Construction of the Spillway for Nam Theun 1 Hydropower Project

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Abstract

The Nam Theun 1 Hydropower Project is located on the Nam Kading River, approximately 220 km from Vientiane in Laos. The Nam Kading River will be impounded in a narrow gorge with a 187 m high curved Roller Compacted Concrete (RCC) gravity dam.

The water from the storage reservoir will be conveyed along a 610 m long power tunnel in the left abutment to a shaft powerhouse before it is returned to the Nam Kading River. The shaft powerhouse has an installed capacity of 650 MW (2x 260 MW EGAT units for export to Thailand and 1x 130 MW EDL unit for the domestic market) with the need to have physically separated units and power transmission lines in the absence of a synchronized grid between Thailand and Laos.

The 187 m high curved RCC dam consists of thirty four blocks in total. In the centre of the dam, the spillway will occupy seven blocks constructed ahead of the right RCC abutment blocks with access through the left abutment due to the spillway and the six large 20.0 m (W) x 17.30 m (H) radial gates being on the critical path. A bottom outlet conduit, sized to enable the reservoir to be drawn down and maintain the water level below the invert of the power intake to allow for inspection, is foreseen in the centre of the dam below the spillway block No.4.

The Nam Theun 1 spillway is designed to pass the very large peak inflows of the Nam Kading River up to the Probable Maximum Flood while only benefiting of a limited flood retention capacity of the reservoir. In addition, there are no saddles along the reservoir rim where auxiliary spilling structures could be located. Sitting the spillway on the abutments, as would be unavoidable with an embankment dam, would require a huge volume of excavation and high rock faces needing protection, as well as large concrete structures. Therefore, only a gated spillway designed as an integral part of the RCC dam, with floods being spilled through six massive bays located in the central part of the dam crest and conventional down a steep chute on the downstream face, ending in a ski-jump bucket terminating in different elevations was found economically feasible for this Project.

However the selected layout is seen to be optimal for the specific characteristics of the Project site, the final design consisted of a real technical challenge given i) the very high design peak floods and velocities along the chute, ii) the very high PGA values calculated at the spillway trunnion for the Safety Evaluation Earthquake about 150 m above the foundation level and forces transmitted by the largest radial gates constructed in Laos PDR, iii) the tight gorge of the valley and the steep slopes (between 30^o and 40^o) at the dam axis location and iv) the likely continuous operation of the spillway for long periods during the rainy season, the spillway had to be designed for.

The layout of the flood release structure including the geometry of the pre-excavated plunge pool at the dam toe has been justified by a detailed hydraulic analysis at the planning stage and confirmed during Project execution by a series of comprehensive hydraulic laboratory model tests. The structural analysis of the spillway gates, ogee, piers, trunnion support, chutes and flip bucket has been performed using 3D finite elements methods.

The RCC placing activities and the installation of the bottom outlet are currently proceeding and the civil works at the spillway flip buckets have recently commenced. The spillway facilities including the concrete works and the erection of the six radial gates are expected to be substantially ready for impounding and subsequent testing and commissioning by the onset of the rainy season 2022.

1. The Nam Theun 1 Hydropower Project

The Nam Theun 1 Hydroelectric Power Project is located in the Bolikhamxay Province in central Laos on the Nam Kading River, approximately 33 km upstream of its confluence with the Mekong River and 220 km from Vientiane. The Nam Kading River is one of the major tributaries of the Mekong River, with a catchment area of 13,856 km^2 at the dam site. The Nam Kading River will be impounded in a narrow gorge with a curved gravity RCC dam.

The Nam Kading River will be impounded in a narrow gorge with a curved gravity dam. The dam is of curved Roller Compacted Concrete (RCC) gravity type and its maximum elevation difference between the foundation and crest is 187 m. The spillway is located on the central part of the dam crest. The probable maximum flow is rated at 30,200 m^3/s and will be regulated through six gated bays located in the central part of the dam crest designed with conventional chutes on the downstream face, ending in a ski-jump bucket terminating in different elevations.

The reservoir provides around 2,020 Mm^3 of usable storage at Full Supply Level and water from the storage reservoir will be conveyed along a power waterway with a pressure shaft in the left abutment to a shaft powerhouse before it is returned to the Nam Kading River to produce about 2,560 GWh/year, 80% of the power being fed into the grid of the Electricity Generating Authority of Thailand (EGAT), while the remaining 20% is supplied to Electricité du Laos (EDL).

An overview of the project arrangement is shown in Figure 1.

Fig 1: Nam Theun 1 project layout

2. Project set up and responsibilities

The overall project has been divided in various distinct contracts covering also the early works and environment and social works. A snapshot of the relevant contracts for the spillway along with a brief description of the awarded works are as follows:

- Contract A: Civil and hydro-mechanical works (1999 FIDIC Red Book)
- Contract B: Electro-mechanical works and switchyards (1999 FIDIC Yellow Book)

AFRY has been contracted by the project Owner to act as his Engineer under FIDIC and was tasked to provide project management, contract administration, interfaces management, site supervision, design review of hydro-mechanical and electro-mechanical equipment, civil construction design and environmental and social services for the whole project.

From a design and engineering perspective, the above means that AFRY is responsible for the coordination at design level between contractors and for issuing fully integrated construction drawings to the main civil contractor who will then prepare the subsequent shop drawings.

3. Spillway components

The spillway of the Nam Theun 1 dam is an integral part of the dam structure. Floods will be spilled through six bays located in the central part of the dam crest and discharged down through six separate chutes terminating in different elevations. The flow regime of Nam Kading River means that the spillway will be in continuous operation for several weeks of most years.

The narrow river gorge at the dam site limits the space available for the arrangement of the spillway into the dam body and the dam was curved for hydraulic purposes but also to improve the structural performance in case of an earthquake event . The alignment of the dam across the river in plan has been given in form of a circular arc. The non-overflow sections of the dam have been given a radius of 700 m, while the middle overflow section of the dam has been given a radius of 500 m as shown in Figure 2. The selected smaller arch radius of the central part of the dam will help in directing the flow from the spillway towards the middle of the river.

