Innovative solutions for the development of the 1410MW 5th Hydropower Extension Project at Tarbela Dam, Pakistan

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Abstract

Tarbela Dam on the River Indus is one of the largest rock and earth-fill dams in the world and was constructed in the 1970s primarily to provide water for irrigation. During Tarbela's subsequent operation, its role in providing hydropower generation has become more significant. As a result, successive hydropower stations have been added to the irrigation water release tunnels over the last few decades. Recent studies have been undertaken to assess the potential for hydropower generation on the 5th tunnel. Unlike the other tunnels, the 5th tunnel is situated within the left abutment of the dam and was never envisaged for power generation. Thus, converting it for generation has presented a unique set of challenges. Many of these challenges particularly relate to its location between two large spillways, their associated plunge pools and a common discharge channel known as the Dal Dara channel. The proposed designs for the scheme uses an innovative approach to maximise energy production, ensuring similar levels of generation comparable to the other Tarbela stations, whilst combining a buildable design with continuing safe operation of these large spillways.

1. Introduction

Tarbela Dam on the River Indus in Pakistan was commissioned by the Water and Power Development Authority (WAPDA) in the mid-1970s primarily as a water resource reservoir for irrigation and was at that time the largest rock and earth-fill dam in the world. During Tarbela's subsequent operation, its role in providing hydropower generation has become more significant. As a result, successive hydropower stations have been added to the water release tunnels over the subsequent decades. Power stations on tunnels 1 to 3 currently provide 3,478MW of installed capacity. Currently, the 1410MW 4th Hydropower Extension Project (4EP) is being constructed on the 4th tunnel. These power plants utilise tunnels through the right abutment of the dam which discharge directly to the Ghazi Barotha headpond – a headpond formed by the downstream hydropower scheme which effectively forms a constant tailwater level for the four right-bank power stations.

