Design and Construction Techniques for a Safe Planning and Execution of High CFRDs

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Abstract: Progress in design and construction of CFRD have been reached by taking measures to correct deficiencies observed in other dams which have affected the performance with the presence of high leakages. This article discusses the strategy taken by designers and constructors to improve the behavior of the perimetric joint, to control fissures on the slab, to analyze cracking sub parallel to the plinth, to design compressive joints to prevent spalling, and to avoid high leakages. The article also present design rules recently applied in very high dams to prevent these problems and the excellent performance reached in modern high CFRDs.

Key words: Concrete face rockfill dams, compression joints

1 Introduction

The design of CFRD’s has suffered continuous evolution in order to improve the behavior in deformation, prevention of slab ruptures and high leakages observed in the first dams built using this type of structure. The risk factors associated to these problems can be summarized as follows:

(1) Opening and off set of the perimetric joint with the waterstop ruptures.
(2) Presence of cracks and slab fissures close to the perimetric joint
(3) Deficiency in rockfill grading causing low compressibility modulus.
(4) Geologic aspects to define plinth location and to avoid abutment instabilities.
(5) Deficiency in the central compression joint design, causing excess of compression stress, ruptures and high leakages.

The purpose of this article, is to review these risk aspects and to discuss solutions experienced by the author to improve the performance of new high CFRD’s.

2 Evolution of compacted rockfill concrete face dams.

With the development of the vibratory rollers in the sixties, this type of dam has been increasing in height to reach values close to El. 250 m shown on Figure 1.

Some of these dams have presented problems related to the perimetric joint opening, fissures close to abutments, moderate to high leakages and disruptions at the face slab causing breakage of the concrete and distortion of the reinforcement, producing damages to the water stops. However, the integrity and safety of the structure has never been affected.

3 Opening and off set of the perimetric joint

The perimetric joint of a high concrete face dam
always opens and off-set. These movements are well defined in the technical literature, as opening, settlement and displacement sub-parallel to the joint (Shearing effect).

During the construction of the Alto Anlichayá dam, 140 m, Colombia, the movements registered were very high causing the failure of the central water stop. This rubber water stop was the only water stop installed in the middle of the joint. At the right abutment were registered movements as follows:

Opening = 12.5 cm

Settlement = 10.0 cm
Shearing = 1.5 cm

These movements were caused by the erosion of the material close to the plinth. A creek located at the upper zone of the right abutment increased in floods causing this damage and the re-compaction of the material was extremely difficult to execute due to the steepness of the abutment.

The leakage increased to values of 1,800 L/s.

The remedial treatment was carried out by placing a mastic (IGAS) over the joint with a cover of silty clay as depicted on Figure 2.

This treatment resulted in a reduction of 90% of the maximum registered leakage.

Treatment of the perimetric joint was feasible because the reservoir was lowered by a draw-off tunnel. However, the area many sites where is not possible to lower the reservoir due to the high flows of the river. For this reason in Foz do Areia, 160 m, Brazil, the perimetric joint was designed with various lines of defense. Figure 3 shows the perimetric joint in Foz do Areia with the following protections:

1. A copper water stop located at the bottom of the joint.
2. A central PVC waterstop.
3. A sand-asphalt mixture located under the joint.
4. An upper protection with mastic.

Nowadays, most of the high CFRD’s are adopting various lines of defense for the perimetric joint. The central water stop has been eliminated in some dams, but more emphasis is given to the protection of the upper joint and using the bottom copper stop.

4 Presence of cracks and slab fissures

During the construction process of the slab, cracks and fissures are presented due to problems of temperature retraction. These fissures generally have dimensions smaller than 0.3 mm. When the fissures is less than 0.3 mm no treatment is applied to the face.

In very large projects an effort to control this cracking has been carried out using products
which apparently reduce the cracking. China has reported the use of a product called PAN (Poly Acrylo Nitrile), a synthetic fiber that attenuates the presence of fissures.

In dams with steep abutment or with difference in compressibility modulus, the presence of cracks sub parallel to the plinth, as shown in Figure 4 for the Xingó Dam, 150 m, Brazil, is very frequent.