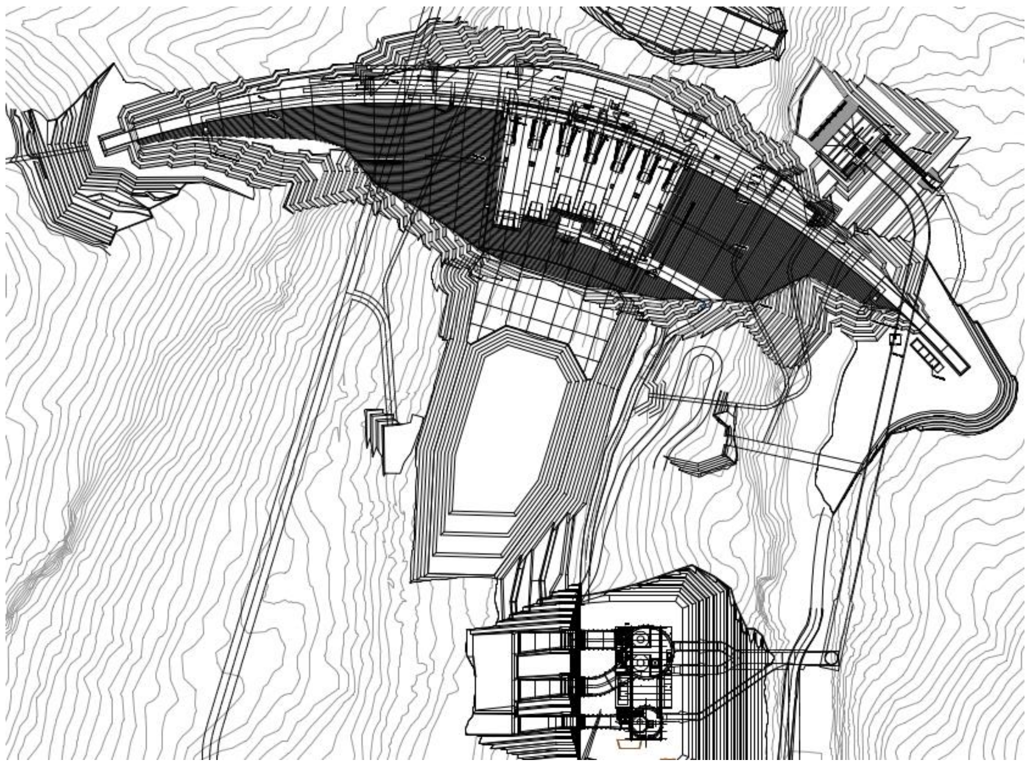

Fig. 2: Spillway and Dam layout

The spillway has been placed in the section of the dam which lies in the main flow section of the river to deliver the spilling discharge directly back into the river and the pre-excavated plunge pool without involving any major rock cutting along the banks. In order to accommodate all the jets from spillway bays inside the river, and also to avoid concentration of the jets in one single point, the chutes are terminated in different locations and various elevations for the bucket exit angles were selected. The proposed spillway structure comprises the following main components:

- A standard ogee-shaped overflow weir at the upstream end consisting of six independent bays with radial gates that controls the discharge rate and accelerates the flow. To improve approach flow conditions, curved wing walls are provided at both ends of the overflow weir.
- Six independent steeply sloping chutes with lateral guide walls and aeration slots where the flow velocity is accelerated.
- Six separate flip buckets at the downstream end of the chutes designed with dent blocks increasing the disintegration and breaking-up of the hydraulic jets that return the flow to the river after energy dissipation.

The spillway salient features are summarized below and a 3D rendering of the spillway is shown in Figure 3.

- Ogee crest elevation: 272.9 m a.s.l.
- Type and number of stoplogs: Sliding, 2 nos. (stored at the dam crest using a gantry crane)

- Type and number of gates: Radial, 6 nos. (2 nos. with flap gate, 4 nos. without flap)
- Size of gates (H x W): 20.30 m x 17.30 m
- Width of each chute: 17.30 m
- Number of piers: 5 middle piers + 2 side piers
- Width of the piers: 7.00-5.35 m (middle piers), 7.00-5.94 m (side piers)
- Slope of the chute (V:H): 1:0.75 (V:H)
- Dissipation: Flip buckets with dent blocks
- Radius of flip buckets: 25 m