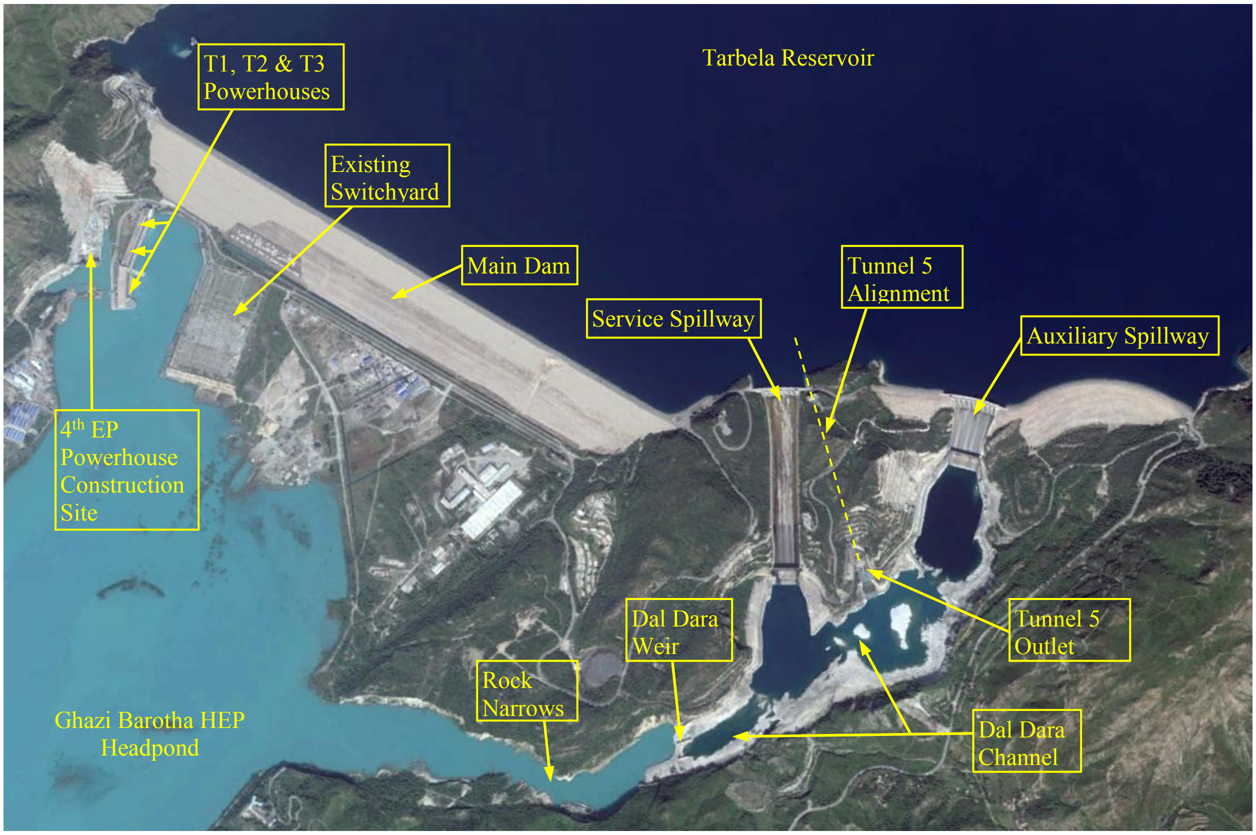

Fig. 1. Aerial view of Tarbela Dam showing key structures.

Unlike the other tunnels, the fifth release tunnel (T5) is situated within the left abutment of the dam and was never envisaged for power generation – only for irrigation release. Thus, it was situated at a higher level than the other tunnels and discharges into the Dal Dara channel. This channel also receives the discharge from Tarbela's two spillways (with a combined design flow of 47,000m^3/s) and conveys this water, along with any T5 release, to the Ghazi Barotha headpond, to join the rest of the Indus flow.

2. Background and need for the Project

As mentioned above irrigation demand remains the primary purpose of Tarbela and with over 60% of Pakistan's population still employed in the agricultural sector this remains a dominant need. If the 5th Extension Project (5EP) is to go ahead as smoothly as possible the irrigation release capabilities of the scheme must not be put at risk. During the high flow months of July to October the flow in the Indus River is much higher than can be passed through the existing generating facilities and the remainder is discharged through the irrigation discharge tunnels (like Tunnel 5) or over the spillways. Whilst this release fulfils the irrigation demand, it provides no power benefits. The economic analysis undertaken during the 4th Extension studies demonstrated that, as the majority of the infrastructure (dam, tunnel etc.) was already in place, the construction costs were relatively low resulting in short pay-back periods. Hence, a brief review of the hydrological and cost data associated with installing generation on Tunnel 5 was prepared during the 4th Extension studies which confirmed the economic viability of the scheme.

2.1. Energy generation situation in Pakistan

The Tarbela 5EP proposes to add 1410MW of additional generation capacity to the existing 4,888MW capacity currently installed or being constructed at the Tarbela Dam site in Pakistan [1]. The majority of this additional power produced will be in the July to September period when demand on Pakistan's power network is at its highest. Current comparisons of summer demand against summer generating capacity shows a shortfall, with resultant load shedding being a constant reality. With the power demand of the national system forecast to increase at an annual average growth rate of 4.8%, there is an extensive capital program to increase supply which includes the 5EP.

2.2. Sedimentation and Raised Intake

Since commissioning in the mid-1970s, Tarbela reservoir is progressively filling with sediment. Figure 2 shows a bathymetric survey of the lower part of Tarbela reservoir undertaken in 2012 [2].

