New Development of Dam Construction Technology in China

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Abstract. With the development of economy and society in China, the water conservancy and hydropower has made rapid development in recent years; construction of reservoir dam has obtained great progress, a number of the reservoir dams have been built with functions of flood control, water supply, irrigation, power generation, shipping and ecology conservation. Meanwhile, the damming technology also made some important breakthroughs, such as CSG (Cemented Sand and Gravel) and RFC (rock filled concrete), as well as new materials, new technology and new methods for intelligent dam. New technologies above have been widely used in dam engineering, and many milestones of dam construction have experienced, such as completion of dam over 100m, 200m and 300m in height. The highest arch dam, concrete face rock-fill dam and roller compacted concrete dam in the world have been successively built in China, especially, a number of world-class water conservancy & hydropower engineering with complex technologies, such as Three Gorges, Xiaowan, Jinping, Xiluodu and Xiangjiaba, have been built and put into operation, marking China’s damming technology ranked in the international advanced level. The construction of reservoir dam in China has played an important role in the development of economy and society as well as energy security and ecological security. The dam technology innovation is promised due to development of information, digital and intelligent technologies. For all aspects of dam construction and management, the digital, internet and automatic control technologies with perception, simulation, analysis, early warning and decision focused, have been utilized to improve the accuracy of construction management, and enhance the dam construction and management level.

Introduction

With the development of economy and society in China, the water conservancy and hydropower has made rapid development in recent years; construction of reservoir dam has obtained great progress, a number of the reservoir dams have been built with functions of flood control, water supply, irrigation, power generation, shipping and ecology conservation. Meanwhile, the damming technology also made some important breakthroughs, such as CSG (Cemented Sand and Gravel) and RFC (rock filled concrete), as well as new materials, new technology and new methods for intelligent dam. New technologies above have been widely used in dam engineering, and many milestones of dam construction have experienced, such as completion of dam over 100m, 200m and 300m in height. The highest arch dam, concrete face rock-fill dam and roller compacted concrete dam in the world have been successively built in China, especially, a number of world-class water conservancy & hydropower engineering with complex technologies, such as Three Gorges, Xiaowan, Jinping, Xiluodu and Xiangjiaba, have been built and put into operation, marking China’s damming technology ranked in the international advanced level.
Status Quo of Dam Construction in China

Hydroelectric Power

At present, our country has built all kinds of reservoir dams over 980,000 with installed hydropower capacity up to 320 GW, ranked first in the world. Presently, there are above 46000 hydropower projects in China; among them, 142 projects with individual installed capacity over 300 MW, and 477 projects with individual installed capacity of 50~300 MW, total installed capacity of 619 projects reached above 257GW, accounting for 80% of total national installed hydropower capacity. The installed hydropower capacity in China realized a leap development from 100GW to 320GW from 2004 to 2015, and reached 1100TWH in 2015. In 2015, non petrochemical energy accounted for 12% of total energy of China, increased by 3.4% in comparison with that in 2010; among them, the share of hydropower make an important contribution.

Status Quo of Dam Construction

The reservoir dams built in China account for half of the total amount of dams in the world. China has about 38,000 dams over 15m in height and 6500 dams over 30m, main dam types cover earth dam (TE) and core wall rockfill dam (ER), arch dam (VA), gravity dam (PG), concrete face rockfill dam (CFRD), roller-compacted concrete gravity dam (RCCPG) and roller-compacted concrete arch dam (RCCVA). Fig. 1 shows the statistics on height and type of dams built in China.

As of 2012, China has built over 180 dams over 100m and 16 dams over 200m. The hydropower projects built and to be built in recent years in China are mainly distributed in the southwest region.

Overview of Dams Built in Recent Years

Dams Built and under Built in Recent Years

In recent years, many high dams have been constructed in China, most of dams close to or over 200m were built after 2000; for example, Three Gorges Dam completed in 2008, Xiangjiaba Project, Xiluodu Dam and Jinping 1st dam which have been built. The relevant parameters are shown in Table 1.
Table 1. Schedule of dams over 200m built and under built in recent years in China.