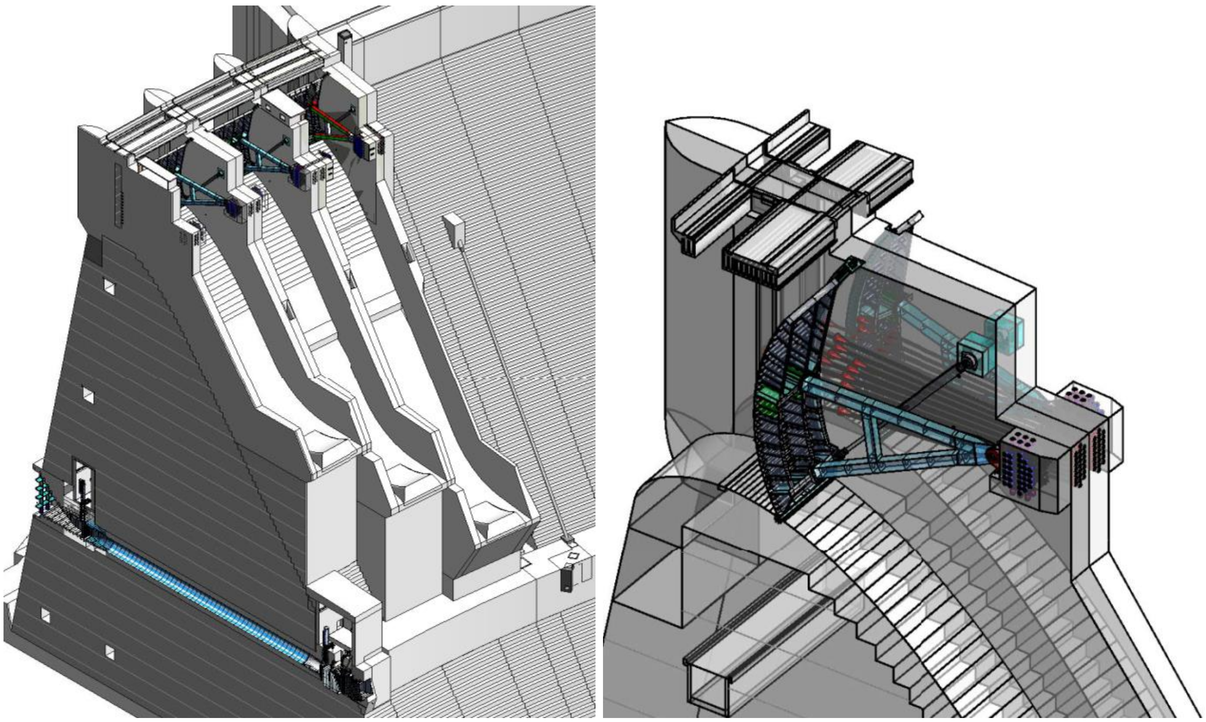

Fig. 3: 3D rendering of the Nam Theun 1 spillway

4. Spillway hydraulic design

For the hydraulic design of spillway, a theoretical analysis has been coupled with laboratory investigations. The preliminary theoretical analysis performed at planning stage is based on empirical formulae while the hydraulic studies of the spillway performance, jets and plunge pool performed during implementation were carried out using 1:80 (overall dam) and 1:60 (partial of three chutes) reduced scale physical models, adopting Froude similarity, built at the Asian Institute of Technology (AIT) in Bangkok, Thailand.

The spillway model, built in PVC was designed to accommodate modifications and several alternatives for the chutes and flip buckets (varying the lip angle and provision of dents). Erosion in the plunge pool was studied using a movable bed. To minimize the scour depths in the plunge pool, the spillway flip buckets were fitted with dents. The flow patterns for different alternatives of buckets are illustrated in Figure 4.

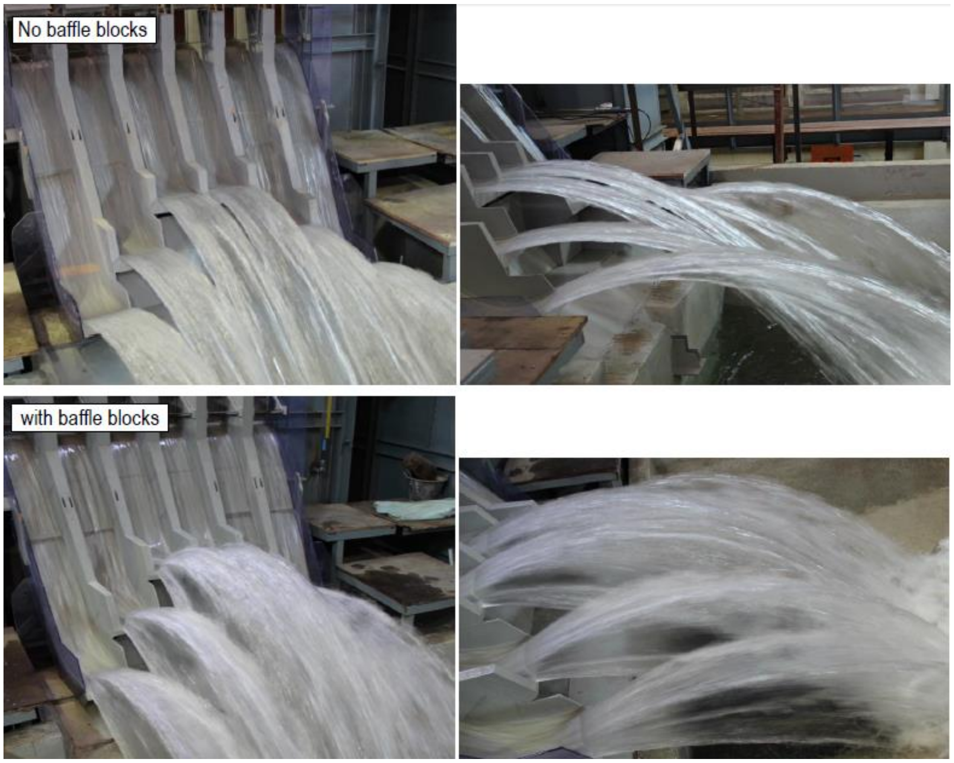

Fig. 4: Laboratory investigations (AIT, Bangkok)

The 1:80 overall model reproduces a part of the reservoir and of the dam, the entire spillway (sill, gates, chute, flip buckets), the plunge pool and the powerhouse tailrace together with a downstream river reach for implementing the downstream tailwater condition and was used for the design of the flip buckets and the pre-excavated plunge-pool.

The 1:60 partial model was used to accurately define water surface profiles, water depths, velocities and cavitation index along the chutes for the design floods and PMF through the fully and partially opened gates as shown in Figure 5. This information was used to confirm the hydraulic performance and the hydraulic shape of the ogee, determine heights of the side walls of the spillway chute, estimate the location of the chute aerators and define the various hydraulic forces applied to the chutes and the flip bucket as basis for the structural design.

Because the NT1 RCC Dam belongs to the high hazard dam category, and in accordance with the recommendations of the ICOLD Bulletin 125 "Dams and Floods. Guidelines and Case Histories, 2003), the 10,000-year flood was chosen as the design flood for the design of the spillway weir, chutes and dissipating structures, with a safety margin provided by the freeboard to pass the 10,000-year routed flood with 5 (6 -1) gates in fully open position. The NT1 dam was also been checked to pass a routed PMF (check flood) without overtopping. During the occurrence of the PMF, all gates were assumed to be fully open.

5. Spillway civil design

5.1 Coordination and interfaces management at design level

The main civil and hydro-mechanical Contractor has been contracted for the construction of the spillway. AFRY's responsibility included the design review of the hydro-mechanical works including the spillway radial gates, stoplogs and the gantry crane designed by the Contractor and the management of the civil and hydro-mechanical interfaces and requirements, the coordination being mainly carried out using 2D drawings with 3D models as required.