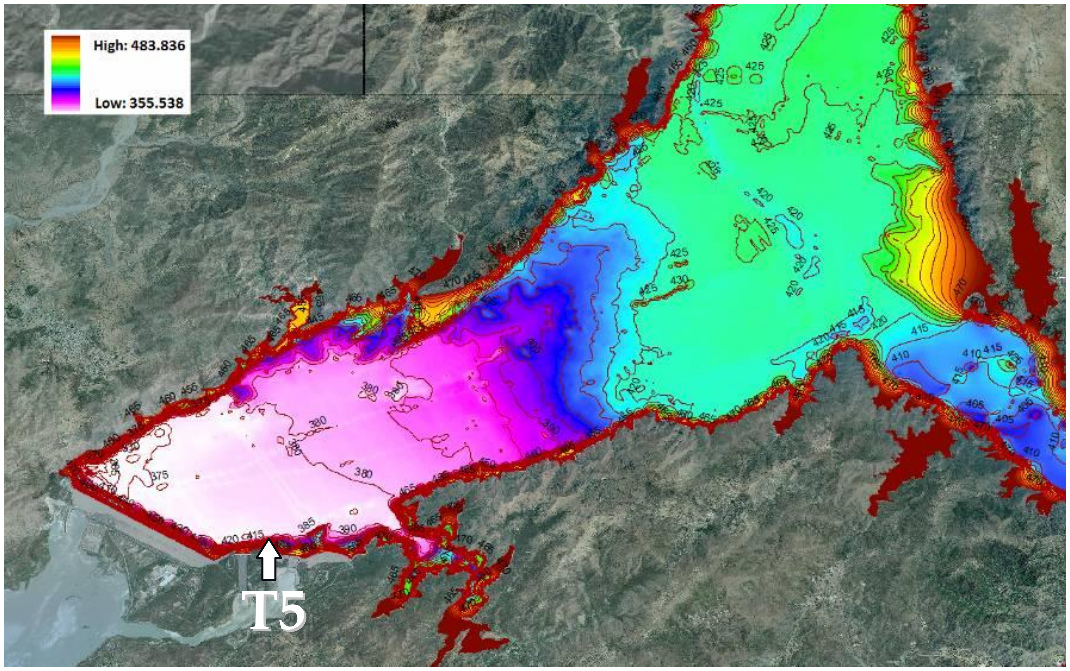

Fig.2 Bathymetric survey of Tarbela Reservoir (2012) showing the distance of the sediment delta from the dam.

It can be seen how the sediment delta is encroaching towards the dam face, with the 5th tunnel intake (marked with an arrow) being closer to the encroaching sediment delta than the other tunnel intakes on the right bank. The studies for the 5EP therefore evaluated the future suitability of the existing intake to maintain a reliable supply of water to the power station considering the sediments and delta encroachment on the intake area. The experience gained through the development of the 4EP proved useful given its similarity. For the 4EP, it was decided that a raised intake would be constructed on both tunnel 3 and 4 to mitigate, in the short-medium term, the risk of the intake becoming blocked due to sediment and the impact this would have on energy generation. Hence, a raised intake on tunnel 5 was also considered, recognising the more challenging location required for constructing this intake due to the proximity of the service spillway approach channel and steeper slopes around a potential raised intake location (this is further discussed in Section 3.1 below).

3. Proposed project layout and associated challenges

The overall project layout is shown in Figure 3, with the various key project components further described below [3].

3.1. Geology

The 5EP area is occupied by the Kingriali Formation consisting of thin to thick beds of dolomitic limestone, phyllites and quartzites. Basic igneous rock (dolerite/diabase) is also present as sills and dykes in the area; one thick and massive intrusion of dolerite is exposed along the right side of the spillway channel. It is on this that the powerhouse excavation is situated.

