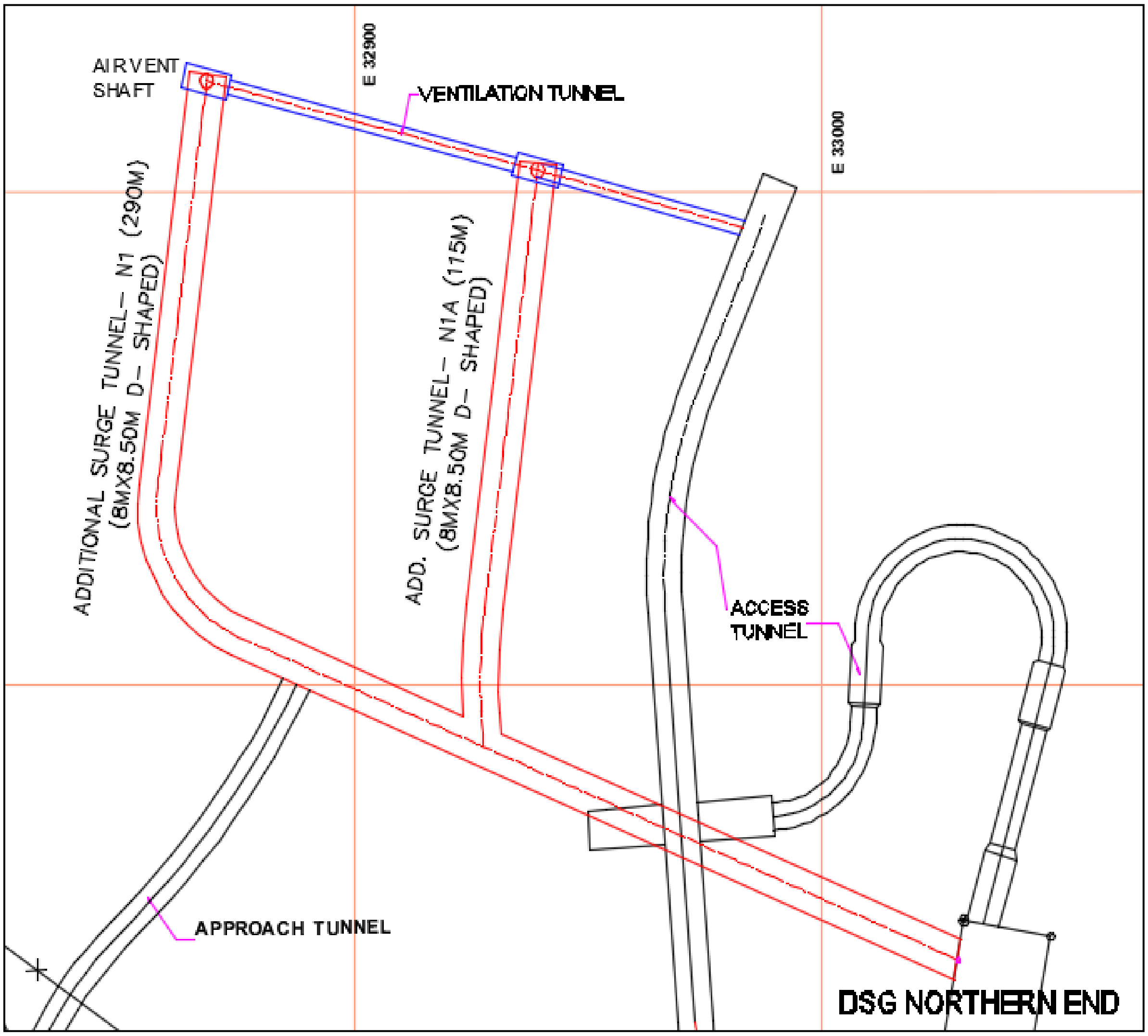

Fig. 12: Additional Surge Tunnel Layout Plan AT DSG Northern End

4. Conclusions

1. The primary objective of this revised hydraulic transient analysis is to restore the hydraulic stability of the Downstream Surge Gallery (DSG) after the cavity formation and consequent abandoning of the middle portion of the DSG for about 155m, which resulted in about 48% reduction in the volume of the chamber.

2. In order to compensate for the lost volume, additional surge galleries have been provided on both sides. In the Southern side (where 4 DTs are joining), the additional gallery area required is **9600 sq.m** (plan area) and in the Northern side (where 2 DTs are joining), the additional gallery area required is **3240 sq.m** (plan area). These additional areas has been provided from **EL 573m to EL. 581.50m sloping at nominal gradient (1 in 150) towards Downstream Surge Gallery (DSG).** These has been provided in the form of tunnels of D Shape on both sides. The planning and construction of these additional galleries has been carried out considering the site conditions and geology.

3. The **maximum up surge level is EL. 599.63 m** occurring in Northern Surge Gallery (ST1) corresponding to load case 110-0-33 (UP). This level is less than the gate platform level of EL. 608.5m, by 8.87m. The maximum up surge level in the Southern Surge Gallery (ST2) is **EL. 595.65m.**
4. The **minimum down surge level is EL.573.23 m** in Northern and **EL. 572.93 m** in Southern Surge Gallery, corresponding to load case 66-110-0 (DOWN). As the top of draft tube opening in the DSG is at EL. 571m, the water cover above the draft tube is around 2 m even during the worst down surge condition. This satisfies the codal requirement and is acceptable.
5. The load acceptance by 2 turbines only is considered simultaneously. The balance units are to be started subsequently (either one or two turbines at a time), providing sufficient time gap. The critical time shown in the summary of results shall be kept in view.
6. Since the layout of downstream surge system is complex having two surge tanks (North and South side) and additional galleries and also many input parameters are used in the transient analysis, it is suggested to carry out **physical model studies** for confirming the extreme surge levels under different load cases.

References

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