HARDFILL MANUFACTURE - APPROPRIATE DAM TECHNOLOGY FOR AFRICA

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ABSTRACT

In this paper the author describes the peculiar constraints prevalent in the development of infrastructure in remote locations in Africa and the specific challenges faced during the design and construction of a Hardfill dam in central Africa. In the process, the reader is introduced to a technology that is particularly appropriate for implementation on fast-track, small and medium-size hydropower projects on large rivers in remote locations.

1. INTRODUCTION

In remote portions of Africa, the development of new infrastructure has traditionally been constrained by limited existing infrastructure. Construction activities are heavily reliant on locally available materials, equipment and manpower and where specialist materials and equipment become necessary; importation from more developed areas becomes the only option. Logistics and transportation through undeveloped areas further limit the options available for the application of modern construction techniques. The use of basic construction technologies for dam and hydropower installations has accordingly been the norm in central Africa, requiring innovation and lateral thinking to overcome the constraints the remote environment to provide cost effective and fit for purposes installations.

2. DESIGN DEVELOPMENT

2.1 General

In the case of a recent small hydropower project in central Africa, the initial design concept for generating electricity was based on 5m high rockfill weir with an upstream concrete skin. The concept design entailed a small rockfill weir diverting flow into a canal which would bypass a steep portion of the river. Dropping flow through a penstock, power would be generated through the head created by the shortcutting of the river. Owing to the length and topography involved in the canal, the client and design team at that stage undertook a high level trade-off study to review implementation options and it was decided to rather relocate the weir to the location of the power house.

The project was then approved for implementation as a fast track project and the design progressed from conceptual into detail. In the interim, construction proceeded on the associated powerhouse, which had already developed out of the original canal concept.

With very little knowledge of the foundation conditions at the dam site, a preliminary design indicating a rockfill structure was proposed. This would raise the water level above the river bed by some 20m, while contending with potentially poor foundation conditions in its distributed mass. In order to ensure impermeability, various measures including a clay core and concrete core were considered, with the final choice also being dictated by the interface with the foundation. However, design flows in excess of 1000 m³/s were expected in the river, negating the use of such structures for a medium sized dam. In order to overcome both the unknown foundation conditions and these overtopping requirements, a “hard” overtoppable type dam wall was required. The use of concrete was discounted on the basis of its expected high cost in such a remote location and its specific requirements for competent rock foundations, deciding on the implementation of a Hardfill dam.
A Hardfill dam is a symmetrical trapezoidal dam which utilizes cemented sand and gravels for its body, with strengths in the order of up to 5 MPa (compared to 10-25 MPa for concrete). Its symmetrical shape allows for distributed pressures on the foundation without tensions at the heel. It can be fitted with an integrated erosion resistant concrete spillway capping in the form of concrete or grout enriched Hardfill.

Significantly, the dam footprint was markedly reduced, addressing some of the concerns regarding the foundation. Total quantities of dam building materials, together with the rapid construction techniques of Hardfill construction also meant that the construction period could be reduced. In the end energy dissipation of the overflowing water was provided through the construction of a conventional stilling basin, designed to the guidelines of the US Bureau of Reclamation.

2.2 Topographical and Geological Setting

General geological mapping of the region indicated the likelihood of basaltic foundations.

The fast track nature of the project limited detailed investigations to a condensed regime of core drilling in the areas accessible to the available drilling equipment in the region. At that time, the first stage river diversion facilities had already been implemented to facilitate the power house construction and the river was diverted onto the left flank of the river, leaving only the far left flank, the diversion berm itself and an area close to the power house available for such exploration.

![Figure 1. Overview of Site at Time of Initial Foundation Investigations](image)

Six 85mm diameter cores were extracted, two at each location at the expected upstream and downstream extents of the structure. These indicated moderately jointed rock with Rock Mass Rating (RMR) values varying between 40 and 75, overlain by soft materials. Expected foundation depths to acceptable rock levels varied according to the remaining overburden in the river, which consisted of soft alluvial materials and boulders.

