Discussion on design theory for high CFRDs and its application in China

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1. Statistics of CFRDs in China
2. Main technical progresses
3. Typical projects
4. Conclusions
1. Statistics of CFRDs in China

CFRDs have good performance in:

- Safety
- Economy
- Simple and fast
- Environment friendly

Develop fast and become a popular and competitive dam type in China

Statistics of dams (H>30m) constructed in China since 2000:

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRD</td>
<td>149</td>
</tr>
<tr>
<td>Arch Dam</td>
<td>101</td>
</tr>
<tr>
<td>RCC Dam</td>
<td>89</td>
</tr>
<tr>
<td>ECRD</td>
<td>52</td>
</tr>
</tbody>
</table>
Based on Atlas 2009, there are 477 CFRDs higher than 30m which are completed or under construction, and 240 CFRDs in China.
Development of CFRDs in China

More than 15 dams over 200m under construction or to be constructed

Year

Xibeikou
Qinshan
Jiudianxia
Hongliadu
Shuibuya
Jiangpinghe
Houziyan

Height

Typical problems with high CFRDs

- Slab cracks
- Slab voids
- Slab rupture
- Serious leakage

Results:
- Great economic losses
- Increased dam risks

Main reasons:
- Uncoordinated deformation
- Unreliable seepage control system
Panel composite seepage coefficient (cm/s)

- $[K]_1 = 5 \times 10^{-6}$ cm/s
- $[K]_2 = 1.4 \times 10^{-6}$ cm/s
- $[K]_3 = 6.8 \times 10^{-7}$ cm/s
- $[K]_4 = 2 \times 10^{-7}$ cm/s

Unit seepage $K$ for concrete face
2. Main technical progresses

Two new concepts and relevant technologies

**Dam structure**
1. Numerical modeling
2. Material property testing
3. Centrifuge modeling
4. Safety monitoring
5. High-quality & rapid construction

**Seepage control system**
1. Waterstop under large deformations & high pressures
2. Slab crack control
3. Dams on deep covering
4. Slab crushing rupture control
Integrated deformation coordination of High CFRDs

**Basis**

- Contents
  - Dam zones
  - Filled Rock & Slab
  - Temporal coordination
  - ...

**Criteria**

- Upstream & downstream rockfill modulus ratio < 1.5
- Net height of rockfill > 20m
- Pre settlement rate: 2-5mm/month
- ...

**Deformation control**

**Purpose**

Safety of high CFRDs under complex conditions
1. Reveal the rockfill rheological mechanism
2. Grasp the stress and deformation behavior
Integrated deformation coordination
— Material property testing

Large three axis shear apparatus Max.
confining pressure: 7Mpa

Large three axis rheometer
Max. stabilizing time: 6 months
Combination of field/laboratory tests and back analyses

Field tests

Back analysis

Accurately grasp the characteristics of rockfill materials

Determining the properties of rockfill materials based on the results of field/laboratory tests, and back analyses
Integrated deformation coordination — Centrifuge modeling

Modeling the interactions of rockfill dam and cutoff wall, high toe wall and high retaining wall

Large centrifuge

Modeling a CFRD

Centrifuge modeling complex structures
Integrated deformation coordination — Safety monitoring

Data analysis models

Project applications

Advanced safety monitoring equipments
Integrated deformation coordination
Construction control--High-quality & high speed

- Slope-fixing with turned-over formwork

- Rapid construction

- Heavy compaction (25-36t)
Typical section of Bakun CFRD designed by tradition method
Typical section of BAKUN CFRD designed by integrated deformation coordination.
Concept on Stable waterstop structure for high CFRDs

1. Material variety
2. Multi layers
3. Independent & stable layer

Sealing principles  New structure & materials  Sealing simulation tests  Numerical analyses

Sealing safety under large deformations & high pressures to avoid serious leakage

Construction equipments & technologies
Numerical analysis

Test equipment for sealing simulation

Construction for stable waterstop
Seepage control system
— Slab crack control

Modification mechanism of concrete materials

Relationship between lime concentration in water & age

Methods for improving concrete crack resistance & durability

- High performance admixture
- Mixing materials
- Shrinkage reducing
- Toughening fiber
- Steel fiber
Seepage control system
— Dams on deep covering

