Implementation of the Dam Complex at Upper Atbara, Sudan, in challenging site conditions

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Introduction

The reservoir of the Dam Complex of Upper Atbara Multipurpose Project DCUAP impounds the Upper Atbara and the Setit River approximately 20 km south and upstream of their confluence, located in the Gedaref Governorate in East of Sudan. DCUAP is set up for irrigation of more than 300,000 ha, power generation of 320 MW, flood control and water supply for around 450,000 consumers by a pipeline executed within the frame of the connected Gedaref Water Supply Project GWSP.

The plant is owned by the Dams Implementation Unit DIU under the Ministry of Electricity and Dams. The civil works are executed by the Joint Venture of China International Water & Electric Corp. CWE and China Three Gorges Corporation CTGC. The works related to the supply of Gedaref by 75,000 m³ of water per day purified according to WHO-Standards are executed within the scope of a separate EPC-Turnkey-Contract of a 55 Mio. USD volume awarded to CWE. The electromechanical works are implemented by Harbin Electric International Company HEI, China. The total costs for DCUAP are approximately 1.1 Billion USD, financed mainly by Arabic Development Banks. The construction works of DCUAP started in the year 2010, and the first reservoir impounding has been completed by end of 2016. Two of four Powerhouse Units are commissioned by first half of 2017. The first kilometers of the GWSP water pipeline have been embedded at this time as well.

The Consultancy Services by Lahmeyer International GmbH LI, Germany, related to DCUAP are mainly comprising the review of the previous design and tender documents, provision of support during the tendering phase, and the construction supervision. For GWSP, the tasks of LI included the design review of the Contractor’s EPC-Design, the contract administration and the site supervision, whereas the review of the design of the technical equipment was carried out to large extent by the LI-subsidiary GKW Consult GmbH. The Consulting Engineers of LI have been working in the Sudan continuously for around 40 years in the fields of planning, designing and supervising construction of electric power plants and their distribution systems.

Multipurpose-Projects as DCUAP are of highest importance for Sudan. A continuous water supply throughout the whole year is the key for further developing the high potential of the agricultural economy favored by fertile soils, high level of irradiation and warm temperatures. At the same time, an increase and decentralization of the national electrical capacity is needed in order to develop further industrialization and improve the living conditions. Currently, the 1,250 MW Merowe HPP located at the Nile supplies around 50% of the country’s electrical energy.

Challenges experienced during implementation of the Projects DCUAP and GWSP are mainly related to the local climate conditions and the associated extraordinary flood regimes of the rivers, as well as to the particular bedrock conditions. Further, the remote location resulted in long shipping times of the construction materials and equipment as imported from overseas by the Chinese Contractors. The thin local infrastructure required comprehensive site preparation and installations. While most of these challenges had to be mastered during times of construction, the flood regime and sediment loads of the rivers will have to be controlled during the whole operation time of the plant.

1. The Main Characteristics of the Dam Complex of Upper Atbara

The interconnected DCUAP dams of the “Rumela” System on the Upper Atbara River and the “Burdana” System on the Setit River have a total length of about 13 km and a dam crest elevation of 525 masl. Both dams consist of a zoned earth fill embankment dam at the river sections with maximum heights of around 50 m, and a system of zoned and homogeneous embankment dams with maximum 25 m of height. The total fill volume for the embankments is 11.9 million m³. A volume of nearly exactly the same amount was excavated. The impoundment with a maximum gross head of 41.4 m is created by a total storage volume of 3.7 billion m³ (active 2.5 billion m³). Reinforced spillway structures with 950,000 m³ concrete in total have been built to enable maximum discharge of 6,150 m³/s
(Rumela) and 9,810 m³/s (Burdana). Both spillways are equipped with Bottom- and Surface sluices with radial gates. Riprap protection layers upstream and downstream of the concrete structure are placed for river bed stabilization. Cut-off walls with in total 7,900 m² of plastic concrete are located across the riverbeds of Setit and Upper Atbara sealing the alluvial layers. Beyond the actual river beds, very heterogeneous and partly permeable soils prevail. In order to avoid cost overruns, LI provided a design solution with a partial sealing element consisting of a Mixed-In-Place (MIP) Wall which utilizes the in-situ soil as construction material by mixing it with water, cement and bentonite. In total around 3,400 m length reaching up to 20 m into the bedrock, resulting in more than 61,000 m² of such MIP Longitudinal Sealing Element have been executed. The unit rates for the MIP are approximately one third of the rates for a conventional partial plastic concrete Cut-Off-Wall.