5.2 3D modelling

AFRY developed a fully integrated 3D model of the entire spillway as basis for the design coordination with Contractor A and to facilitate the production of design drawings. The Autodesk Revit model includes the 1st and 2nd stage concrete outlines, all concrete openings and recesses as well as embedded pipes, first and second stage embedded parts available from the hydro-mechanical supplier, sleeves pipes for the post-tensioned anchors, waterstops and allowance for the floor finishing. The following components have been received from Contractor A and subsequently incorporated into the 3D model and shown on the design drawings, such as:

- Stoplogs
- Radial Gates
- Gantry crane and temporary erection crane
- Hydraulic piping and electrical works

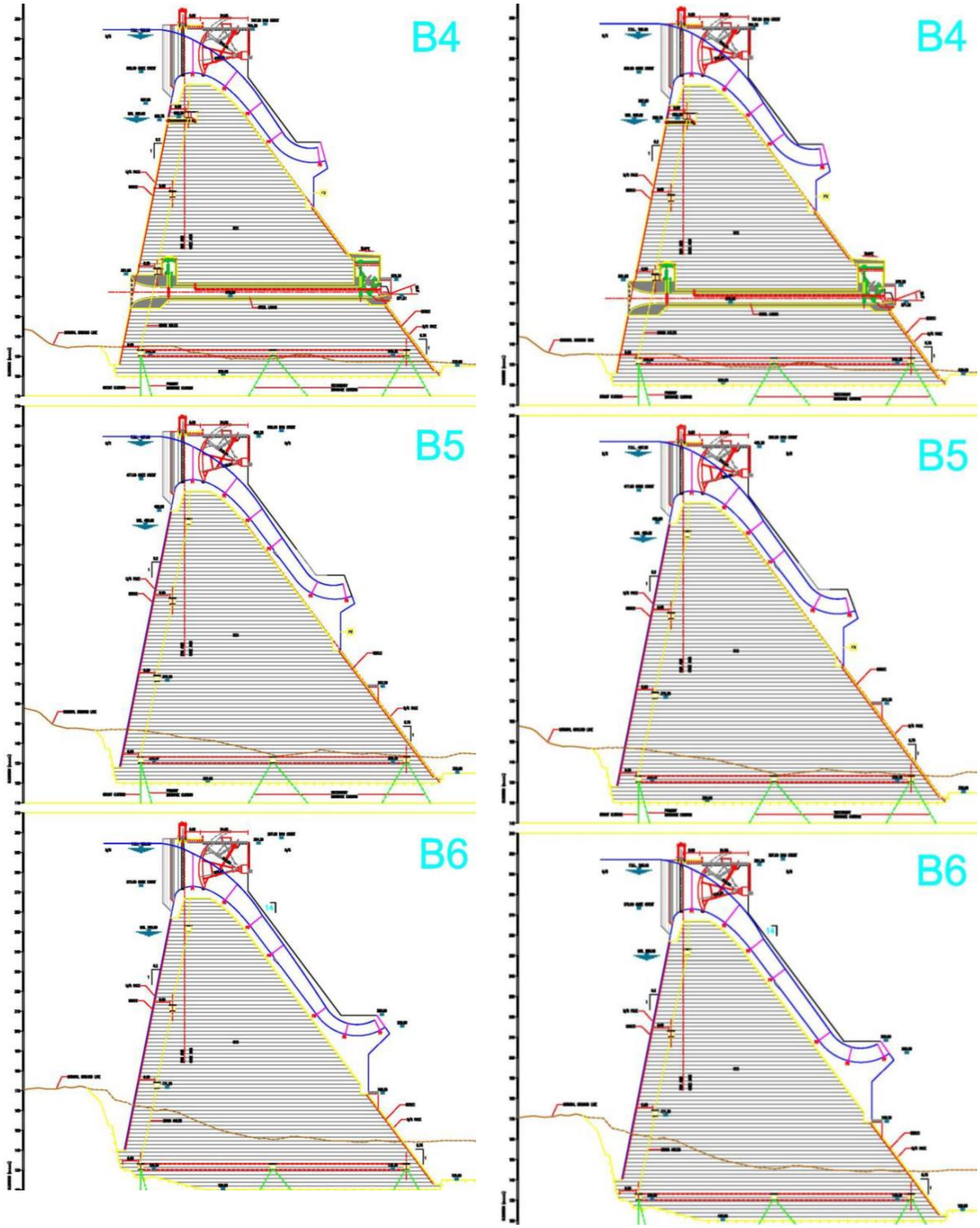

Fig. 5: Water surface profile measured along the chute centerline during 10,000-year flood (left) and PMF (right)

5.3 Evaluated key structural aspects

In the course of the modelling and analysis, close co-operation with the hydro-mechanical supplier was required to achieve a safe design of the spillway gates and piers and four-step approach was adopted as follows:

- Step 1: Dynamic time-history analysis of the RCC dam for the Safety Evaluation Earthquake (SEE) by AFRY using a finite element model and definition of three sets of stochastically independent acceleration-time histories at the gate support bracket as input for the subsequent design of the gates.
- Step 2: Static analysis and dynamic time-history analysis of the radial gates by the hydro-mechanical supplier and definition of forces at the trunnion supports as input for the subsequent design of the spillway piers and chutes by AFRY.
- Step 3: Qualitative comparison of conventional reinforcement vs. post tensioned anchors alternatives for the spillway concrete piers considering time and cost benefits for the Project.
- Step 4: Detailed finite element model of the spillway piers and chutes including the modelling of post-tension anchors.

The dynamic time history analysis of the Nam Theun 1 curved gravity RCC dam was carried out using a finite element model and the software ABAQUS considering non-linear effects in geometry and material behaviour. After amplification through the dam, the gates and the piers were designed for a horizontal Peak Ground Acceleration (PGA) of about 1 g calculated some 150 m above ground level which is about three times the PGA at the ground level in case of a SEE event (see Figure 6). At the gate supports, the forces were calculated to about 89,000 kN for each arm.