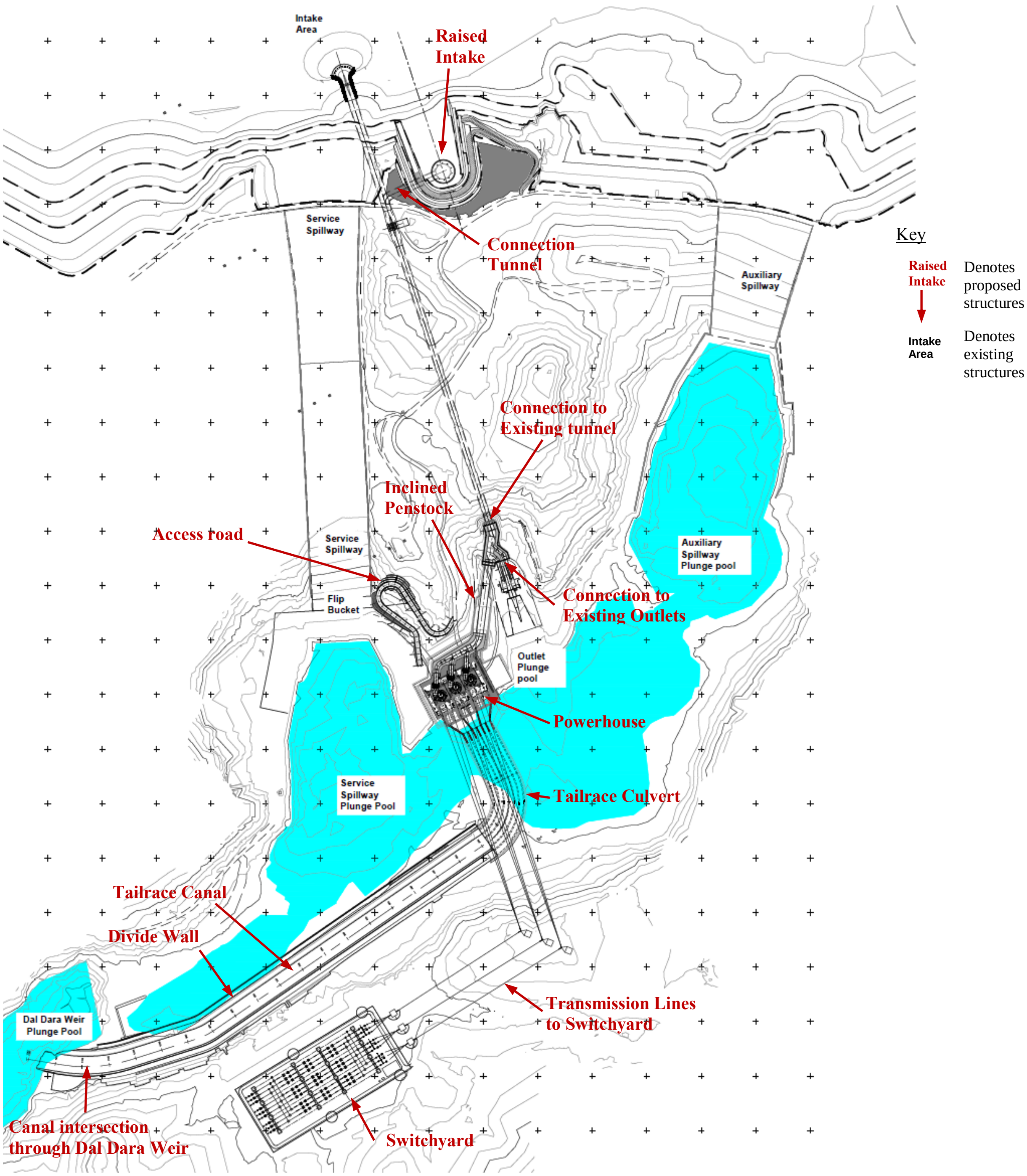

Fig. 3 Project layout and scheme components.

3.2. Intake

WAPDA have proposed that the raised intake at Tunnel 5 will be taken forward to tender design and constructed at the same time as the other 5EP works; however, the raised intake could be delayed for 10 years or more (depending upon how quickly the sediment delta approaches which in turn depends upon how the reservoir is operated),

Figure 4 shows the components of the raised intake which include:

- Radial intake concrete superstructure

- Bellmouth shaped approach
- 13m diameter drop shaft
- 13m diameter connecting tunnel
- Connection piece to the existing 13m diameter tunnel

The location of these structures is also shown in relation to the existing structures in Figure 4. The intake would be located with a sill level of El 421m (which raises the intake slightly over 58m) in an excavated section of the left bank slope. The excavation will require the removal of about 1.3 million cubic metres of rock and is envisaged as a surface excavation, this requiring sloping benches to provide access ways to facilitate this. Construction risks have been assessed with particular attention to issues that have been experienced during the construction of the raised intake of the 4EP. Further investigation of the geology around the intake structure is required, but initial indications show challenging conditions within various types of limestone which are moderately to highly conductive.