The Powerhouse of DCUAP hosts four identical vertical Kaplan turbine machine sets in Semi-Umbrella constellation, each of 80 MW. The plant has a separate intake structure with four penstocks of a diameter of around 8 m. Envisaged by the Owner is a supplement of the national electric grid during peak demands.

The GWSP Water Treatment Plant is located on the DCUAP area adjacent to the Outlet-Structure for the Irrigation Channel at the Upper Atbara River close to the Rumela Spillway. Two Pumpstations are transporting the water through the DN1000-DIP-Pipeline of a length of approximately 75 km to a reservoir nearby the City of Gedaref.

![Map of Upper Atbara and surrounding areas](image)

**Fig. 1.1: Dam Complex of Upper Atbara – Overview**

### 2. Challenging Environmental Conditions

#### 2.1 Flood Regime of the Rivers

Upper Atbara as well as Setit exhibiting due to the seasonal precipitation in their catchments within the highlands of Eritrea and Ethiopia during the Monsoon period an extraordinary hydrological regime with very high floods between July and September. While usually falling dry during most time of the year, the two years return period was identified based on the available historical data for the Upper Atbara by 2,100 m³/s, and for the Setit by 3,800 m³/s. The spillways are designed to spill the discharges of a 10,000-year return period flood event. The area behind the Stilling Basins and the slopes had to be protected by Rip-Rap to withstand the associated violent floods (Fig. 2.1).

![Hydrograph of Setit River and River Bed and Slope Protection](image)

**Fig. 2.1: Hydrograph Setit River; River Bed and Slope Protection by Rip-Rap**

#### 2.1.1 River Diversion

The extreme hydrographs of the rivers form particular challenges for the river diversion. This concerns the properties of the construction pit cofferdams during the 1st phase (bypassing) as well as the conditions during the 2nd stage river diversion, with rivers channeled through the spillways still under construction (Fig. 2.2). The temporary cofferdams for the structures of DCUAP have been designed with crest elevations to withstand the flood levels of a 100 years return period. This resulted in large related fill quantities. In order to proceed with the erection of the Main Dams, the
natural river bed had to be closed bypassing the flow through the bays of the sideward located spillways, which forms the 2nd stage of the river diversion. As the available flow crossection is limited from this moment on, increased upstream water levels due to impounding effects had to be considered for the flood season ahead.

2.2 Sediment Loads of the Rivers
The load of suspended solids of both rivers shows pronounced peaks in particular at the beginning of the flood season. Concentrations in the range of 30 kg/m³ (30,000 ppm) have been sampled in advance of dam erection, while typically observed amounts vary around 2,500 to 10,000 ppm. While the named sediment loads had only limited influence to the construction works, the design in particular of the Spillways had to be adapted. 6 Bottom Outlet Sluices at the Burdana Spillway (Setit) and 4 Bottom Outlet Sluices at Rumela Spillway (Upper Atbara) allow effective sluicing and flushing of the reservoir. The surfaces of the Stilling Basin and the Piers are protected against abrasion by C70/85 high strength concrete (Fig. 2.3). For the same reason, at the Powerhouse Turbine Runners a particular abrasion-resistant soft-coating has been applied.