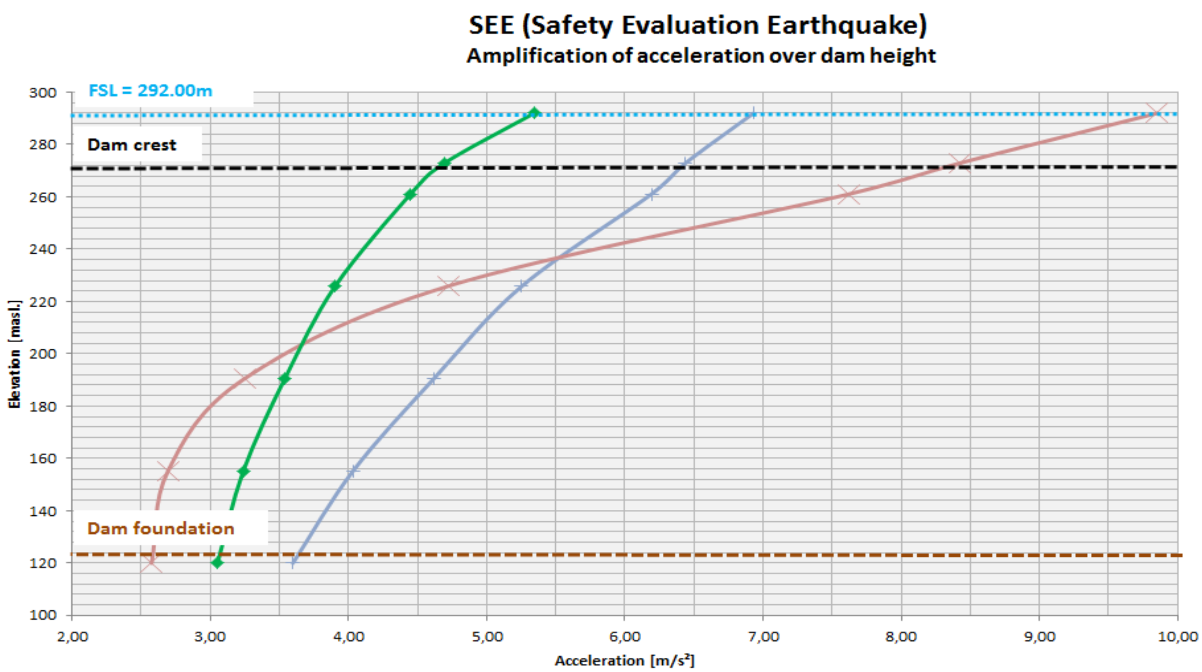

Fig. 6: Amplified accelerations (SEE) at NT1 RCC dam, blue across valley, red in valley direction, green vertical

A preliminary design of the piers and gate support brackets was developed using conventional reinforcement only (alternative No.1) on the one hand and a combination of post-tensioned anchors and surface conventional reinforcement (alternative No.2) on the other hand as basis to assess the pros and the cons of each alternative. For that purpose, relatively simple 2D strut and tie models were first developed and it was ultimately concluded that the very dense reinforcement (∅32/150/150) including numerous lap splices required for alternative No.1 would take longer and would be less economical by about USD 1.5 million to install while it may also negatively affect the quality of the concrete due to a lack of space and expected poor compaction between rebars. Furthermore, a safe force transition from gate support to the reinforcement bars was also a concern due to the very long anchorage length.

Based on the above, it was decided to design the spillway for alternative No.2 as shown in Figures 7 to 10 using two finite element models (mainly with 2D shell elements) to calculate the main conventional reinforcement and two models (3D volume elements) considering the installation sequence of the anchors to calculate the internal forces and the required split tensile reinforcement at the middle and side piers. DYWIDAG high grade Y1860/22 products (or equivalent) were selected to design the spillway.

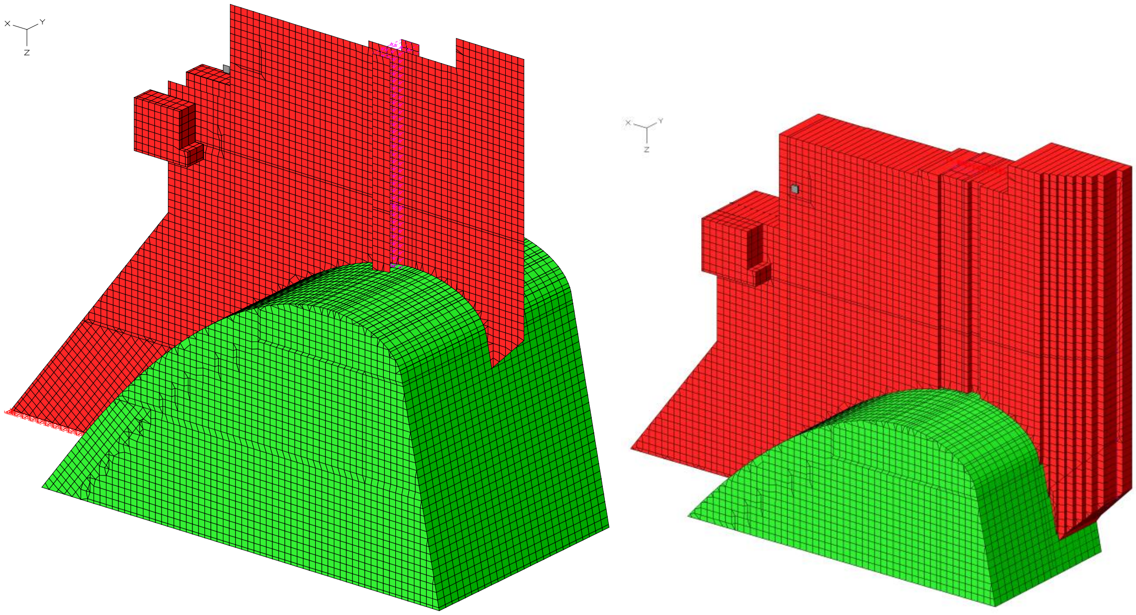

Fig. 7: Spillway FE-model (middle pier and side pier)

