DESIGN AND CONSTRUCTION ADVANTAGES OF HARDFILL SYMMETRICAL DAMS - CASE STUDY: SAFSAF DAM IN EASTERN ALGERIA

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SUMMARY

The hardfill symmetrical dam concept has been developed and applied in dam construction in the last two decades. The advantages are numerous in terms of stability, hydrological and hydraulic safety and construction. The paper illustrates those advantages through the case study of SafSaf dam in Eastern Algeria, 36 meter-high, constructed between 2007 and 2011 on a highly fractured and weak limestone foundation.

1. INTRODUCTION

1.1. ORIGIN OF THE FACED SYMMETRICAL HARDFILL DAM (FSHD) CONCEPT

The original concept of a symmetrical gravity dam was introduced by Jérôme Raphaël in 1970 (“Optimum gravity dam”).


It has also been addressed in the French research program BaCaRa for RCC dams, in the ICOLD bulletin n°117, “The gravity dam - a dam for the future”, in a paper for the ICOLD Barcelona congress, 2006, “Hardfill symmetrical dams - 10 year experience feedback”, Q.84, R.71, by Michel Lino and orally presented at the ICOLD Brasilia congress, 2009, “Concrete faced hardfill symmetrical dams and safety towards design and construction floods”, Q.88, by Thibaut Guillemot.

Since the nineties, several projects have been completed: Marathia (Greece, 1993), Moncion (Santo-Domingo, 1995), Rio Rejo and Rio Grande (Peru, 2003), Cindere (Turkey, 2003).

The concept has been adapted by the Japanese engineers after 2000 under
the denomination of cemented sand and gravel (CSG) dam and several dams were built.

1.2. **DESIGN ADVANTAGES OF FACED SYMMETRICAL HARDFILL DAM (FSHD)**

1.2.1. **Stability analysis**

The symmetrical profile of the dam gives good stability conditions despite a low density and reduced shear strength due to the mix design and the simplified placement, respectively $\gamma = 21.5 \text{ kN/m}^3$, $\phi' = 35^\circ$ and $c' = 0 \text{ kPa}$ for SafSaf dam.

A comparison with a conventional gravity dam profile of the same height shows reduced stresses on the foundation, no tensile stress develops apart for strong seismic loading, the stresses during construction and operation do not vary much, and most of the settlements develop during construction.

Thus, on a foundation where a conventional gravity dam would not be feasible because the loads exceed the rock shear strength, a FSHD can be considered.

1.2.2. **Hydrological safety and overtopping**

The stability conditions are poorly affected by water levels above the maximum water level, in terms of stress variations and sliding stability. As a rigid dam, it can resist to overtopping. These advantages are important with regard to embankment dams in case of design flood exceeding.

1.2.3. **Internal erosion**

The rigid dam body is not subject to internal erosion as for embankment dams. This failing mode was critical in the case of SafSaf dam with the karstic foundation. The initial design did not take into account a systematic search and treatment of sinkholes, which would have been a hard, expensive and possibly inefficient work. The dam had to be founded on the alluvial deposit of the riverbed. Sinkholes under the alluvial deposit would not have been identified before the dam construction and the risk of piping into the foundation was high.

The design change with a hardfill dam neutralized this risk.

1.2.4. **Integration of hydraulic structures**

Integration of hydraulic structures such as spillways, pipes, galleries,
diversion culverts, etc., is much easier in hardfill dams than in embankment dams.

For structures across the dam body, the watertightness is made by linking the concrete face of the dam to the concrete structure. The contact between the structure and the dam body, which is a weak interface for internal erosion in embankment dams, does not need special treatment or provisions.

For spillways, the installation on the crest of an embankment dam is a delicate operation and hardly ever applied for high discharges or high heads for safety considerations. On a hardfill dam, spillways can be securely installed as on conventional gravity dams.

1.2.5. Monitoring

When hardfill dam is chosen as an alternative to earth-fill dam, monitoring devices can be significantly simplified. Typically, hardfill dams are provided with pressure cells, weirs, survey reference points and eventually pendulums.

1.3. THE INITIAL SAFSAF DAM PROJECT

The SafSaf dam is located 60 km southwards from Tebessa city in Easter Algeria, near the Tunisian border. It aims at delivering a 5.8 hm³ volume of water a year for irrigation (3.0 hm³) and for drinking water (2.8 hm³). The reservoir volume is 19.8 hm³ and the watershed surface is 1 348 km².