2.2.1 Reservoir Sedimentation
The development of Reservoir Operation Rules in order to mitigate the loss of reservoir retention volume by sedimentation was the target of related Studies by Deltares, Netherlands. Two particular operation phases are introduced. During the beginning of the flood season triggered by the exceedance of certain inflow threshold, sluicing with maintained reservoir level is applied for increased flow velocities preventing a settlement of the suspended solids inflow. In advance of the filling phase, flushing is applied, which means a sudden reservoir draw down applied to erode deposits.

2.2.2 Impact of Suspended Solids to the GWSP Water Supply
During the impounding periods in the flood seasons of 2016 and 2017, suspended solids concentrations between 60 and 300 ppm have been sampled in the reservoir directly at the raw water intake while the Water Treatment Plant of GWSP is in the position to maintain the targeted capacity of 75,000 m³ per day up to amounts of suspended solids of around 800 ppm. Therefore, it is not expected that further presedimentation measures are required.

2.3 Impacts due to Precipitation
2.3.1 Retardation of Construction Progress
Due to the high plasticity and adhesion of the local clayey soil under the influence of humidity, the borrow areas could temporarily not be accessed and exploited by heavy machines during the wet season. Furthermore, gained material could not be built in as exceeding acceptable moisture contents limits. As a consequence, the embankment
Fill rates during the rainy season have been affected. While during the dry season typical total filling rates between 300,000 and 1,000,000 m³ per month could be achieved, with around 40,000 m³/month only around 10% could be attained during the rain periods of usual precipitation rates (Fig. 2.4).

In contrast, the DCUAP concreting rates with peak volumes of 45,000 m³ per month were not seriously affected during the rainy seasons. The prevailing Vertisol of the southern Butana Clay Plain forms a morass during times of the rainy season which prevents frequently entering with heavy machines for trench excavation and pipeline placing. The pipeline execution works for GWSP had therefore to be suspended. Flexible connections of the individual DIP pipes ensure axial adaptability of the pipeline required due to the pronounced moisture-related swelling of the “Black Cotton Soil”.

2.3.2 Rainstorm Damages
The local yearly average rainfall rate is reported by around 690 mm. For July and August, the rates vary around 170 to 190 mm. However, typically these amounts are not adding up within prolonged steady rain, but during individual events of partially extremely heavy rainstorms within a few hours. The local Extreme Precipitation Index is close to 200 mm/24 hrs. Normally dry Wadis turn into torrential rivers during such occurrences and led to erosion damages also on the DCUAP site, with the permanent dewatering systems not having been implemented yet (Fig. 2.5).

2.3.3 High Ambient Temperatures
The chart of local average ambient temperatures shows two peaks in May and November. Maximum air temperatures of around 42 - 44 °C are frequently experienced. These high temperatures mainly have to be considered for the concreting works in order to limit concrete core temperatures during hydration. Mass concrete was therefore cooled down to 22 °C. No thermally caused concrete cracks were observed in the block units of up to 3500 m³, which might be supported by low temperature differences between the hydration-heated core and the environment.

2.3 Local Infrastructure
With the closest river transverse for heavy vehicles formed by the Kashm El Girba Dam 80 km downstream, the construction of bridges crossing Upper Atbara and Setit was needed before the actual construction works could start. The non-availability of electric grid connections close to the location of DCUAP Site made necessary the installation
of two temporary Diesel power plants of each around 10 MW for electrical supply of the site installations and equipment as cranes. Water purification plants and two clinics have been established for the staff of the site, with during peak times around 3500 accommodated people. For the construction materials, as approximately 250,000 t of cement and 60,000 t of reinforcement, shipping times of at least 2 months had to be considered as imported from overseas requiring a “just-in-time” material management in particular for goods sensitive to heat or humidity.