Similar cracks have been observed also in Itá, 125 m and Itapebi, 120 m, in Brazil.

After analyzing these cracks it has been recommended to improve the reinforcement, in a band close to the plinth as indicated on Figure 5.

![Figure 4 Xingó Crack sub-parallel to the plinth](image)

This band is usually 20 m width and the reinforcing is increased to values of 0.5% of the section in both direction (horizontal and vertical).

The reinforcing bars are placed in horizontal areas (See Figure 5) for a practical disposition of the reinforcement.

This preventive treatment has been applied in Campos Novos, 202 m and Barra Grande, 185 m, Brazil and also in El Cajón, 188 m, México and Kárahnjúkar, 196 m, Iceland¹.

In some places where the abutment is very steep, it is a good practice to split the width of the face lane from 16 m to 8 m as done in Shuibuya, 233 m, China.

5 Deficiency in rockfill grading causing low compressibility modulus

Grading of the rockfill is important to guaran-

tee high modulus of compressibility of the fill. Well graded fill with coefficient of uniformity higher than 15 generates low void ratios and high compressibility modulus. Consequently, deformation of the fill is low.

Gravels are excellent materials to obtain high modulus of compressibility and deformations of the fill are 5 – 6 times lower than dams built with rockfill.

Basalts from the south of Brazil or in South Africa produce grading very uniform, with coefficient of uniformity lower than 10 and void ratios exceeding 0.30 – 0.32. These fills, present modulus of compressibility varying between 40 – 60 MPa when compacted gravels have modulus higher than 150 MPa.

During the construction of the Aguamilpa dam, 187 m, México, gravels were located upstream with modulus of compressibility of 250 MPa and rockfill was placed downstream with average modulus of 50 MPa. The high deformability of the rockfill produced a crack, 1.5 cm width, between slabs 17 and 26 as shown on Figure 6, for El. 180. Minor fissures were also presented at the upper position of the face slab.

When the dam site offers the possibility to use gravels and rockfill, it is useful to run parametric analysis using FEM to define the best location of the materials and to define the zoning of the dam.

6 Geologic aspects to define plinth location and dimensions and to avoid abutment instabilities

Definition of the plinth dimension and location is highly related to the geotechnical parameters of the foundation and to the height of the reservoir.
An excellent correlation has been obtained using the Rock Mass Rating (RMR) from Bieniawski and the gradient required to avoid erosion of the foundation (Figure 7).

During the construction of Berg river, 60 m, South Africa\textsuperscript{1}, where the plinth foundation was slightly weathered (Figure 8), the dimensions of the plinth (external and internal) were determined using the graph of Figure 7.

The rock foundation was mapped, every 25 m, and calculated the minimum RMR and the high of the reservoir on the plinth. Then the external plinth and the internal slab were determined as follows:

\begin{align*}
H & : 45 \text{ m} & \text{RMR}=44 \\
\text{For RMR} 44 \quad G & =8 \\
\text{Width} & =45 \div 8=5.63 \text{ m.} \\
\text{External plinth} & =4 \text{ m.} \\
\text{Internal slab} & =1.63 \text{ m} \approx 2.00 \text{ m} \\
\end{align*}

The performance of the dam was excellent, despite some places registered RMR as low as 30.

Similar criteria has been applied in Merowe, 45 m, Sudan, and Bakun, 205 m, Malaysia.

The geological mapping of the abutments is important to record weak strata with high compressibility or with low strength parameters affecting the stability of the abutment.

During the construction of the Itapebi dam, Brazil, intrusions of Biotite – Schists (BX) were presented within the massive gneiss as shown on Figure 9. The presence of this BX bands required to articulate the plinth as shown on Figure 10.

Similar solutions were adopted in Salvajina, 148 m, Colombia where the plinth on sandstone found a zone of weathered rock affected by hydrothermal process.

7 Deficiency in the central compression joint design, causing excess of compressive stress with ruptures and high leakages.

The compression joints, located at the center
of the face slab, behaved well in CFRD’s located in wide valleys with 160 m height. A good example is the performance of Foz do Areia, where a central compression joint was designed as shown on Figure 11.