The dam site is on a non-perennial rive with irregular flow rates. There is no flow most of the time, with a deep groundwater level, and there are sudden floods a few days a year.

The foundation is constituted of weak limestone (density of 22.5 kN/m³, compressive strength of about 12 MPa), highly fractured (RQD < 25%), with medium karstification (a few sinkholes of metric dimensions have been identified during the investigations and the excavations under the dam body).

![Fig. 1](image)

Rock samples of the dam foundation and right abutment during excavations
Such a foundation, with low shear strength, cannot bear a classical concrete gravity dam and the initial design in the nineties planned a 30 meter-high zoned embankment dam, founded onto the alluvial deposit of the riverbed. Thus, the spillway, designed for a 2 660 m$^3$/s flood, was settled on the right bank, next to the embankment, which demanded large rock excavations.

Furthermore, to limit the excavation volume, the spillway shape was designed with a highly curved crest upstream and a tight channel across the rocky pass, which resulted in a poor efficiency against design flood exceeding.

In addition, the diversion canal, under the dam body, was designed for a construction flood of 400 m$^3$/s.

2. CHANGES BETWEEN THE INITIAL PROJECT AND THE FINAL DESIGN OF SAFSAF DAM

2.1. PROJECT REVIEW

In 2006, ISL Ingénierie was commissioned by the Agence Nationale des Barrages et Transferts (ANBT, owner) to review the initial design of the dam, to supervise the works and to produce the construction drawings. Reviewing the initial design yielded to major changes to improve the safety of the dam during construction and operation.

The initial design was considered critical towards hydrological safety: the hydrological review showed that the initial study underestimated the floods volumes and peak flows. The initial design flood of 2 660 m$^3$/s and the construction flood of 400 m$^3$/s were far under what is to be considered for an embankment dam: they roughly corresponded to the 500 year-flood and the 2 year-flood. The design flood was upgraded to 5 220 m$^3$/s (10 000 year-flood).

2.2. DESIGN ADAPTATIONS TOWARDS HYDROLOGICAL SAFETY

According to the hydrological review, the project had to be redesigned to prevent overtopping during construction and during operation. The diversion and the spillway capacities would have had to be dramatically increased to secure the flood spilling.

The cost of the project would have been strongly affected. Thus, ISL Ingénierie proposed to the owner a major change in the project to improve its safety while keeping it financially viable: the embankment dam was replaced by a
FSHD, 36 meter-high, founded on the bedrock beneath the alluvial deposit of the river and topped with a free overfall crest spillway, designed for a 7,5 meter-high head. A stilling basin of 60 meter-long, 113 meter-wide and 7 meter-deep at the downstream toe of the dam dissipates the energy of the flood discharges.

The costs figured by the contractor are 30 M€ for the embankment dam (design flood: 2 660 m$^3$/s) and 33 M€ for the hardfill dam (design flood: 5 220 m$^3$/s).

The plan view and the typical cross section are shown in Fig. 2 and Fig. 3.

![Plan view of the dam and the spillway](image1)

**Fig. 2**

Plan view of the dam and the spillway

![Typical cross section of the dam and the spillway](image2)

**Fig. 3**

Typical cross section of the dam and the spillway (slopes: 0,7 H / 1 V)

The diversion canal, 7 meter-wide and 5 meter-deep, the capacity of which is 150 m$^3$/s, in the range of the annual flood, was placed on the right bank and founded on the bedrock. The dam construction site is protected by upstream and downstream hardfill cofferdams. The canal was reused for the intake pipe and the bottom outlet after the diversion closure. The reason for lowering the diversion capacity compared to the initial design is explained below.
3. HARDFILL MIX DESIGN, PRODUCTION, PLACEMENT AND CONTROL FOR SAFSAF DAM

3.1. Mix Design

SafSaf hardfill is made of local aggregates taken in the riverbed (grading between 0,08 mm and 80 mm), an addition of 8% of fine sand, taken in the reservoir area, 120 kg of CEM II/A 42,5 cement per cubic meter and water to the optimal water content resulting from modified Proctor test (about 8%).

Alluvial aggregates are taken in selected zones where they are clean and well graded. They do not need any treatment but screening above 80 mm. The quantity found in the reservoir area was large enough to ensure the total production of hardfill for the project. On Fig. 4 is shown the type of aggregates used for hardfill. The grading curves show the specified grading envelope (red), the samples taken in zones fitting the specifications (blue) and in zones to be avoided for aggregate use (grey).