3. Challenging Foundation Conditions

The rifting situation at the site resulted from a fracturing of the Nubian Sandstone package in a mainly SE-NW running and is nearly perpendicular to the fault system. The joint and fault pattern is more or less vertical. This pattern was determining the orientation of the actual main river beds and the main erosion gullies. After a long period of erosion of the cretaceous sandstone the area was buried by the younger fluviatile and lacustrine sediments as clay, silt, sand, gravel, cobbles (Karab material) transported from the Eritrean and Ethiopian Highlands into a huge river delta and even paleo-lake environment.

The design for the embankment dams on soil foundation developed for the tender design was based on the understanding that the foundation soils are accentuated and include soil layers to certain depths, but will be sufficiently impervious to be keyed by core material of limited depths (~ 5 m) into the rock.

When Lahmeyer International inherited the project, the experts decided to run site investigations to confirm this initial perception of the site conditions, which was mainly based on geophysical investigations.

At two locations of the project, the Fashaga section and the Burdana Right Bank section and for lengths of 1400 m and 2000 m respectively, investigations including core drilling however revealed very complex foundation conditions. The drilling demonstrated that the soil foundation is composed of clayey, silty, sandy and gravelly alluvial and colluvial deposits to greater depth. In top levels the clays, silts and fine sands dominate the foundation, while medium to coarse poorly graded sands as well as gravelly layers govern the lower sections. In Sudan, these soils are typically referred to as Karab formation (Fig. 3.1). Such layers reached into depths of 20 - 30 m under the foundation of the dam.

At the start and end points in Fashaga, the dam can be founded on the Nubian Sandstone formation. In the central part of Fashaga the site investigations identified a deep pervious zone with a length of approximately 1,600 m, which led to the hypothesis of a paleontological channel in the foundations filled with pervious materials, but fines as well. The depth of the ancient valley is about 70 m below ground level in deeper sections.

The paleontological channel, if crossing the dam axis may trigger additional flow from upstream to downstream. A final conclusion on its existence could not be confirmed until today.

The horizontal deposition of more and less permeable soil layers causes anisotropic flow conditions under the dam foundations. However, the continuity and the sequence of the layers did not present any defined pattern. It was understood that such formation may present locally high permeabilities and could result in increased seepage and critical hydraulic gradients at the downstream toe of the dam.

![Fig. 3.1. Eroded morphology of Karab formation](image)

The overall coefficient of permeability could be determined with $10^{-4}$ m/s to $10^{-6}$ m/s in the pervious formation. This could be demonstrated by grain size distribution analyses from foundation samples as well as from pumping tests. Gravelly banks are likely to have permeability coefficients up to $10^{-3}$ m/s.
The downstream toe of the embankment in Fashaga and on the Right Bank of the Setit is not plain and even, but rather consists of deep cuts and Wadis in immediate vicinity of the toe. Wadis are connected to the Setit in the section under consideration. Pervious sections are likely to emerge at the surface. The groundwater level is connected to the river water levels.

3.1 The Mixed In Place Sealing Element

The results of the investigations made clear that the initial design with a keying of the dam core into the foundation required important amendments including a barrier to cut flow in pervious formations. Lahmeyer initially recommended a conventional two-phase cut-off wall, which would have been the appropriate choice at earlier design stage. However, the contracts were already signed and such measure would have increased the costs of the project significantly because of the total length of 3.4 km and the maximum depth of about 70 m into the foundation to reach the rock foundation. It was estimated that a conventional cut-off wall would lead to additional costs of 100 Mio USD corresponding to about 10% of the total project costs. This was not feasible, especially in a sensitive economy such as the Sudan, and for an item that was not predicted by the responsible third Engineer during tender design. The project partners Lahmeyer and DIU investigated on cost efficient and technically sound but innovative solutions to overcome the challenging foundation situation.

3.1.1 Numerical modelling of measures to control seepage

So as to accommodate the complexity of the issue and eliminate all possible risks, parametric flow model analyses were performed. Lahmeyer investigated on vertical seepage barrier solutions in combination with parameter variations:

- Investigation of partial or full seepage barriers
- Partial seepage barriers with varying penetration depths
- Variation of the range of the soil permeability
- Flow under homogeneous and inhomogeneous isotropic and anisotropic geotechnical conditions
- Effect of a shallow impervious layer

A typical section of the embankment dam used for the model is shown in Figure 3.2.