Subsequent mineralogical analysis has shown that the foundation rock comprises metamorphosed dolerite. Review of the core drilling and exposed rock surfaces revealed that the dolerite is most likely a fairly narrow intrusion into the surrounding basalts. The initial alignment of the dam was accordingly adjusted to ensure that the structure and specifically the stilling basin could be constructed on the dyke. On eventual exposure of the foundation, joint mapping confirmed a primary dip of some 30 degrees upstream, with five distinct foundation types of varying rock quality.

2.3 River Flows

The Congo River basin dominates the central African region with its tropical hydrology. Located on the great Central African Plateau, the basin is massively broad and flat with a number of tributaries. The heart of the basin area enjoys an equatorial climate with no dry season. Annual average rainfall varies between 1 500 mm and 2 000 mm, with evapotranspiration between 1 200 mm and 1 400 mm per
annum. Temperatures in the endemic tropical rainforest typically range between 21°C and 32°C, resulting in a water surplus situation unequalled by any other large river basin in Africa.

Being a tributary of the Congo River, the river flow at the dam site broadly follows general trends of the larger Congo River, with a limited variation in flood flow intensity. With a Francou-Rodier “K” value of between 2.6 and 2.8 flood estimates range from a 2 year annual exceedance probability peak flow of approximately 425 m³/s to a 200 year flow of 680 m³/s.

2.4 Powerhouse

While the powerhouse construction had commenced significantly before the dam configuration had been finalized, construction sequencing of the two entities created a number of challenges. Crane access and scaffolding for the powerhouse needed to take precedence over the requirements for the dam, to the extent that excavations and foundation works for the closure embankment of the right side of the structure could only take place once the powerhouse civil works had almost been completed.

Being originally designed to generate power on a canal, modification of the powerhouse to integrate it into the dam wall was undertaken. On the right flank, an additional concrete skin sloped at 0,125(H) : 1(V) was added to the external walls onto which the closure embankment on that side of the structure could be compacted. A protruding flushing canal on the left side of the structure complicated the interface with the Hardfill dam on the other side. The void below this canal was filled in with mass concrete, leaving a sloped interface above rock level onto which the Hardfill could be placed. The concrete additions on both sides of the structure were provided with retrofitted water-bar seals to prevent flow bypass. Curtain and interface grouting was also specified to limit seepage below the powerhouse and its additions.

3. HARDFILL DAM

Excavation for the powerhouse, which is located on the right flank of the river, required the removal of soft overburden materials which formed a spur running down to the dam. While the powerhouse was ultimately founded on rock, the materials to the right of the structure remained very soft and unsuited to Hardfill construction. The non-overspill crest of the dam closing off the right side of the structure was accordingly configured as a zoned earthfill embankment.

![Image of the installation layout]

**Figure 2. Layout of the Installation**
The main portion of the dam which crosses from the power house to the left abutment is configured as a symmetrical faced Hardfill dam, with an integral spillway. Upstream and downstream slopes of 0.75(H) : 1(V) were selected. The non-overspill crest is configured as a vertically faced structure 6m wide and 6m high, forming the apex for the sloped portion of the dam. The overspill crest of the dam is provided above the trapezoidal base of Hardfill in the form of a conventional concrete ogee, which is doweled to the Hardfill, as indicated in Figure 3 below.

![Figure 3. Hardfill Cross Section](image)

A core characteristic of Hardfill dams is a separate impermeable barrier on the upstream face. For this purpose, the provision of a Carpi membrane (Sibelon® CNT 4400 geocomposite) provided both the required programming advantages as well as cost efficiency. A reinforced concrete plinth was provided at the upstream heel of the dam from which curtain grouting and drainage was installed. The membrane was attached to both the plinth at the heel and the conventional concrete at the crest to ensure impermeability. The Hardfill itself is accepted to be pervious and suitable drainage was included in the structure, chiefly through no-fines concrete on the foundation and at the upstream face, together with drilled drainage holes at the downstream toe.

