Hydraulic Model Studies for Removing the Sediment Deposition in the Existing Tail Race Channel by Creating Turbulence: A Case Study.

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***Abstract**: The study includes Hydropower project which is a run-off-river Hydro Power Plant having high head located in Himachal Pradesh, India. It has two power generation units with separate tail race tunnels. Tunnels converge into single tunnel at point around 60 m d/s of power house. It is having closed loop water cooling system for the heat exchanger units placed in the tail race tunnel just downstream of draft tubes. The present arrangement is experiencing heavy sediment deposition around heat exchanger units which is affecting its performance and efficiency. Physical hydraulic model studies were conducted at Hydraulic Laboratory, to assess the flow conditions in tail race tunnels for effective removal of the deposited sediments by creating turbulence in the vicinity. The studies indicated that due to the step in the layout of the tail race tunnel, low velocities and return eddy currents persisted in the vicinity of heat exchanger units. This was the measure cause for deposition of sediments. In order to remove the deposition of sediments automatically different alternatives were studied on the model, such as, increasing the invert level of the tunnels, changing the location of heat exchanger units, reduction in width of tunnel. The studies indicated that none of the above-mentioned alternative was effective in removing of deposited sediments. These observations indicated that increasing the turbulence in the vicinity of heat exchanger units was the key to effectively remove the deposited sediments. As such many structural interventions, having arrangement of tees and beam in the upstream and downstream vicinity of heat exchanger were studied on the model. A combination of tee and beam arrangement at specific location was found to be most effective for entire removal of deposited sediments. The solution was cost effective, permanent in nature and would not require any maintenance. The model studies demonstrated that how efficient and effective solutions be obtained without any ambiguity.*

***Keywords:** Tail Race Tunnel, Heat Exchanger, Froude's Similitude, Discharge, Sediment Deposition.*

1. Introduction

One of the Hydro power plant located in the Himalayan ranges in India is having two power generation units consisting of Pelton turbines. The net head is very high and the design discharge for each unit is 12.6 Cumec. The maximum power intake discharge when both units are generating 120% of rated capacity, is about 32 Cumec. The hydropower plant has a closed loop type water cooling system for the turbine and generator. Two heat exchangers, one for each unit, were installed in the tail race and submerged in tail race water. The Heat Exchanger (HE) was placed in the depression at the start of the tail race with a reverse slope after the turbine pit. Figure 1 gives detailed layout plan and section of cooling water system arrangement. The water inflow from the rivers has a high sediment load in the monsoon months. It is observed during past years that, the sediments were getting deposited around the heat exchanger which was affecting its efficiency. Photograph 1 below shows the sediment deposition in between the econocoils of the heat exchanger.

The insufficient cooling in the Heat Exchanger raised the temperature of circulating water in the close loop system which ultimately results in increasing the bearings temperature. Sometimes the temperature reached so high that load on the machine had to be reduced forcefully. Right from the time when silt accumulation around heat exchangers has been observed, it has been seen that most of the silt is accumulated on the right bank of heat exchangers. The size of this accumulated sediment is more than 500 microns including small medium size pebbles. This can be attributed to the clockwise rotation of the runner. Because of clockwise rotation, most of the water left the runner was forced towards the left side of the heat exchanger and thus there was no or less accumulation of silt. On the other hand, due to less velocity of water on the right-hand side of the heat exchanger, the heavy silt, shingles, and pebbles were not carried away with the water into the tail race tunnel. Photograph 2 shows the heavy deposition of sediment on the right-hand side of the wall. To solve this problem, project authorities were planning some modifications like relocating Heat Exchangers or raising the level of heat exchangers. To know the effect of these suggested modifications and to assess the suitability of any other alternatives, physical model studies were proposed and carried out at Infraplan Hydraulic Laboratory, Pune.