![Fig. 4](image)

Typical aggregates used for hardfill production

The majority of alluvial deposits proper for hardfill production show a lack of fine particles to reach a percentage between 5% and 15% smaller than 0,08 mm, specified for compaction efficiency.

The first mix formulations in laboratory were made with 8% of limestone filler from a local cement factory and 80 kg/m³ of cement. This was giving good results in terms of density and compressive strength, but as the filler might be unavailable at some periods of the construction, it was replaced with fine sand (8%) and an addition of 40 kg/m³ of cement. A loss of dry density of 3 to 5% was observed in the samples, resulting in a loss of about 20% in compressive strength.

As the mix without filler, with fine sand and 120 kg/m³ of cement was meeting the specifications (dry density of 21,5 kN/m³ and compressive strength at
90 days of 7 MPa), it was adopted for the dam construction.

### 3.2. Production

The production is made with a concrete mixing plant of 120 m$^3$/h capacity (Fig. 5), producing an average of 15 000 m$^3$ of hardfill a month during the construction.

**Fig. 5**
View of the concrete mixing plant

### 3.3. Placement

Hardfill is placed as a conventional roller-compacted concrete, with embankment equipment. The compaction is made with a V3 type vibratory roller.

**Fig. 6**
Hardfill placement on the dam
3.4. CONTROL

The method statement for placing hardfill was elaborated during a field test at the beginning of the upstream cofferdam construction. Apart from the laboratory tests on hardfill components, the quality control consisted in dry density measurements with a radiation-type densimeter and control of compressive strength at 90 days.

The samples for compressive strength were not made with a vibrating table because the hardfill was too dry. A procedure similar to Proctor sampling had to be developed to reach a sample density close to the specified density. The hardfill samples were cylindrical with a diameter of 25 cm and a diameter over length ratio of one.

In situ coring was tested on the site but was abandoned: the contrast between hard gravels embedded in a smooth paste resulted in damaging the sample surface within the coring device. The samples were not cylindrical after extraction.

4. SPECIAL CONSTRUCTIVE PROVISIONS FOR SAFSAF DAM

4.1. CONSTRUCTION JOINTS

The crest length of the dam is 270 m and the base length is 120 m, without any construction joint. The hardfill layers are continuous on the dam length and width. Small lateral vertical cracks, a few \(1/10^{th}\) of millimeter opening, have been observed on hardfill layers at regular interval of about 10 m. On the upstream cofferdam, left without concrete cover during the construction, no leakage was observed in the cofferdam body during floods, what tends to show that the cracks can heal after opening.

Furthermore, the watertightness of the dam is given by the concrete face and small contraction cracks are not problematic for the dam safety and operation.

4.2. INTER-LAYERS TREATMENT

The stability calculations have been carried out with a friction angle of 35° and no cohesion into the dam body. As the watertightness of the dam is provided by the upstream concrete face, the layer surfaces received a minimal treatment consisting in dragging a harrow after compaction and cleaning with air before spreading the next layer.
4.3. **UPSTREAM CONCRETE SLAB FOR WATERTIGHTNESS**

The upstream reinforced concrete face, 30 centimeter-thick, was cast with a slip form after the completion of the dam body, when most of the settlement of the dam occurred. The concrete slab is cast on a drainage system constituted of pipes, connected to the drainage gallery.

4.4. **DOWNSTREAM FACE PROTECTION DURING CONSTRUCTION**

To prevent the downstream hardfill face to erode in case of overtopping during construction under high velocity flows, it is armored with precast concrete elements, 60 centimeter-high, also used as formworks during hardfill placement.
5. CONCLUSION

SafSaf dam is a good example of a rigid dam that could be built on a weak rock foundation, where a conventional gravity dam was not feasible, and as a good alternative to an embankment dam. The remarkable points are:

- a symmetrical profile to insure the dam stability on a weak bedrock by limiting the stresses applied to the foundation, compared to a conventional gravity dam,
- a low sensitivity to design flood exceeding during operation and to strong earthquake,
- no risk of internal erosion of the dam body in the karstic foundation,
- a minimal and cost effective diversion canal,
- a good reliability in case of overtopping during construction,
- an easy integration of hydraulic structures in the dam body, compared to earthfill dams,
- simplified constructive provisions compared to RCC dams (use of local riverbed aggregates, minimum inter-layer treatment, no construction joints).

Fig. 9
SafSaf dam during construction

Fig. 10
SafSaf dam after completion
Dams: SafSaf (Eastern Algeria)

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