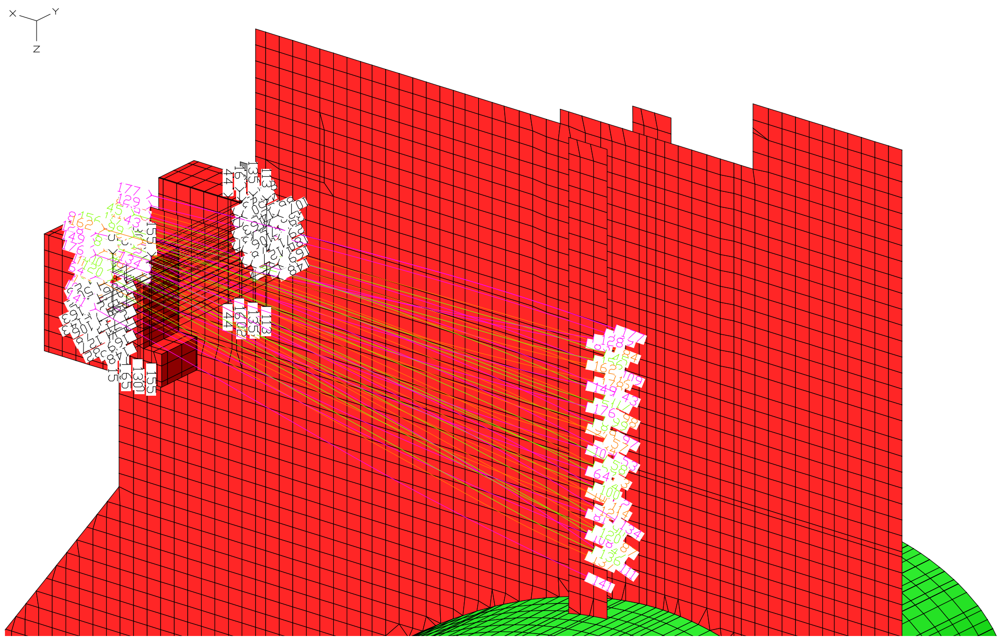

Fig. 8: Post-tension anchor design in FE model

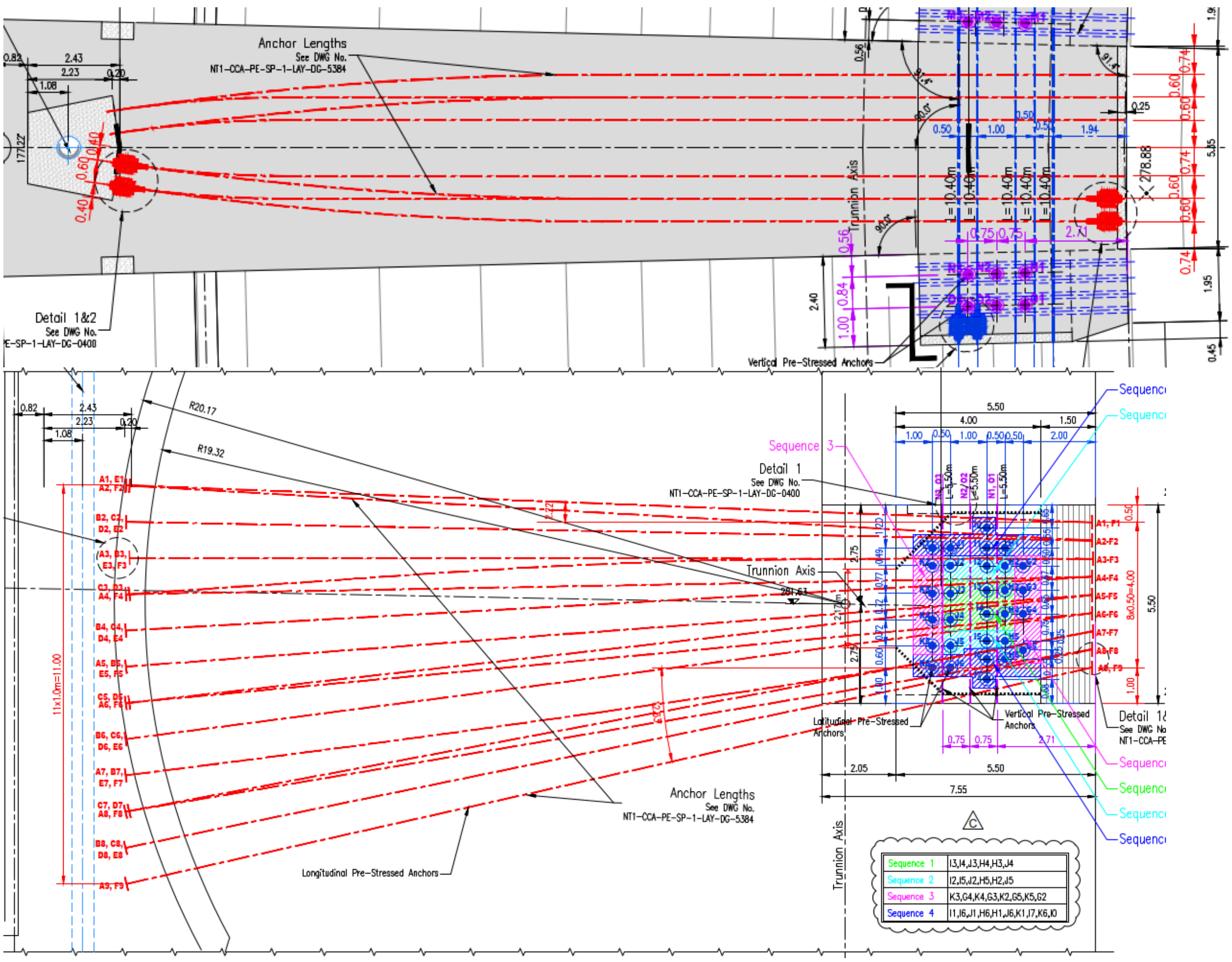

Fig. 9: Post-tensioned system

The following load cases were governing for the design of the post-tensioned anchors in combination with the surface conventional reinforcement:

- Middle pier – Normal operation: One gate closed and one gate opened resulting in an asymmetric loading of the structure and high bending moment at the pier wall.
- Middle pier – SEE: Two gates closed resulting in high tension forces at the pier wall
- Side pier – SEE: One gate closed resulting in high tension forces and bending moment at the pier wall.