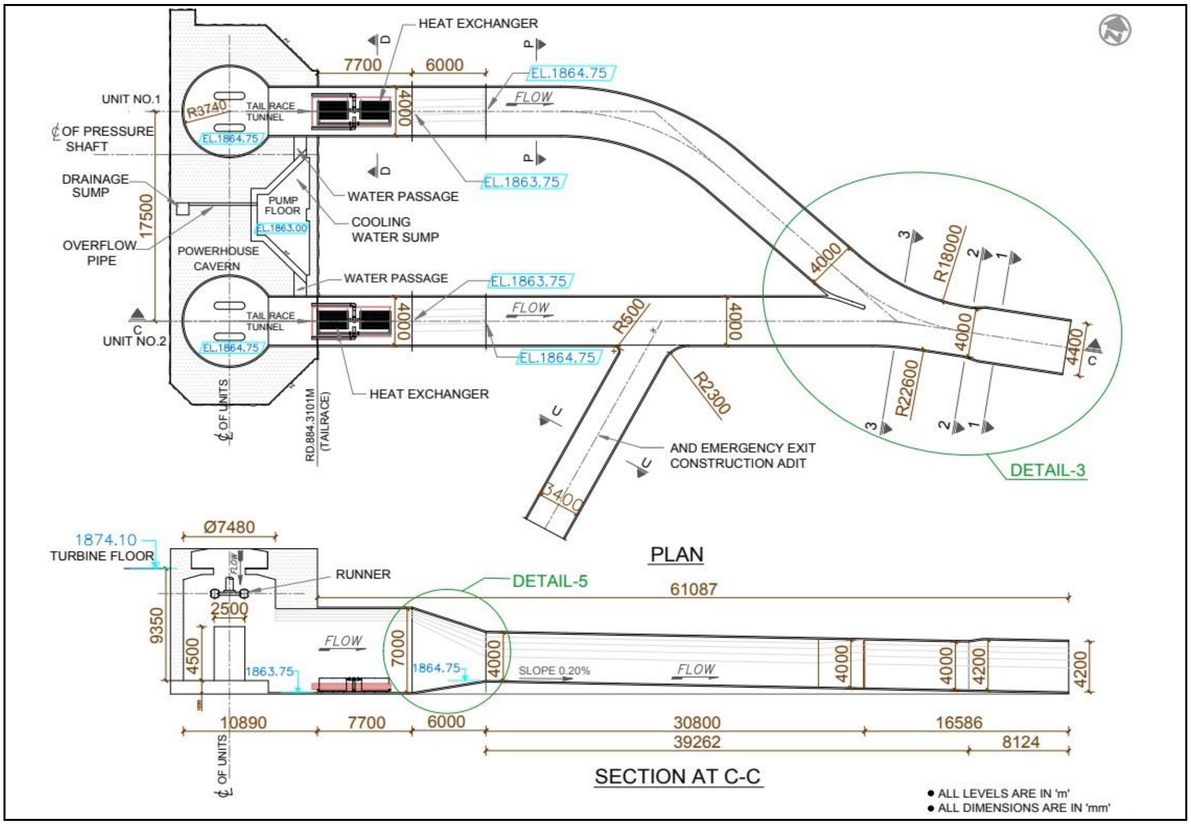


Figure 1. Layout plan and longitudinal section of Cooling water system arrangement in the tail race tunnel at the HPP

Photograph 1. Sediment Deposition in between econocoils of heat exchangers

Photograph 2. High Sediment Deposition on RHS of wall in TRT

2. Physical Model

To visualize and analyze important aspects of the system properly, an appropriate scale is necessary. In the present study, various scale ratios were analyzed to come up with the most feasible model scale. After giving a thorough consideration, it was decided to construct a geometrically similar (undistorted) Comprehensive Physical Model for Qualitative Studies of the Tail race tunnel as per Froude's similitude to the scale of a 1:10. A physical model reproducing the two Tail Race Tunnels converging into single tunnel, along with Heat Exchanger Unit of HPP was constructed and set up at Infraplan Hydraulic Laboratory. The total length of tail race tunnel reproduced was 65 m. It mainly comprises of following components;

1. Tailrace tunnels from two units along with a junction on the downstream.
2. An ADIT connecting to tailrace tunnel of 2nd unit
3. Heat Exchanger Units.

The tailrace tunnel was constructed in the Transparent Perspex to visualize the flow condition and the sediment deposition pattern around the heat exchangers. Heat exchangers were constructed using Mild Steel plates as shown in Photograph 3 and 4. The model layout is presented in Figure 2.