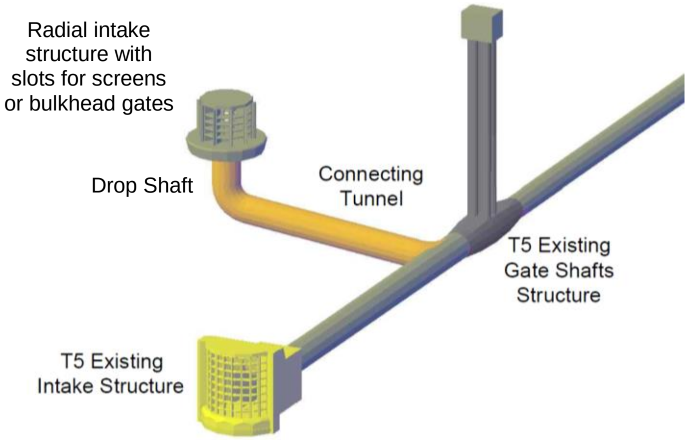

Fig. 4. Raised Intake schematic showing existing and new structures

Unlike the new raised intakes for tunnel 3 and 4 which are situated directly above the tunnels, the 5EP raised intake is offset from the tunnel and requires a vertical drop shaft plus a connecting tunnel to connect the raised intake. This is because of the proximity of the Service Spillway which potentially competes with the raised intake for flows. A 3D model using a Computation Fluid Dynamic (CFD) programme was used to check that flow paths were reasonable with the proposed arrangement in various flow configurations and that there were no issues that could potentially have negative consequences on the operation of the various hydraulic structures. Figures 5 and 6 show example outputs from the model, with Figure 6 confirming that the flow streamlines are acceptable for operation of the intake at the same time as operating the Service and Auxiliary Spillways.

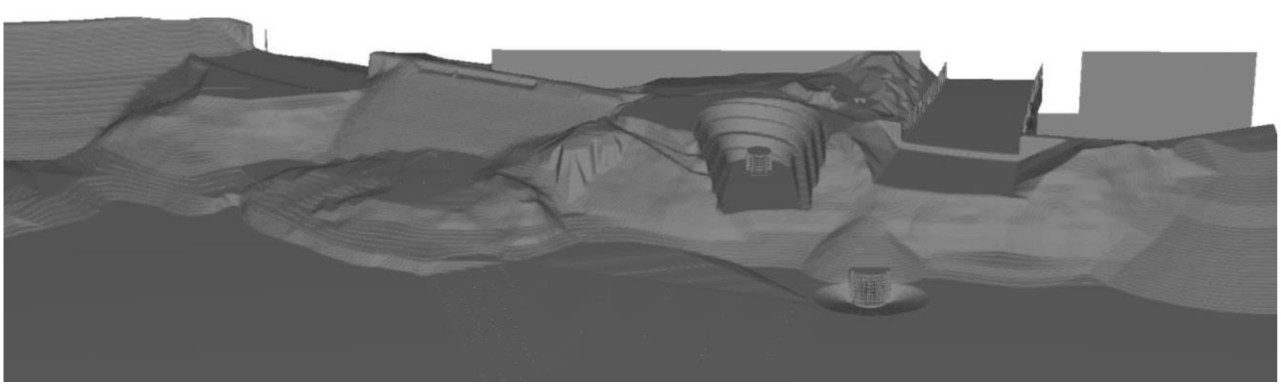

Fig. 5. Raised Intake 3D perspective view from Flow3D model – looking from the upstream side.

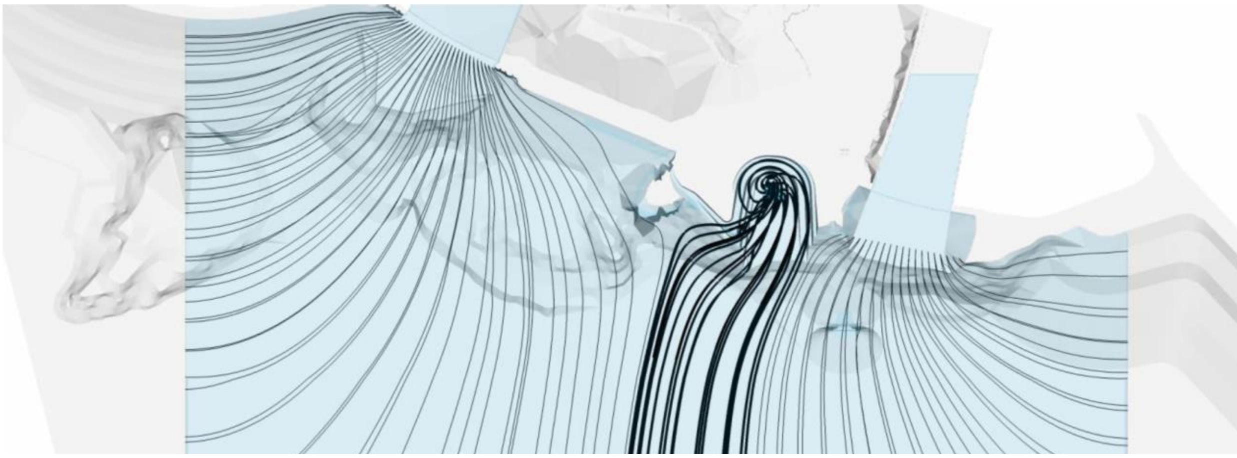

Fig. 6. Flowlines showing operation of Raised Intake along with both spillways (from Flow3D model).