Recent projects permitted the reduction of the compressive area by placing the mortar pad inside the slab and building deep V notch at the upper portion of the compression joints.

Problems related to this compression joint were presented for the first time in the Tiang Sheng Qiao, 178 m, in China. Figure 12 shows the damage caused to the central joint.

Similar distresses were presented at the dams of Barra Grande (Figure 13), and Campos Novos (Figure 14), Brazil and Mohale, 145 m, Lesotho. Photos 5 and 6 show typical distresses observed in these dams.

Important facts observed in these three dams were that the grading of the basalt rockfill was very uniform, the dam was located in a narrow valley and the compressibility modulus of the fill was relatively low. Main characteristics of the valley and rockfill compressibility are:

<table>
<thead>
<tr>
<th>Dam</th>
<th>Country</th>
<th>$H$ (m)</th>
<th>$A/H^2$</th>
<th>Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barra Grande</td>
<td>Brazil</td>
<td>185</td>
<td>3.15</td>
<td>50</td>
</tr>
<tr>
<td>Campos Novos</td>
<td>Brazil</td>
<td>202</td>
<td>2.60</td>
<td>67</td>
</tr>
<tr>
<td>Mohale</td>
<td>Lesotho</td>
<td>145</td>
<td>3.85</td>
<td>32</td>
</tr>
</tbody>
</table>
Dams located in narrow valleys, shape valley factor $A/H \leq 4$, with low modulus of compressibility, may cause over excess of compression at the central lanes of the face slab with concrete ruptures and distortion of the reinforcement bars.

After a careful analysis of the behavior of these dams it has been concluded:

1. The ruptures occurs at $30\%-40\%$ of the dam height, where the largest deformations are presented.

2. Low modulus of compressibility causes more deformation and high stresses in the central portion of the dam.

3. The design of the compression joint should be reviewed to avoid that the compressive area reduces by elements introduced within the joint.

4. It is important to reduce the thickness of the fill layers and to increase the compaction effort for high dams located in narrow valleys.

5. A non dimensional graph relating the rockfill modulus vs valley shape factor may be useful to identify CFRD’s with potential problems.

Note that the dams under a limit may present problems as experienced in the three dams with ruptures of the face.

Figure 5. shows the effect of the valley VS non dimensional modulus.\(^{(12)}\)

8 Conclusions and recommendations

1. The perimetric joint of a high CFRD always opens and off set. It is important to provide various lines of defense: Internal copper water
stops, external water stops, mastics or migrating fines which can plug the joint. Recent corrugated water stops and products with rheological characteristics are effective to control leakages.

(2) It is good practice to increase the percentage of reinforcement close to abutments when the dam is located in steep valleys as commented in this paper. Also splitting the face slab lanes close to abutments have produced better performance in high CFRDs.

(3) Use of gravels is recommended due to low deformability. However, when rockfill is also used it is important to reduce the layer thickness and to increase the compaction specially if the grading is uniform as presented in some basalts.

(4) It is recommended to carry out geological mapping of the abutments recording weak strata with high compressibility or with low strength parameters affecting the stability of the abutments.

Defining geo mechanical characteristics of the foundation plinth is a practical way to determine the dimensions of the plinth using external and internal slabs as commented in this article.

(5) Use the non dimensional graph to identify if a high CFRD built in a narrow valley may present potential problems of rupture and distresses in the central compression joints. Recent built dams have adopted measures as follows:

1) Reduce the fill layer thickness increasing the number of passes of the vibratory roller.

2) Place the mortar pad to support the copper water stop outside of the theoretical thickness of the slab. Eliminate upper V notch.

3) Increase thickness of the face slab at the central lanes to provide more compression area.

4) Use always anti–spalling reinforcement.

5) Place a filler in the central compression joint to mitigate any excessive compression stress.

6) Treat all the joints with corrugated water stops and mastic as designed for Shuibuya dam.

7) Increase the fill on the face slab.

El Cajon, Mexico; Kárahnjúkar, Iceland; Bakun, Malaysia; Caracoes, Argentina and Shuibuya, China have applied some of these recommendations with good results.

References