Photograph 3. Whole Model Set-up at Laboratory

Photograph 4. Heat Exchanger units reproduced out of Mild Steel

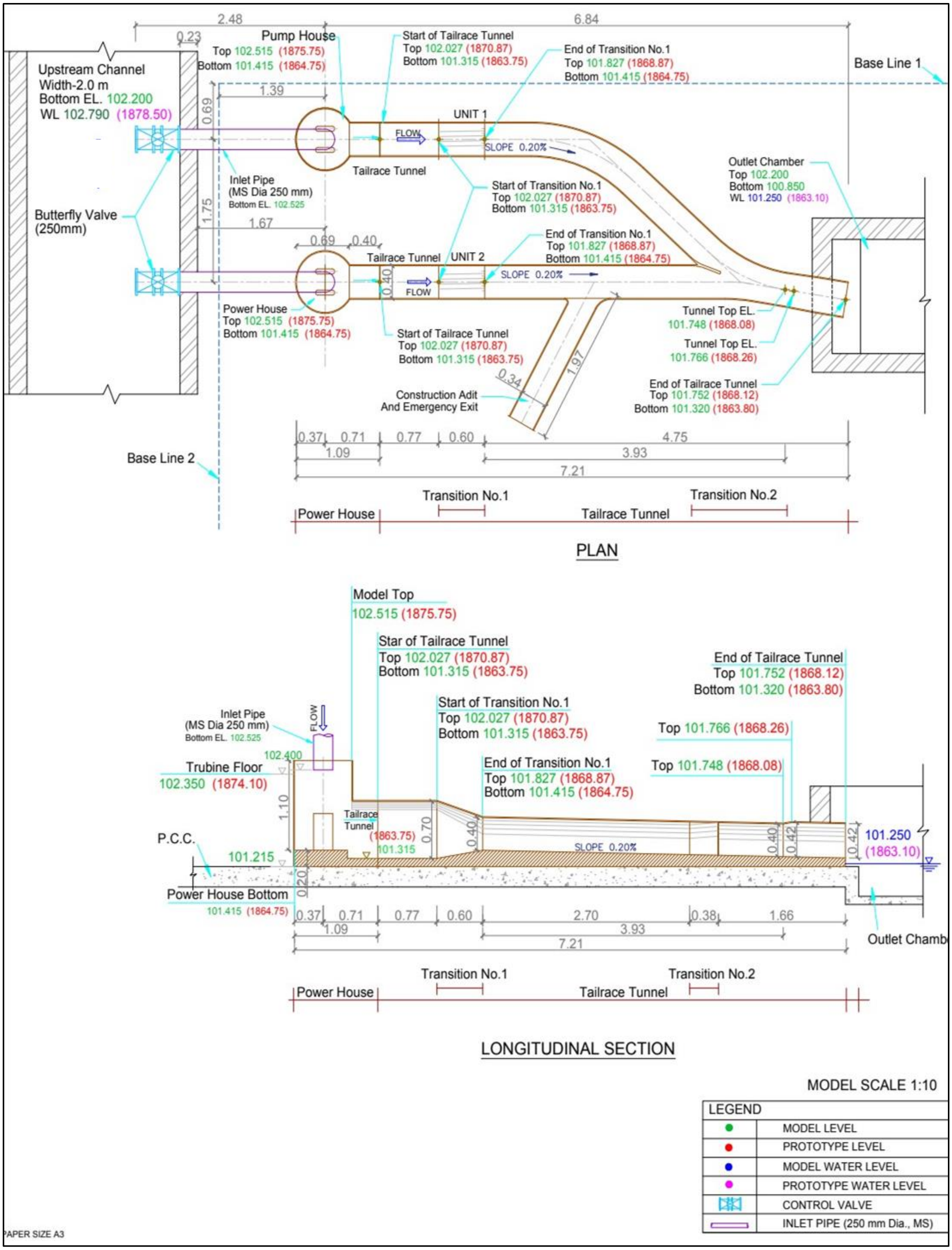


Figure 2. Model layout plan of tailrace tunnel of HPP

2.1. Sediment Simulation

Sediments used in physical hydraulic model should have equivalent properties as that of sediments found at an actual prototype. This similarity is necessary for the model to demonstrate actual sediment behavior depicting the prototype. Following discussion presents the approach adopted in sediment simulation for Tail Race Tunnel model studies. Einstein and Chien suggested that similar sediment movement can be achieved in both the prototype and physical model, only if the similarity is established in all the dimensionless parameters of the Shield's entrainment diagram. Refer Figure 3. When employing this approach, dimensionless parameters such as the Froude number, Particle Reynolds number, and Shields parameter are commonly involved. Nevertheless, achieving similarity between the physical model and prototype requires model distortion. In the absence of distortion in the models, selecting a sediment size that matches with the sediment transport parameters becomes challenging. One of the Important parameter is model-simulated ‘shear stress’ to assess sediment mobility in the model. The sediment movement for a specific particle size depends on the condition that, the boundary or bed shear stress τ_b is higher than thecritical shear stress τ_c, i.e., $\tau_b > \tau_c$. This criterion solely establishes the potential mobility of a particular particle size, indicating the likelihood of sediment movement or transport. The critical shear stress for particle motion was determined using equation (1), while Shield's diagram shown in Figure 3 was utilized to evaluate sediment movement.

$$\tau_c = \theta^*(s-1)\rho g d_{50} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,

τ_c = Critical Bed shear stress,N/m^2
θ^* = Dimensionless Shield’s Parameter of given particle size,
s = Specific gravity of particles
ρ = Density of water, kg/m^3
d_{50}= Mean particle size, m

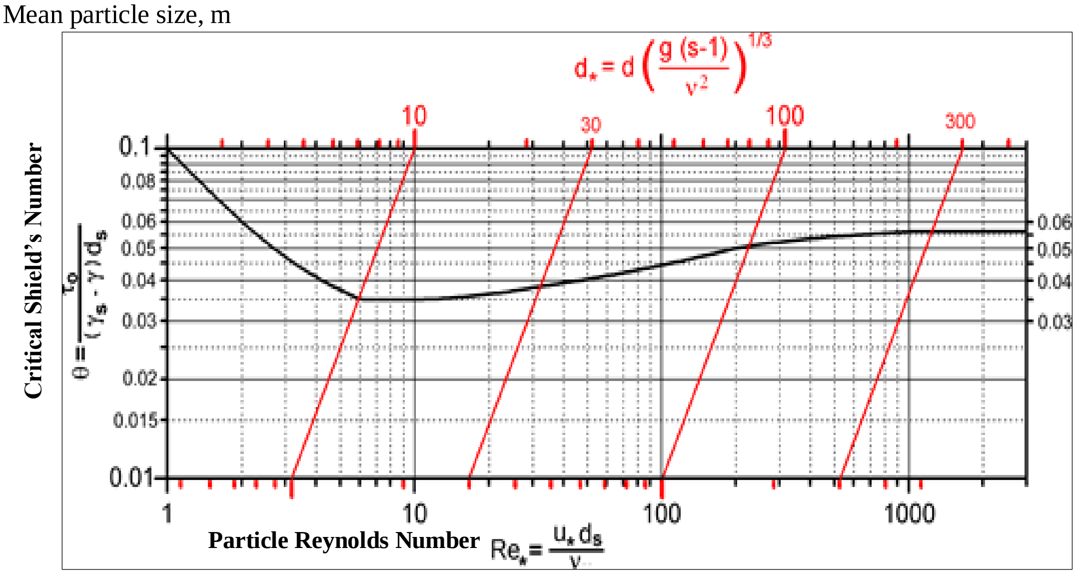


Figure 3. Shield’s Diagram for sediment incident motion

Where,

d	Grain diameter	w	Density of water
u	Velocity	τ	Wall shear stress
u_*	Shear velocity	θ	Shields parameter (index c, critical Shields parameter)
v	Settling velocity	ν	Viscosity
s	Density of sediment	μ	Friction coefficient

The following approach was adopted to simulate the sediments in view of the proposed studies and based on the suggestions given by Hunter Rouse and C. A. Pugh. The fall velocity is simulated for the model particles. The fall velocity for actual prototype sediments were calculated and scaled down to model velocities. The model particle diameters are chosen so as to reproduce the required fall velocity in the model. Two different materials have been compared for sediment simulation. Primarily the sand having specific gravity of 2.65 was used to simulate the required fall velocity. Alternatively, the coconut shell powder having specific gravity of 1.2 was used. The Table 1 shows the required particle sizes of the sand as well as coconut shell powder.