Internal forces were calculated with response spectrum analysis for the middle piers and the results in case of a SEE event show a clear 3D behaviour of the wall with a high concentration of the loads at the ogee crest as shown in Figure 10 due to the pier section above the ogee crest acting as a quite rigid wall part in comparison with the upstream and downstream parts of the pier wall. The above suggests that a simple 2D calculation of the pier only would have likely underestimated and overestimated the required reinforcement in different areas, hence justifying the use of a more sophisticated 3D model.

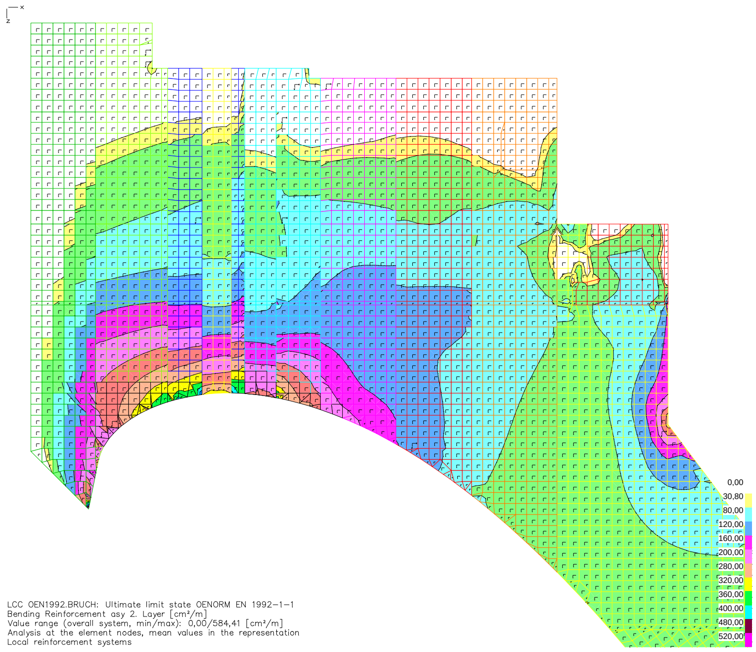

Fig. 10: Vertical reinforcement for SEE load case combination at middle pier

A time-history analysis was performed for the side piers due to non-linear behaviour and the additional damping effect provided by the interface with the RCC block right next to the piers as shown in Figure 11.

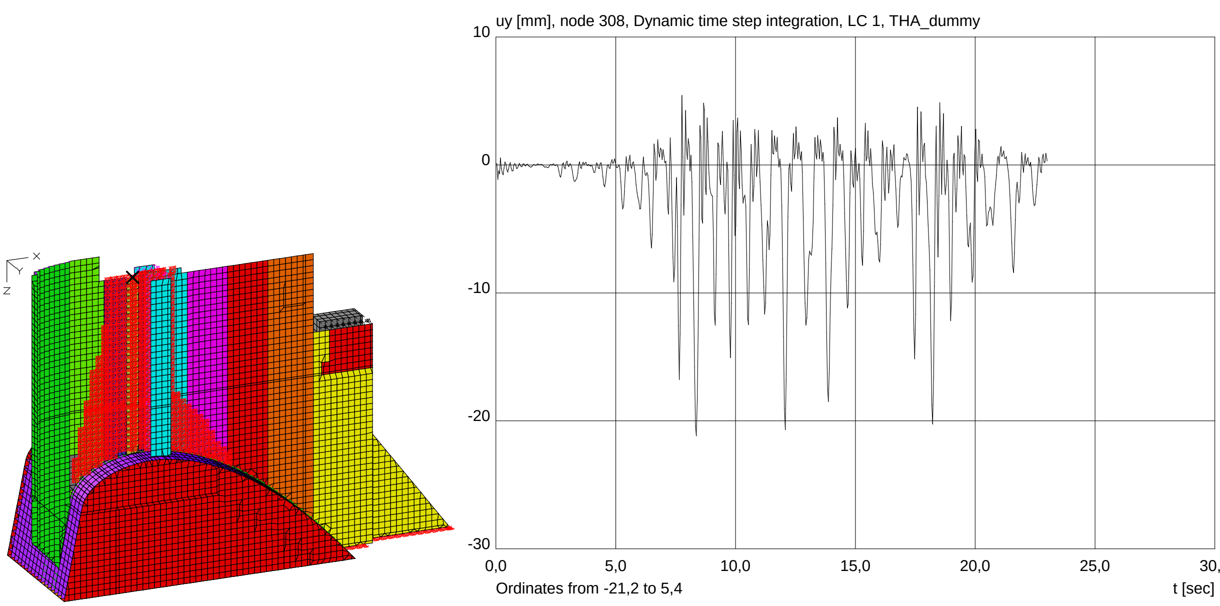

Fig. 11: Deformation at side pier during SEE (THA)

The spillway gate support bracket was designed with horizontal and vertical anchors to avoid split tensile forces and pre-press the bracket against the pier to prevent the opening of possible joints and the development of cracks in the concrete as shown in Figure 12. The maximum stresses developing in the anchors and the concrete were computed and compared against the maximum allowable stresses after each main installation step and supported by surface conventional reinforcement whenever tensions forces were anticipated as shown in Figure 13.