3.3. Penstock and Low Level Outlets (LLO) connection

Figure 7 shows the penstock arrangement which has similarities to that being constructed for the 4EP, being a 13m diameter pipeline with branches to the three turbines, a spare relief valve and two branches to LLO gates. Analyses of various penstock, powerhouse and tailrace culvert/canal alignment options were undertaken. One of these options was similar to the 4EP design and would replace the existing LLO structure with a completely new powerhouse structure that would include new LLO. However, an economic analysis showed that a solution retaining the LLO was more favourable. Figure 6 below show the envisaged connecting penstock that would have branches connecting to the existing LLO structure (see connecting transitions in black). The penstock initially has an expansion section from 11m to 13m diameter to reduce headlosses through the various bends and bifurcations. The base case design proposes the majority of the new penstock to be buried in a deep trench that runs from a new cut-back Tunnel 5 outlet portal to the rear of the powerhouse. An alternative proposal with a similar estimated cost places the majority of the penstock within a tunnel excavated upstream of the powerhouse. The tunnelled arrangement reduces excavation quantities and the thickness of the powerhouse rear wall but due to complexity of works is not the currently preferred solution.

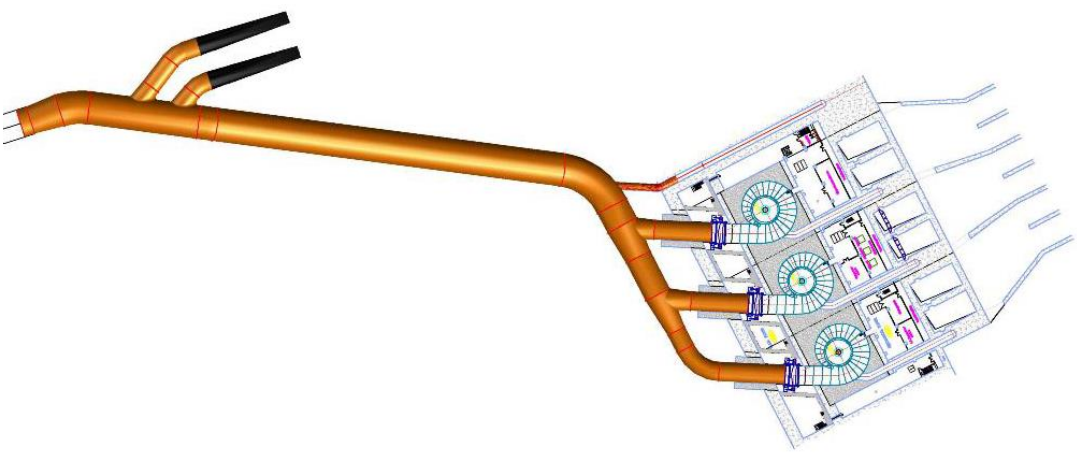

Fig. 7. Plan of the proposed connecting penstock.

CFD was undertaken along the penstock length to predict their hydraulic performance, estimate headloss, examine flow lines and test for cavitation. The penstock bifurcations to the LLO were carefully designed to reduce the potential for cavitation. However, results showed that at the most extreme flow release there would be pressure fluctuations from a non-steady element of flow that show a cavitation potential would exist. Since use of the LLO in the future will only normally be used for flushing, a slightly reduced flushing flow of 2100m^3/s is recommended which removes the cavitation risk.

3.4. Powerhouse

Figure 8 below shows a cross section through the penstock and powerhouse. The generating units for the 5EP will be similar to those for the 4EP, as a result the general internal layout of the mechanical and electrical equipment will be broadly similar. However, there are several notable design differences that will affect the overall structure. The installation of the tailrace culvert and canal (to maximise available head) results in a unit setting elevation that is similar to 4EP. This setting of the turbine is lowered to a point where the turbine centre line is approximately 50m below current ground levels and the foundation of the powerhouse would be 80m below ground. With the greater depth, there are more floors within the powerhouse. This allows greater flexibility in the location of auxiliary and balance of plant and means the offices and admin blocks and workshop are located within the powerhouse structure below the access level at EL 371m.