While it is common to utilise pre-cast or extruded kerbs to form the outer faces of Hardfill dams, this was found to be impractical due to the isolation of the project. Conventional formwork similar to that for RCC dams was accordingly utilised. The upstream face was created utilising available 600mm wide Econoform panels, which were leapfrogged after every fourth Hardfill layer. To provide a suitable surface onto which the Carpi membrane could be installed, the steps were provided with large chamfers and were infilled with no-fines to aid drainage. The downstream face was created using a double set of Econoform panels to produce 1.2m high steps, which could nominally assist with spillway energy dissipation.

In consideration of the formed surfaces, the upstream faces of the dam were constructed though grout enrichment of the outer zones of Hardfill. Grout was introduced to the base of each layer as well as on the layer surface. The Hardfill was then loosened by hand to facilitate grout distribution and subsequent compaction by immersion vibration. Unfortunately the strength of the enriched Hardfill was inadequate to provide an erosion resistant surface for the spillway steps and the downstream face of the spillway was formed utilising conventional concrete trucked in by mixer trucks.

4. HARDFILL MIX DEVELOPMENT

While it was recognised at the onset that construction materials for the Hardfill dam could not be sourced from river gravels as is often used for Hardfill construction, suitable materials could be produced through quarrying. A regime of laboratory testing was consequently implemented to verify the suitability of the available materials.

The search for suitable construction materials for the dam was instigated immediately the decision to proceed with the hard type of dam was made. Although access and timing constraints resulted in the
identification of very limited number of rock quarries surround the site, a granitic outcropping only some 2.5 km away was ultimately selected for the production of Hardfill materials.

While drilling and blasting operations at the identified quarry site quickly got underway, the importation of a crusher to produce gravels took a further four months. A regime of laboratory testing was commenced early on to develop suitable Hardfill mixes and to test cementitious requirements. Various sand sources, crushed rock gradings and cement contents were tested to arrive at a suitable combination which could be used in the field. Ultimately a mixture of 85% crushed rock of 40mm maximum sized aggregate and 15% river sand was selected to provide a suitable grading for the Hardfill.

5. CONSTRUCTION

A local contractor already established in the region was designated to undertake the construction of the installation. The company had undertaken the construction of a number of civil works in the region, but while familiar with the logistical challenges of construction in remote areas, their experience did not extend to dam construction and only one of the contractor’s personal had ever been on a dam construction site.

It was accordingly necessary to develop a co-operative partnership between the contractor, the dam owner and the design team. Training in new techniques and concepts was implemented to develop the skills and procedures associated with dam construction and in particular, foundation preparation and Hardfill manufacture and placement.

5.1 River Diversion

The river diversion initially conceived envisaged two stages of construction. The first stage comprised a longitudinal coffer dam and excavated canal on the left flank of the river. This facilitated the opening of the foundation between the berm and the power house and the subsequent construction of the right side of the dam, which comprises slightly more than half of the final length of the dam structure.

Comprehensive planning for construction of the remainder of the dam during the second stage diversion was only fully considered after the author became involved in the project, after construction of the powerhouse had already commenced. To complicate matters, first power generation was required during the second stage river diversion, implying that the water levels must be raised sufficiently to divert flow into the power house. Second stage diversion ultimately necessitated the provision of a diversion channel between the Hardfill dam and the power house, together with significant sized clay cored rockfill coffer dams.

5.2 Hardfill production

Preliminary calculations of placement volumes for the Hardfill dam structure indicated that layer placement would peak at about 800m³. With the goal of placing at least one layer per day a fairly large batching and mixing plant was required. With the civil works of the power house in full production, the available batching plant was fully occupied and would in any event not have provided the production rates required. The importation of additional large equipment which would have very little likelihood of re-use in the region was found to be totally uneconomical and alternative mixing methods needed to be developed.