Table 1. sediment diameter estimation for sand and coconut shell powder for sediment simulation (fall velocity approach)

Sr. No.	Proto dia., mm	% fine	% finer	Fall velocity, Prototype, m/s	Fall velocity, Model, m/s	Model Particle Dia., mm (Using Sand with Sp.Gr. 2.65)	Model Particle Dia., mm (Using coconut shell powder with Sp.Gr. 1.2)
1	32.00	1	100	0.588	0.186	3.25	26.50
2	16.00	2	99	0.415	0.131	1.70	13.25
3	8.00	5	97	0.293	0.093	0.90	6.75
4	4.00	15	92	0.206	0.065	0.55	3.50
5	2.00	25	77	0.144	0.046	0.35	1.85
6	1.00	25	52	0.098	0.031	0.25	1.00
7	0.50	15	27	0.062	0.020	0.17	0.60
8	0.25	7	12	0.033	0.011	0.12	0.37
9	0.13	3	5	0.012	0.004	0.07	0.20
10	0.06	2	2	0.003	0.001	0.04	0.10

Extensive studies have been carried out to find the suitability of material and the sand was found to be the best option for simulation. Detailed studies conducted for using Coconut Shell Powder and results for particle sizes of 5 mm and below were very promising. However, in order to reproduce particles of 5 mm and above, it was not feasible with Coconut Shell Powder, as the required diameters were more than 6 mm and upto 26.5 mm as seen from the above table. As such it was considered to study the sediment deposition with keeping in mind due uncertainties in simulation of the sediments. The detailed studies indicated that the sand is suitable for simulating the particle movement in the model. It is concluded that the sediment material sizes proposed in the model are heavier and larger than the required sediment properties. The studies conducted with this gradation curve indicated that the sediment deposition pattern was adequately simulated in the model. The very similar deposition pattern was observed in the model for the design discharge. It may be mentioned here that simulation is very qualitative in nature. However, they are very good for assessing the efficiency of the alternatives that were studied on the model for flushing of sediments in the vicinity of the heat exchangers. The fall velocities for the prototype and model diameters shows very good match. The fall velocities for the higher sizes model diameters were little below the required values. This ensures the sediment deposition in the model.

Subsequently, to evaluate the sediment movement further trials were carried out. Following parameters namely, 1) Critical boundary shear stress, 2) shear velocity and dimensionless parameters, 3) Grain Reynold number and 4) Shield's parameter, were calculated for prototype as well as model grain sizes. The shear velocities were calculated for comparing expected velocity and actual shear velocity of modelled sediments. The comparison shows in Figure 4 demonstrates a good match for larger diameters. For lower diameters the actual shear velocity of model particles was higher than the required. It ensures that the model sediments were moved at higher velocities than prototype and movement observed in the model is always on safer side to predict the prototype behavior.

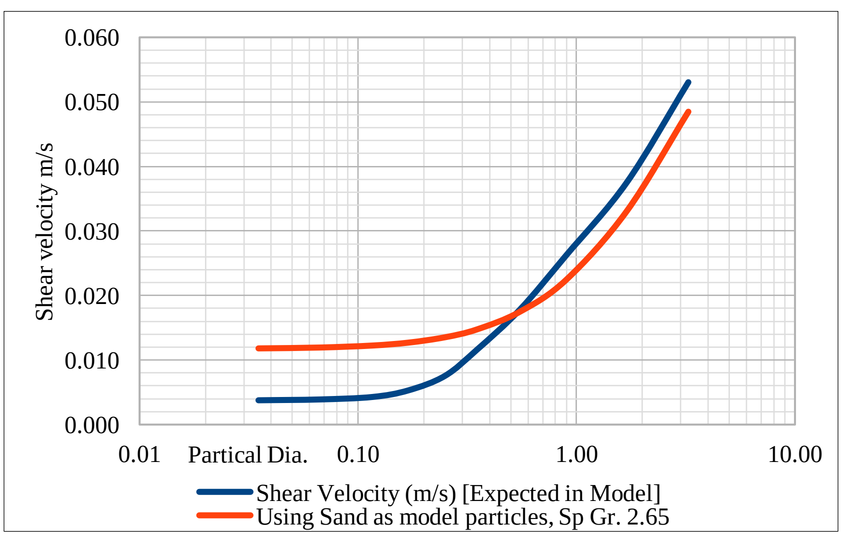


Figure 4. Shear Velocity Comparison

2.2. Model Calibration

Calibration of the model with respect to the known hydraulic phenomena is necessary to validate the model results. For this purpose, the prototype measurements were used for water levels in the tail race tunnel. These measurements were recorded by project officials at 10 m downstream of confluence of TRT units, for three different discharges with the help of a camera installed on the opposite wall of the Tail Race Tunnel. As per the data supplied, the water levels were measured when Unit No.-1 was in operation. When unit-1 was running, the water levels were matching with prototype observation, on the right side of the tunnel, whereas, along the left side of the tunnel water level was lesser than anticipated due to high velocity flow was passing, which can be attributed to geometry of the junction. Subsequently, the water levels reproduced in the model for three different discharges were found satisfactory and the model calibration was achieved successfully.