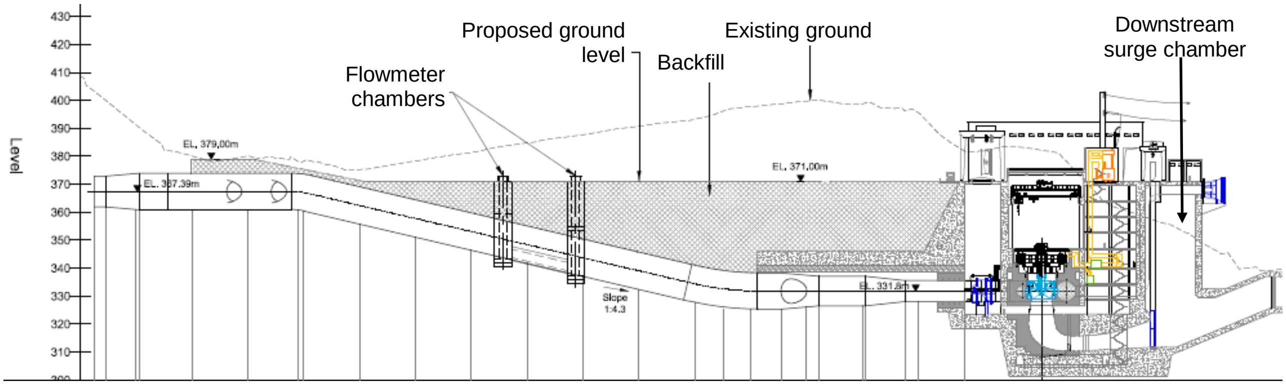

Fig. 8. Section through penstock and powerhouse.

Due to the depth of the powerhouse an additional transfer crane has been specified to bring equipment from a loading floor at EL 371m to the upstream side of the main powerhouse and lower it onto a more standard loading bay at floor level EL 347m. To reduce the length of the powerhouse, the transfer crane rails will run perpendicular to the main station crane, with loading bays on either side of the erection bay.

The tailrace culvert also requires a downstream surge chamber which will be located immediately downstream of the draft tubes and integral with the powerhouse structure. This will result in a large access platform above the surge chamber on the downstream side of the powerhouse structure.

The powerhouse excavation will mainly be within the basic igneous intrusive dolerite, which is known to be a competent rock suitable for founding the powerhouse. However, further ground investigations (GI) are required to determine the full extent of this dolerite and also to identify the properties of the surrounding limestones and quartzites. Following this additional GI it is envisaged that further optimisation of the powerhouse arrangement can be achieved to further reduce construction risk and costs. One area of optimisation that has been identified relates to the way the penstock connects to the powerhouse. The preferred option of installing the penstock in an open excavation results in a large, deep excavation upstream of the powerhouse. The backfill surrounding the penstock manifold will need to be supported by an upstream powerhouse retaining wall. The size of this retaining wall will depend on the height and type of backfill used. The size of the retaining wall will be minimised if the backfill height is minimised leaving a void upstream of the powerhouse structure. There is the possibility of installing the penstock manifold within a tunnel, thereby bringing the upstream excavated face closer to the powerhouse. This could reduce the space between the excavated slope and the powerhouse to a point where it is viable to completely fill the void with concrete, creating the powerhouse upstream wall. Either the open excavation or tunnelled option are deemed feasible and are estimated to have similar cost. To minimise underground works and associated risk, the open excavation has been retained as the base case for the detailed design. The tunnelled option may however be considered at a later stage according to the ability and preference of the contractor. Also, if the open excavation for the penstock is adopted, there may be a possibility to use value engineering studies to determine other powerhouse layout that could result in reduced cost.

3.5. Tailrace

The proposed powerhouse is located on the Dal Dara channel between the service spillway and existing LLOs upstream of the Dal Dara weir. The weir acts as the main hydraulic control in this section of the channel to ensure adequate water levels in the spillway plunge pools. Consequently, water levels upstream of the weir are significantly higher than those immediately downstream. A long tailrace culvert/channel is proposed that hydraulically connects the 5EP turbine draft tubes to Ghazi-Barotha headpond downstream of the Dal Dara weir utilising this additional head to provide additional generation (see Figure 3). The main components of the tailrace are a buried reinforced concrete box culvert leading from the powerhouse underneath the Dal Dara channel to the left bank, a concrete lined canal connecting the culvert to the Ghazi-Barotha headpond and a dividing wall that runs along the right bank of the canal, separating canal flows from the main channel.