The use of a soil stabilizer/recycler was investigated through trials at an ongoing road construction project in South Africa, where a G3 gravel was mixed with a nominal cement content. While the trials proved to be encouraging, the specific procedures for the manufacture of a Hardfill material still needed significant development if the technology was to be used in the central African dam project. The design team felt confident that this could be achieved through a series of site tests and a second-hand Wirtgen WR 240 was procured and exported to the site. It is foreseen that this equipment will be used in future projects, either for a similar purpose, and/or for conventional road construction.

It was not deemed possible to fully control the mixing of the Hardfill on the dam surface using the recycler. A dedicated mixing platform was accordingly constructed which would facilitate the mixing and loading of materials under controlled conditions, allowing for wastage and safe working conditions. The platform consisted of a flat prepared area some 120m x 90m in extent near the dam site. The surface was compacted and capped with 150mm of the same gravels as was intended for
use in the dam. The final surface was carefully levelled and stabilised to create a hardstand area suitable for mixing, working and picking up mixed Hardfill materials.

Five mixing lanes along the breadth of the platform were set out, each provided with levelling pegs at either side to control layer thicknesses. In order to consistently mix the crushed gravels, river sand, cement and water in the established proportions, a specific procedure was developed, together with the necessary quality control systems to ensure conformity. Conventional techniques used for final layer road construction were used as a basis for the system which included the following:

- First the gravels are laid down on the platform and graded using a road grader to within 5mm of a set level. In order to optimally mix with the recycler, a total lane width of 7m as indicated in Figure 4 is used. This includes for three individual mixing sub-lanes with appropriate overlaps.
- Thereafter the river sand is dumped at set spacing’s and also graded to specific tolerances, accounting for the recorded levels of the underlying layer.
- The two layers are then mixed using the recycler.
- The moisture content and density of the mixed layer is then established using a nuclear densitometer, suitably calibrated. This information is then used to establish the spacing of cement bags on the layer, as well as the necessary additional moisture to be dosed by the recycler to obtain the required moisture content of the Hardfill mix.
- When the material is required at the dam, the pre-placed cement bags are broken open and spread on the surface of the mixed layer, with mixing following immediately thereafter.
- Once mixing in the second of the three mixing sub-lanes has commenced, the potentially unmixed edges of the first lane are trimmed off using a road grader, and the first sub-lane picked up by front-end loader and deposited into ADT trucks for transportation down to the dam.
In keeping with the simple construction techniques necessary at this isolated site, it was decided to transport the mixed Hardfill down to the dam in articulated dump trucks. However the pervasive afternoon showers meant that mud and dirt picked up on the truck’s tyres and subsequent contamination of the Hardfill surface needed to be avoided. Special wash bays were accordingly constructed immediately before the ramps onto the dam to clean off the tyres. The short section between the wash bay and the dam was then constructed from the same gravel materials used in the Hardfill, and sometimes even excess Hardfill itself. With this road rising synchronously with the level of the dam, new materials were continually added, keeping the last portion of access route clean.

The dam was subsequently constructed in layers of 300mm thickness using conventional techniques for Hardfill/RCC placement and compaction. At the time of writing this paper the first half of the dam had been completed and preparations for second stage diversion and the installation of the upstream liner were in process.
6. CONCLUSIONS

While retrofitting a dam to a partially constructed powerhouse presented some significant challenges, the implementation of the dam wall as a Hardfill structure and the environment-appropriate arrangements developed for the Hardfill construction represent real advances in appropriate technology for the construction of small/medium-sized dams in Africa, particularly for hydropower schemes. The successful use of simplified methods to mix Hardfill represents an important development that will not only promote the use of this technology in remote areas, but will also allow reduced implementation costs for Hardfill dams.

7. ACKNOWLEDGEMENT

While this paper presents the details of a project in central Africa where the development of Hardfill technology was advanced, specific names and places have been omitted for security reasons. The dam owner is nevertheless acknowledged for his permission to publish the paper in this format and for allowing the sharing of the innovations described.