Fig. 3.2: Typical section of the embankment dam

Starting from the first and second parameter, the reference at the start was to construct a full vertical seepage barrier that would bridge the clay core of the earth-fill dam with the underlying bedrock which was encountered at an average depth of about 40 m and a maximum one of 70 m. It becomes obvious that for a stretch of 3400 m the resources and time required would increase disproportionately. For that reason, different depths of the vertical barrier were analyzed, starting from the case of no seepage wall and full seepage wall, so as to specify the analysis boundaries, and then performing sensitivity runs for 10 m, 15 m and 20 m depths.
As the Karab formation is largely varying, three different permeability coefficients $10^{-4}$, $10^{-5}$ and $10^{-6}$ m/s were used, which cover the range of coarse sand and gravel ($10^{-4}$ m/s) to sandy clay/silt ($10^{-6}$ m/s). For completeness, the parameters for clay core of the dam are $10^{-8}$ m/s and for the seepage barrier $10^{-9}$ m/s respectively.

As mentioned before the Karab formation presented a horizontal layering of successive permeable and less permeable layers. This characteristic imparts an anisotropic permeability to the material which was represented in the analyses with the coefficient. For the purposes of the project, both isotropic permeability conditions $k_H/k_V=1$ and anisotropic $k_H/k_V=100$ were investigated. The anisotropic permeability is more favorable due to the fact that it obstructs the water flow in the vertical direction.

Taking the design into an even more detailed approach, it was observed in some of the investigation boreholes that the higher foundations layers present a rather isotropic character (only sand for example) and the aforementioned characteristic layering was starting at a depth. For that reason, additional sensitivity analyses were performed with the combination of isotropic permeability and anisotropic permeability layers, with different permeability coefficients, different interface elevation and different barrier depths.

Finally, the case of a shallow clay layer very close to the foundation level of the dam was investigated which could result in excessive hydraulic gradients at the downstream toe.

This led to more than 300 finite element seepage analyses performed with the software Rocscience Slide®.

Obviously, the implementation of a seepage barrier is of significant importance for the stability and permeability of the structure. The model demonstrated that without a seepage barrier the seepage may have reached uncontrollable 400 l/s per 100 m stretch or an unacceptable gradient at the downstream toe. These critical values were gradually reduced as the seepage barrier was reaching deeper into the foundation layers. It was observed as well that it would be beneficial if the vertical seepage barrier would penetrate the upper isotropic layers and cut into the lower anisotropic sections with lower permeability. The model displayed that even if the seepage barrier penetrated only one meter into the lower layers, the seepage would decrease by 40% compared to the model with no penetration.

With the above observations and further evaluation, the design was optimized to a 20 m deep seepage barrier, which is the minimum depth to provide sufficient safety for all foundation conditions and permeability coefficients considered.

### 3.1.2 The Mixed-in-Place Wall solution

Different solutions to build vertical seepage barrier walls were developed in foundation engineering. The regular cut-off wall technology used for soil foundations in dam engineering replaces the soil by plastic concrete in two phases. In the first phase, the soil is excavated and the trench is filled with a thick bentonite suspension, which is then concreted from bottom to top with plastic concrete forming this way a non-structural but impermeable element into the ground. This classical technology would have resulted in excessive costs for the long stretch on Karab formation.