3. Model Studies

Heavy sediment deposition around the Heat Exchanger Units is the main cause of concern of this study. It was observed that on the downstream side of the heat exchanger, the flow velocities were very low. That made particles to settle down in this area. A very similar pattern of silt deposition was observed in the model as per the prototype. Various alternatives were suggested and analyzed to effectively remove the deposited silt. It mainly includes raising of platform, reducing the width of tunnel and changing current position of Heat Exchanger units. Table 2 describes the different alternative scenarios considered to conduct the detailed experiments.

Table 2. Various Alternatives suggested for effective sediment removal

Scenario/ Alternative	Provision of Jacketing	Increase in floor level by 750mm	Reduction in width of tunnel by 0.5 m	Finishing width of tunnel	Change in location of HE	Location of HE from u/s end of CL of Powerhouse	Provision of Tee and Beam
Present Scenario	Yes	No	No	4.0 m	No	7.22 m	No
Scenario 1	Yes	Yes	No	4.0 m	No	7.22 m	No
Scenario 2	Yes	Yes	Yes	3.5 m	No	7.22 m	No
Scenario 3	No	No	No	4.0 m	Yes	21.85 m	No
Scenario 4	Yes	No	No	4.0 m	No	7.22 m	Yes
Scenario 5	No	No	No	4.0 m	No	7.22 m	No
Scenario 6	No	No	No	4.0 m	No	7.22 m	Yes
Scenario 7	No	No	No	-	Without Heat Exchanger		No

Present scenario reflects the actual conditions prevailing at site i.e. present location and arrangement of Heat Exchanger. It is seen that lower velocities around the Heat Exchanger causes heavy sedimentation in its vicinity. Such silting in the vicinity of heat exchanger hampers the working of heat exchanger affecting its efficiency. To eliminate the silt deposition, various trials have been conducted on the model. In the first step, when the floor was raised by 750 mm as suggested by project authorities, the sediment deposition was reduced by large extent and sediment removal was achieved. Further decreasing the width of the tunnel by 0.5 m also improved the sediment removal. However, in these cases, the velocity of the flow increased considerably. Consequently, submergence of the heat exchanger was reduced due to the raised floor and the efficiency of heat exchanger was getting hampered. Owing to this, an alternative was needed which would help removing the silt effectively without affecting heat exchanger’s efficiency. This gives rise to idea of removing sediments through a turbulence created by some structural arrangement. After changing the location of Heat Exchanger as suggested project authorities, so that upstream face of Heat Exchanger is located at downstream of invert slope. In this case, very large amount of sediment deposition is observed due to the obstruction created by placing of Heat Exchanger unit. The sediment removal is also not possible as very low velocities are observed. Also, submergence of Heat Exchanger is not maintained, which may affect its working considerably. Hence, this scenario is not feasible.

Various alternatives were tested to achieve effective flushing of silt. Various structures were introduced and tested on the model to create the turbulence for silt removal. Out of the alternatives tested, the one which shows the good results was with Tees and Beam. Two Tees were introduced at the upstream and downstream vicinity of Heat Exchanger. The Beam at Centre portion at top of heat exchanger was also introduced. The floor height and tunnel width were unchanged and jacketing was kept intact as it is. To create turbulence near heat exchangers unit, a thought was given to the tee like arrangement at the upstream and downstream of the heat exchanger and a beam located at the middle of the heat exchanger. Refer Figure 5.