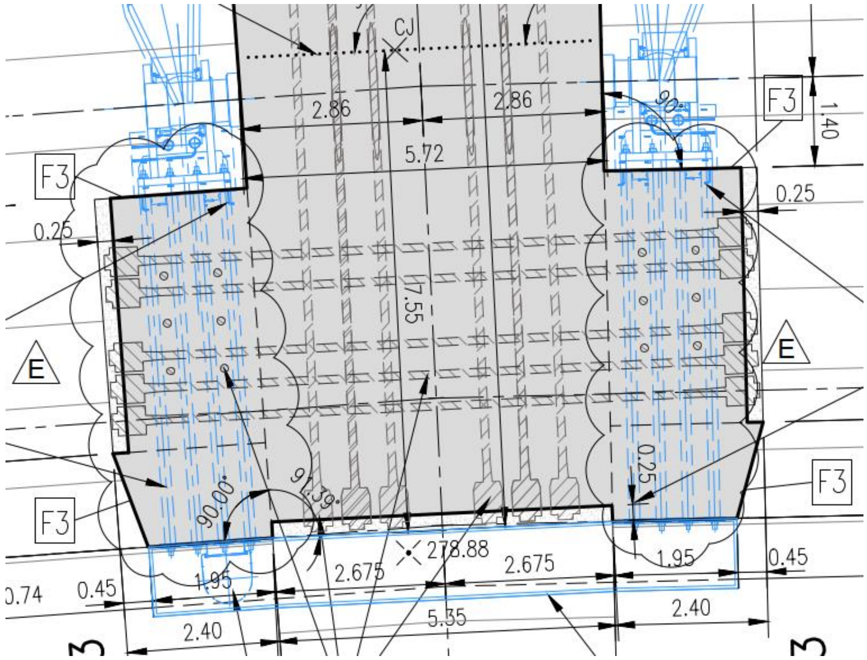

Fig. 12: Post-tension anchors at gate support bracket

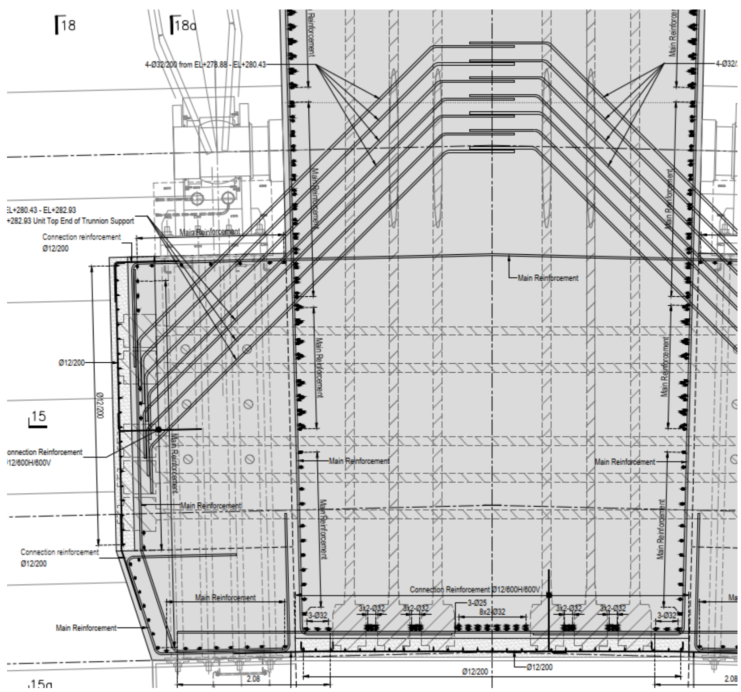

Fig. 13: Example for additional reinforcement, not covered by post-tensioned anchors

5.4 Construction aspects

A vertical shaft was designed upstream of the pier walls as shown in Figure 7 for the anchor heads to remain accessible and allow for correction/repair works at all times during construction. This shaft will be filled up with reinforced concrete after the successful installation and testing of all post-tensioned anchors.

Due to the post-tensioned anchors not being required during construction, sleeve pipes will be embedded in concrete allowing for a full installation at a later stage. This opportunity is expected to reduce the construction time by about 1.5 to 2.0 months per pier which will also benefit the project due to the spillway works being on the critical path.

6. Final word

The spillway was tendered to and constructed by the contractor as of main civil works of Nam Theun 1 HPP. Mobilisation by the contractor started in June 2016 and surface excavation of the RCC dam was completed on June 2018.

The concrete activities of the spillway chutes and flip buckets are currently proceeding at all spillway blocks. Following the installation of the temporary erection crane, the erection of the radial gates is scheduled to start on November 2021. The spillway facilities including the concrete works and the erection of the six radial gates are expected to be substantially ready for impounding and subsequent testing and commissioning before the onset of the rainy season 2022.

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Stefan Gloimüller graduated from Vienna University of Technology at Institute for Mechanics of Materials and Structures with a Master's in Civil Engineering followed up by a Doctoral study (PHD) in numerical and analytical simulations of material and structure behaviour. Mr. Gloimüller, who joined Pöyry in 2012, has more than 9 years of experience in planning, design and construction of large hydropower projects in Europe and South East Asia. During Detail Design of Nam Theun 1 Hydropower Project he worked in the role of Lead Structural Engineer for Bottom Outlet and Spillway.

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Stephan Martin holds an M.Sc. in Hydraulics & Civil Engineering from École National Supérieure d'Hydraulique et de Méchanique in Grenoble. Mr. Martin, who joined Pöyry in 2013, has more than 13 years of experience in project development, planning, design and construction of large scale dams and hydropower projects for major International Consultants working mainly on behalf of Independent Power Producers for his initial years. During the development and initial design phases of the Nam Theun 1 Hydropower Project he was the Project Manager. Following the commencement of execution, he worked in the role of Technical Manager for the Detailed Design Phase.

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Mr. Gabriel Escobar obtained an education in Civil Engineering from Universidad Central de Chile and is currently involved in the construction of the 177m high NT1 RCC dam in Laos. Over the past 20 years he has been responsible for finding innovative solutions to ensure successful construction of RCC dams. His numerous projects include among others the construction of Neckartal RCC dam in Namibia, Gibe III RCC dam in Ethiopia and Changuinola RCC dam in Panama.

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Mr. David Rothweiler graduated from Swiss Federal Institute of Technology (ETH) with a Master's in Civil Engineering. Since joining Pöyry in 2013, he has been working as a Structural Engineer for more than 4 years on large hydropower construction sites in South East Asia. Latest, he was responsible for the review works & execution of the Powerhouse complex and other civil structures of the Nam Theun 1 Hydropower Project on behalf of the Project Owner.