Jiudianxia CFRD (136.5 m+45 m)
Toe built on deep covering (highest in the world)

Rigid connection
Double wall flexible connection
Flexible connection
Seepage control system
— Slab crushing rupture control

Anti-extrusion loop
International Milestone Project
Shuibuya CFRD (233m) — highest in the world
• Max. leakage < 60L/s; Max. settlement < 2.5 m.
International Milestone Project
Zipingpu CFRD (156m) — successfully resist against Wenquan earthquake
International Milestone Project

Hongjiadu CFRD (179.5m) — constructed at asymmetric deep narrow valley

Max. leakage < 24L/s; Max. settlement < 1.37 m.
Jiangpinghe CFRD (221m, under construction) — constructed at deep narrow valley
Jiudianxia CFRD (136.5m) — constructed at deep covering foundation (45 m)
Jielintai I CFRD (157m) — constructed at high intensity area (designed earthquake magnitude 9)
### 3. Comparison of typical CFRD projects in different design phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Dam</th>
<th>Height (m)</th>
<th>Sett. (cm)</th>
<th>Leak. (L/s)</th>
<th>Construction parameters</th>
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<tbody>
<tr>
<td><strong>Empirical &amp; Non quantitative</strong></td>
<td>Tianshengqiao</td>
<td>178</td>
<td>354</td>
<td>150-70</td>
<td>10t, 6</td>
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<td></td>
<td>Aguamilpa</td>
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<td>10t, 8-10</td>
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<td></td>
<td>Campos Novos</td>
<td>202</td>
<td>&gt;310</td>
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<td>10t, 8-10</td>
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<td></td>
<td>Barra Grande</td>
<td>185</td>
<td>&gt;300</td>
<td>1284</td>
<td>10t, 8-10</td>
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<tr>
<td><strong>Theoretical &amp; quantitative</strong></td>
<td>Shuibuya</td>
<td>223</td>
<td>247.3</td>
<td>46</td>
<td>25t, 8</td>
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<tr>
<td></td>
<td>Sanbanxi</td>
<td>185.5</td>
<td>175.1</td>
<td>300</td>
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<tr>
<td></td>
<td>Jiudianxia</td>
<td>136.5+45</td>
<td>132</td>
<td>40-60</td>
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<tr>
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<td>Bakun</td>
<td>203</td>
<td>227.5</td>
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<td></td>
<td>Nam Ngum II</td>
<td>182</td>
<td>160</td>
<td>40</td>
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<tr>
<td></td>
<td>Jiapinghe</td>
<td>221</td>
<td>-</td>
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<tr>
<td></td>
<td>Houziyan</td>
<td>223.5</td>
<td>-</td>
<td>-</td>
<td>&gt;30t</td>
</tr>
</tbody>
</table>
Findings for the theoretical & quantitative phase compared with the empirical phase:

- More strictly controlled porosity
- Heavier compaction equipment
- Smaller ratio of dam settlement to dam height
- Smaller leakage volume

Better performance of CFRDs in the theoretical & quantitative phase
4. Conclusions

1. CFRDs develop fast and become a popular and competitive dam type in China

2. Two new concepts on dam deformation coordination and stable waterstop structure are used for guiding high CFRD construction.

3. The experiences and lessons on the 200m-height scale CFRDs provide a solid basis for constructing the 300m-height scale CFRDs.
Key issues for super high CFRDs of 300m

1. Study of zoning design — Concept on dam deformation coordination.

2. Study of engineering characteristics and calculation models of rockfill materials — Combination of tests and analysis models.

3. Study of design theory and methodology of face slab structure — Design criteria for zoning of face slab thickness, crack control, etc.
4. Study of construction procedures and technology — standards for compaction of rockfill materials, control of settlement rate, placement of rockfill in stages, etc.

5. Study of high-performance waterstop structure — Concept on stable waterstop structure

6. Study of dam safety in high seismic intensity — seismic analysis for super high CFRDs and engineering measures.

7. Study of monitoring equipments — timely monitoring of super high CFRDs and back analysis.
Thanks for your attention!! Thanks for your attention!! Thanks for your attention!! Thanks for your attention!! Thanks for your attention!! Thanks for your attention!! Thanks for your attention!! Thanks for your attention!!