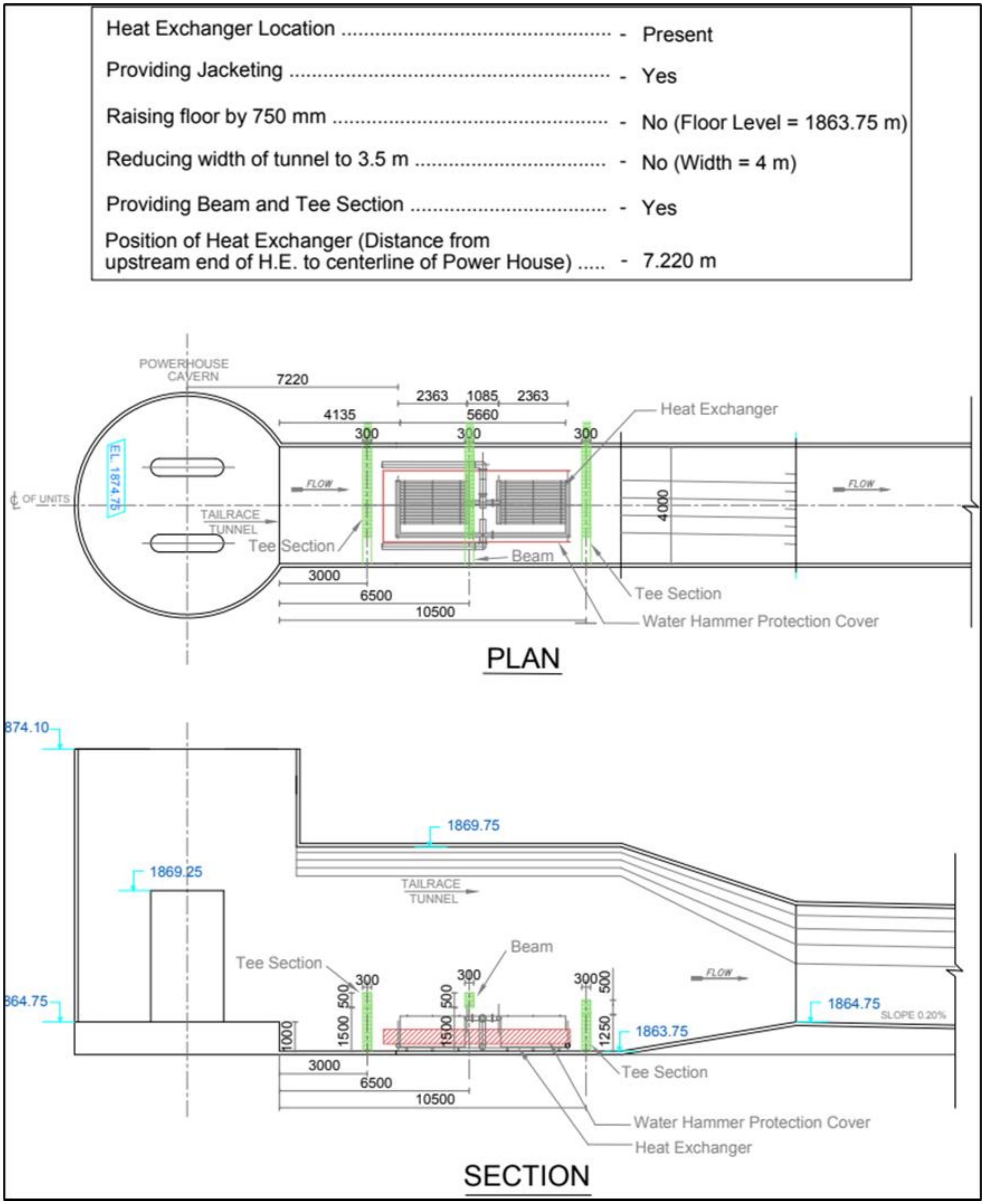


Figure 5. Remedial measures/ scenarios

An experimentation program was carried out to simulate the above-mentioned scenarios, alternatives and various combinations of the suggested measures under these scenarios. Total of 12 experiments were carried out on tailrace tunnel unit 1 and unit 2 by introducing the tees and beam structure. As per literature study, in Himalayan region in general, 3000 ppm sediment load is considered for design of desilting chamber. Based on this assumption, it was considered that at maximum 50% of this sediment load i.e.,1500 ppm would be entered into each power intake unit. Accordingly, sediment load is calculated for the model design discharge. For each experiment, to start with, the model was run for about 60 min, which corresponds to 190 minutes for prototype with sediment injection. After such heavy sedimentation, silt gets deposited in the near vicinity of Heat Exchanger units as well as other parts of the tail race tunnels, such as near confluence of Tail Race Tunnel of Unit 1 and Tail Race Tunnel of Unit 2. Then another run was carried out with clean water to flush out the deposited silt for maximum 60 mins, which corresponds to 190 minutes for prototype. Water surface profiles are obtained for each experiment. During each experiment velocities were measured with the help of current meter on the upstream, downstream and middle cross-section of the heat exchanger to understand velocity distribution around the heat exchanger units, refer table 3 and 4 for velocity profile of present scenario and proposed scenario, after introducing Tees and Beam arrangement. Photographs 5 to 10 were recorded showing flow conditions during sedimentation along with the sedimentation pattern observed on LHS and RHS of model as well as condition after flushing on LHS and RHS of the model and are presented below.

The sediment movement is mainly associated with the boundary shear stress around the individual sediment particle. This boundary shear stress is mainly function on the turbulence rather than the forward velocity of the flow. Thus, to initiate the sediment movement, the turbulence around the heat exchanger shall be increased. When the turbulence is increased at the sides or bottom of the tunnel, the incipient motion shall prevail and deposited silt shall get washed away. Extensive experimentation was carried out on the model so as to generate the turbulence in the vicinity of the heat exchanger. To create turbulence near Heat Exchanger units, a thought has given to the Tee like arrangement at the upstream and downstream of the heat exchanger and a beam located at the middle of the heat exchanger.