It is estimated that the proposed tailrace culvert and canal will provide up to an additional 11.3m of head resulting in on average 236GWh of additional energy annually when compared to a scheme without these tailrace structures – more than justifying the additional cost.

Consideration was given to the height and profile of the concrete divide wall that separates the tailrace canal from the rest of the Dal Dara channel. A balance was required when choosing the divide wall height between the cost of the structure verses the additional energy produced from retaining flow separation at higher flows. Also, the Dal Dara channel capacity must be maintained for the mid to high flood events. By allowing the divide wall to over top, there is increased capacity along the combined Dal Dara channel and tailrace canal at these high flows. Following analysis, a divide wall that would overtop only 3% of the time was found to achieve the best balance. This represented a Dal Dara channel discharge of around 2,500m3/s, with a further 1,385m3/s being the culvert/canal discharge capacity. The final proposal for the concrete lined tailrace canal is for an 11m water depth, 32m base width and design velocity of 3.3m/s. The height of the divide wall varies from a few metres to more than 15m. The canal side slope (0.8 horizontal to 1 vertical) on the right side continues into the divide wall to allow for a varying foundation level and for spill flows to cascade down this face. There is a vertical face on the Dal Dara channel side of the divide wall. The left side slope of the canal is proposed at 1 horizontal to 4 vertical.

In addition to the additional energy, the tailrace culvert and canal also provides significant operational flexibility between the powerhouses. Since the 5EP powerhouse will have a similar efficiency to the other powerhouses (since they will all have the same gross head) then during part flows, the flows can be divided through each tunnel in order to minimise overall project headloss thus improving operational efficiency. Other additional benefits have also been envisaged - such as more easily providing peaking power. Also, by running the 5EP more continuously, there will be less chance of the intake becoming blocked by sediment since it will have some flow continually flushing the intake.

3.6. Electrical and mechanical

Since the available head and flow are similar to that of the 4EP, the specification of the generating units is similar; three vertical Francis generating units each of 470MW rated capacity, 461.7m design discharge and 110m design head.

To limit the upstream pressure transients, a pressure relief (flow bypass) valve will be installed on the spiral case of each unit, with an additional common valve on a separate dedicated penstock branch. The size of these valves will be confirmed during the detailed design; however, it is expected that, due to the lower allowable overpressure of T5 compared to T4, larger valves will be required - in the order of 3.5m diameter.

Each generator will connect via isolated phase bus ducts to three single phase banked transformers located outside on the powerhouse downstream platform. Overhead lines will then connect to the outdoor switchyard on the opposite bank of the Dal Dara channel.

4. Conclusions and Next Stage

This project offers Pakistan an opportunity to install hydropower at a very low unit cost due to the use of existing infrastructure, in this case Tarbela Reservoir and Dam, Tunnel 5, the Dal Dara channel and support infrastructure. The additional power produced will mainly be in the monsoon season, but this is when Pakistan experiences significant power shortages. As such, this is a very desirable and economic project, but one that faces some unique challenges. Additional investigations are planned to further assess some of the challenges outlined in this paper to reduce costs and risks before tendering is undertaken.

Acknowledgements

The author would like to thank Water and Power Development Authority for their cooperation in this project and for permission to present this paper.

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The Author

Brian B. Darling is a chartered civil engineer with 26 years' experience in the renewable energy, water and environment sectors. This experience comprises the study, detailed design and site supervision of various civil engineering works, including hydropower, river engineering, dams, water supply and irrigation projects. Technical specialties include the mathematical modelling experience in the fields of hydrology, hydraulics, water quality and financial analysis models. As a project manager, he has been responsible for leading multidisciplinary teams covering engineering, environment, economics and commercial issues. This has included being the Team Leader for the design studies for the Tarbela 5th Extension Hydropower Project. He has widespread geographic experience including 11 years continuously outside of the United Kingdom, living and working in South Asia (Nepal and Pakistan) and Africa (Uganda, Tanzania, Ghana and South Africa).