Lahmeyer thus analyzed alternative solutions to provide large savings and proposed the Mixed-in-Place method. The Mixed-in-Place method mixes the soil in place through the intrusion of flight augers that bond the geo-materials with grout under high pressure. Lahmeyer proposed this method for the embankments located in the Karab formation of the Upper Atbara Dam Project. The method provided with the following advantages:

- The Mixed-in-Place equipment can reach the required depths of 20 m into the foundation.
- The wall constructed with Mixed-in-Place technology can reach the required permeability coefficient of $10^{-9}$ m/s.
- With the Mixed-in-Place method radical cost savings are possible.
- It is a fast method with high advance rates.
- It is highly adaptable to the geotechnical conditions in soils.
- The Mixed-in-Place method utilizes the in-situ geomaterial as a building material, blending it with the bonding agent into the structure of the wall. This significantly reduces the quantities of cement to be used.

The proposal comprised a novelty in the sealing of the foundation of a large hydropower project with a permanently impounded reservoir. References to the application of this method are limited to dikes or cofferdams, where water retaining is only temporarily.

The specialized contractor BAUER executed a 30-m test section so as to convince the Client and the Panel of Experts about the suitability of the method. The section was excavated to observe the quality of the bonding and provided very positive results (Fig. 3.3).
It was clear that the Mixed-in-Place wall could not be realized with the same control and accuracy as a conventional approach of a two-phase Cut-off wall would guarantee. To convince all parties the teams developed a detailed monitoring program as well as risk mitigation and preparedness plans for safe impounding and operation of the dam. The first consists of magnetic settlement gauges, benchmarks, pore pressure cells, standpipe piezometers and seepage measurement devices in relevant sections together with frequent site inspections. The risk mitigation included the preparedness for installation of filter blankets with weighting berms (ballast), if required, and eventually the construction of relief wells.

In total, 23 monitoring sections were distributed along the embankments. At critical locations seepage measuring weirs were installed at the dam toes.

These measures were convincing to all parties and resulted in the decision to implement a new technology for the permanent sealing of an embankment dam foundation – the Mixed-in-Place wall.

The 3.4 km long Mixed-in-Place wall was constructed in four months in 2013-2014 and the total costs were limited to about 40 Mio USD. The cost savings to the Client were estimated in the range of 50 to 70 Mio USD or 5 to 7% of the project value.

**3.1.3 Observations and Measures**

The impounding of the reservoir started in 2015. Typical daily impounding rates where between 10 and 20 cm.

Exemplarily, Figure 3.4 shows seepage measurement at the location with highest seepage. First seepage was measured on 03 October 2015 at a reservoir level of 513.50 masl. The quantity was approximately 5 l/s. Since this date the debit developed constantly to a rate of approximately 85 l/s. Based on the hydrogeological situation it may be estimated that the measured water is originated from a dam portion with a length of 460 m. The figure identifies a drop in seepage at the beginning of November 2015. This drop results from the improved measurement method by weir measurement, rather than bucket measurement at the pipes that was previously applied. Figure 3.4 confirms that the seepage rate is related to the reservoir water level, which is expected. While the seepage at most other locations did not exceed the expected rates, higher seepage rates were measured at the upper boundary limit of the modelling at the present location (up to 250 l/s). Some higher uplift pressures in the dam toe and the development of initial and small piping holes (few centimeters in diameter) could be observed as well. At any time, seepage water remained clear and the material transport was limited to a few cubic centimeters at the sinkhole spots.

The team of the Engineer, Client and Contractor reacted rapidly and decided to place filters and ballast directly in the dam toe trenches for a stretch of some 300 m.

With these measures implemented, no potentially critical developments were further observed at any location of the embankments. The cost of the aforementioned countermeasures was negligible.
The Authors

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Dr. Yannick Scheid graduated in Civil and Geotechnical Engineering from Darmstadt University of Technology. From 2000 to 2003 he was research assistant at Graz University of Technology, where he graduated with a Ph.D. In 2003, he joined Lahmeyer International and specialized in the field of dam engineering for hydro projects. During his career, he gained scientific and professional experience in Sudan and more than 20 other countries as Dam Expert and Project Manager. He was responsible for the embankment dam design of the DCUAP. Since 2016, Dr. Y. Scheid is employed as manager in the Business Line Hydro of Tractebel Engineering.

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