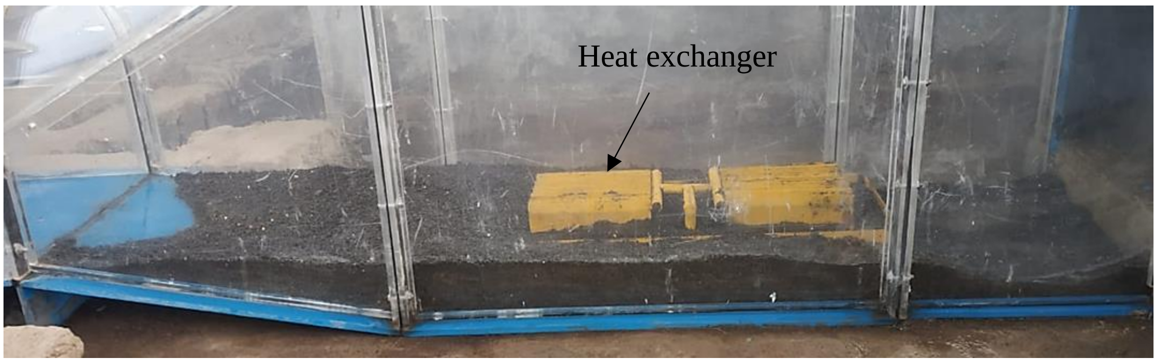
The detailed studies indicated that this arrangement was very useful in creating required turbulence and thereby flushing of all the sediments in the vicinity of Heat Exchanger unit. Satisfactory results were obtained for the model studies carried out, even though sediment material size in the model was little heavier and larger than the required size and gradation of the sediment. Proposed arrangement was very much effective in removing the deposition of silt. Even at very high sediment load, very less amount of silt gets deposited. Subsequently deposited silt gets washed away quickly when the sediment load reduces. Proposed beams may be in the form of steel sections and can be fitted on the sides and bottom of the tunnel. Such an arrangement was introduced previously by us in the project in Bhutan in order to eliminate deposited silt and to achieve uniform flow conditions after construction of the tunnel. Its size can be optimized and even the holes can be provided so as to reduce the drag forces. Further this arrangement ensured that efficiency of Heat exchanger units is not hampered. There are no moving parts or mechanical machinery requirement for this solution. The proposed arrangement was tested with 30% lower and 30% higher discharges and satisfactory results were obtained. It was observed that, the silt removal efficiency increased with increase in discharge. When the proposed scenario was tested without jacketing in place, time required for desilting was lesser. Since removal of jacketing may have heat exchanger units prone to get damaged due to water hammer effect and thus it was recommended not to remove the jacketing.

Table 3. Velocity profile for present scenario

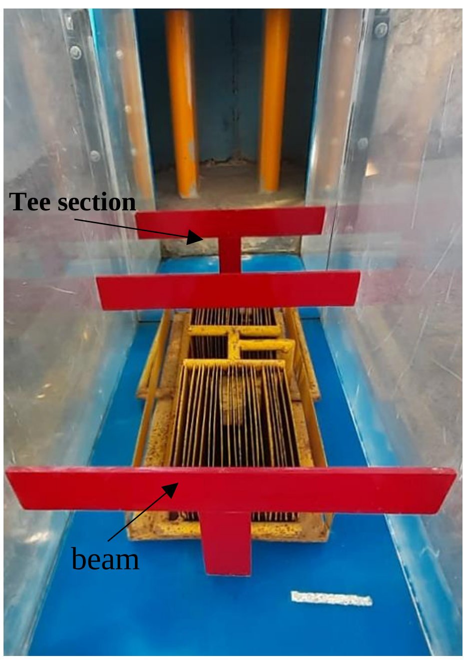
Location of Heat Exchanger			Present		**Tailrace tunnel Unit**		2nd		
Provision of Jacketing			Yes		**Increase in Floor level**		No		
Provision of Beam & Tee section			No		**Reduction in Width of tunnel**		No		
Discharge: 12.6 Cumec			**Velocity Profile**						
	On Upstream of HE			**At middle of HE**			**On Downstream of HE**		
	L	**C**	**R**	**L**	**C**	**R**	**L**	**C**	**R**
0.2d	1.21	2.36	2.22	2.34	-	2.43	2.17	2.29	2.43
0.6d	0.55	1.06	1.06	0.91	-	1.78	0.45	0.12	0.79
0.8d	0.55	0.55	0.34	-	-	-	0.03	0.01	0.24
Mean Velocity	1.10			1.87			0.95		

Table 4. Velocity Profile for proposed Tees and Beam arrangement

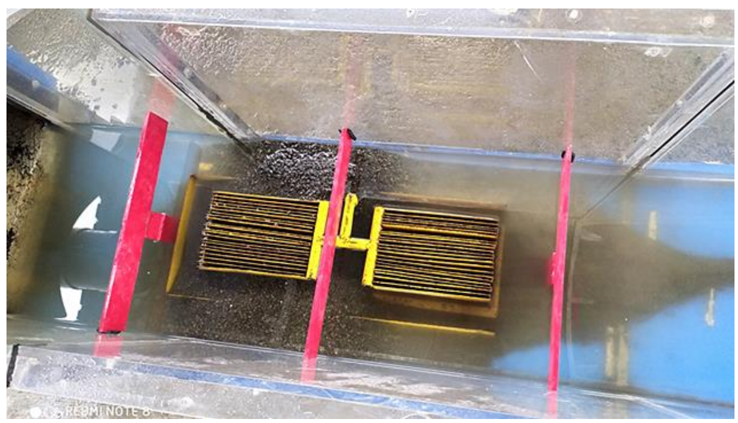
Location of Heat Exchanger	Present			**Tailrace tunnel Unit**			2nd		
Provision of Jacketing	Yes			**Increase in Floor level**			No		
Provision of Beam & Tee section	Yes			**Reduction in Width of tunnel**			No		
Discharge: 12.6 Cumec	**Velocity Profile**								
	On Upstream of HE			**At middle of HE**			**On Downstream of HE**		
	L	**C**	**R**	**L**	**C**	**R**	**L**	**C**	**R**
0.2d	1.06	1.33	1.34	1.53	-	1.27	2.49	2.09	1.83
0.6d	0.53	0.64	1.43	0.63	-	1.06	0.11	0.12	0.06
0.8d	0.07	0.16	0.16	-	-	-	0.37	0.01	0.59
Mean Velocity	0.75			1.12			0.85		



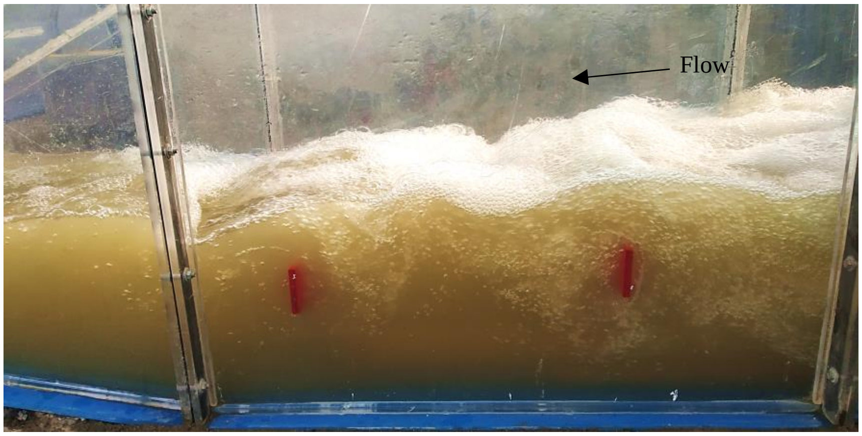
Photograph 5. Sediment Deposition Pattern Observed, left hand side of model



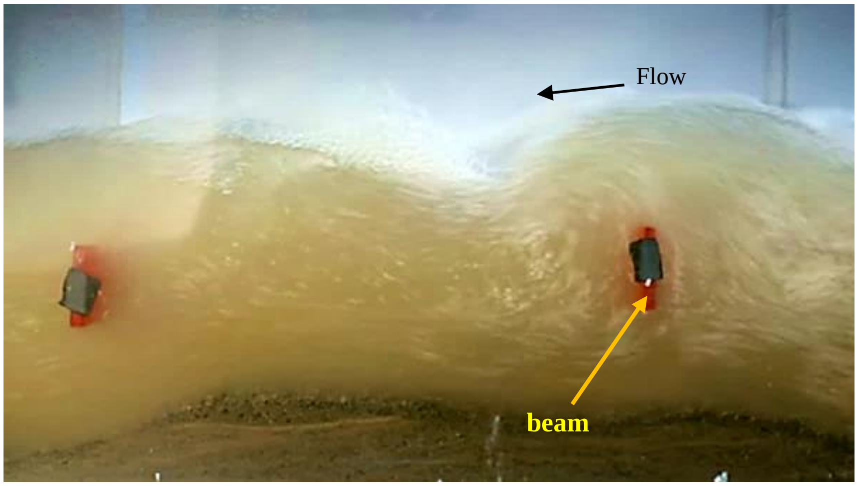
Photograph 6. Front view of model showing Tees, Beam and Heat exchanger unit


Photograph 7. Top view of proposed arrangement in Model


Photograph 8. Flow pattern observed after introducing of Tees and Beam

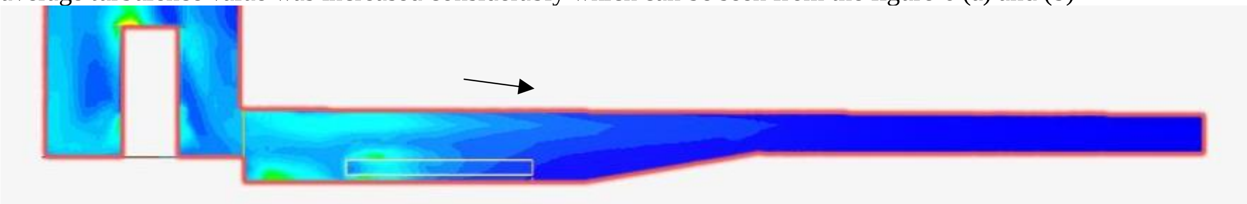


Photograph 9. Movement of sediment due to turbulence due to Tees and Beam



Photograph 10. Movement of sediment due to turbulence created due to Tees and Beam

Subsequently, the mathematical model was prepared in Computational Fluid Dynamics (CFD) software. The results showed the increased turbulence due to addition of Tees and beam structure. The following Figure 6 indicates the CFD results showing turbulence profile at the longitudinal cross section along the sides of heat exchanger units. The average turbulence value was increased considerably which can be seen from the figure 6 (a) and (b)



(a) Present Scenario

(b) After introducing Tees and Beams

Figure 6. CFD studies for TRT showing increased turbulence after introduction of Tees & beam

4. Conclusion

The deposition of sediments was occurring in the vicinity of heat exchanger units in the tail race tunnel. The physical hydraulic model studies were undertaken on a geometrically similar model of 1:10 confirming to Forundian Similitude, to understand the flow conditions around the heat exchanger and evaluate the effect of different remedial measures to be undertaken. Various scenarios studied included measures like increasing the floor level height, reduction in width of tunnel, removing the jacketing and changing the location of heat exchanger units. The detailed model studies indicated that, there is no need to increase the overall average velocity in the vicinity of heat exchanger by any such arrangement. However, some arrangement is required to increase the turbulence in the vicinity of heat exchangers, so as to bring the sediments into suspension and wash away. Various structural interventions were analyzed for this purpose. The arrangement of tees and beam as shown in Figure 5, positioned upstream and downstream and at top of heat exchanger units, was found to be most effective. It is recommended to construct tees and beams as shown in Figure 5, in structural steel sections properly anchored to the floor and side walls. The holes can be provided in the steel beam and tees so as to reduce the drag forces and introduce more turbulence. Such type of arrangement would be cost economical and convenient.

5. Acknowledgment

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