<table>
<thead>
<tr>
<th>No.</th>
<th>Project name</th>
<th>River</th>
<th>Dam type</th>
<th>Dam height (m)</th>
<th>Storage capacity ($\times10^8$ m$^3$)</th>
<th>Installed capacity (MW)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jinping 1st</td>
<td>Yalong River</td>
<td>Double-curved arch dam</td>
<td>305</td>
<td>77.6</td>
<td>3600</td>
<td>2015</td>
</tr>
<tr>
<td>2</td>
<td>Xiaowan</td>
<td>Lancang River</td>
<td>Double-curved arch dam</td>
<td>294.5</td>
<td>150.43</td>
<td>4200</td>
<td>2010</td>
</tr>
<tr>
<td>3</td>
<td>Xiluodu</td>
<td>Jinsha River</td>
<td>Double-curved arch dam</td>
<td>285.5</td>
<td>126.7</td>
<td>13860</td>
<td>2015</td>
</tr>
<tr>
<td>4</td>
<td>Xiangjiaba</td>
<td>Jinsha River</td>
<td>Gravity dam</td>
<td>162</td>
<td>51.63</td>
<td>7750</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Houziyan</td>
<td>Dadu River</td>
<td>Concrete faced rockfill dam</td>
<td>223</td>
<td>7.04</td>
<td>1700</td>
<td>2015</td>
</tr>
<tr>
<td>6</td>
<td>Dagangshan</td>
<td>Dadu River</td>
<td>Double-curved arch dam</td>
<td>210</td>
<td>7.42</td>
<td>2600</td>
<td>2015</td>
</tr>
<tr>
<td>7</td>
<td>Nuozadu</td>
<td>Lancang River</td>
<td>Earth core rockfill dam</td>
<td>261.5</td>
<td>237.03</td>
<td>5850</td>
<td>2014</td>
</tr>
<tr>
<td>8</td>
<td>Shuangjiangkou</td>
<td>Dadu River</td>
<td>Earth core rockfill dam</td>
<td>314</td>
<td>31.15</td>
<td>2000</td>
<td>Under construction</td>
</tr>
<tr>
<td>9</td>
<td>Lianghekou</td>
<td>Yalong River</td>
<td>Earth core rockfill dam</td>
<td>295</td>
<td>101.54</td>
<td>3000</td>
<td>Under construction</td>
</tr>
<tr>
<td>10</td>
<td>Wudongde</td>
<td>Jinsha River</td>
<td>Double-curved arch dam</td>
<td>270</td>
<td>76</td>
<td>10200</td>
<td>Under construction</td>
</tr>
<tr>
<td>11</td>
<td>Changheba</td>
<td>Dadu River</td>
<td>Earth core rockfill dam</td>
<td>240</td>
<td>10.75</td>
<td>2600</td>
<td>Under construction</td>
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<td>12</td>
<td>Huang Deng</td>
<td>Lancang River</td>
<td>RCC Gravity dam</td>
<td>203</td>
<td>14.18</td>
<td>1900</td>
<td>Under construction</td>
</tr>
</tbody>
</table>

Dams to Be Built in China

The next few years, China will successively build a large number of high dams with installed hydropower capacity up to 350-400 GW by 2020, so as to meet the commitments of the emission reduction that non-fossil energy accounts for 15% of total energy consumption in China. Such high dams are mainly concentrated in Jinsha River, Nu River, Dadu River and Lancang River. Table 2 sees as part of the dams to be built.

Table 2. Some dams to be built in China.

<table>
<thead>
<tr>
<th>No.</th>
<th>Project name</th>
<th>River</th>
<th>Dam type</th>
<th>Dam height /m</th>
<th>Storage capacity, $10^8$ m$^3$</th>
<th>Installed capacity /MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Songta</td>
<td>Nu River</td>
<td>Double-curved arch dam</td>
<td>307</td>
<td>63.12</td>
<td>4200</td>
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<tr>
<td>2</td>
<td>Maji</td>
<td>Nu River</td>
<td>Double-curved arch dam</td>
<td>300</td>
<td>46.96</td>
<td>4200</td>
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<tr>
<td>3</td>
<td>Rumei</td>
<td>Lancang River</td>
<td>Clay core rockfill dam</td>
<td>315</td>
<td></td>
<td>2400</td>
</tr>
<tr>
<td>4</td>
<td>Baihetan</td>
<td>Jinsha River</td>
<td>Double-curved arch dam</td>
<td>289</td>
<td>206.02</td>
<td>14000</td>
</tr>
<tr>
<td>5</td>
<td>Xia'erjia</td>
<td>Dadu River</td>
<td>TBD</td>
<td>223</td>
<td>28.00</td>
<td>540</td>
</tr>
<tr>
<td>6</td>
<td>Mengdigou</td>
<td>Yalong River</td>
<td>Double-curved arch dam</td>
<td>200</td>
<td>8.535</td>
<td>1500</td>
</tr>
<tr>
<td>7</td>
<td>Yangfanggou</td>
<td>Yalong River</td>
<td>Double-curved arch dam</td>
<td>155</td>
<td>4.558</td>
<td>1500</td>
</tr>
</tbody>
</table>
New Technologies of Dam Construction in China

RFC Dam Construction Technology

Rock-filled concrete (RFC), a new type of concrete based on the technology of SCC [1-2], was developed for use in massive structures in China [3-5]. The rock-filled concrete technology combined the advantage of masonry and concrete. A lot of stones are used to decrease the consumption of cements, lower the hydration thermal rise and the shrinkage of the concrete, and eliminate the cooling pipe. The employment of SCC frees the vibration, saves much labor.

For RFC, the first stage is the transportation and leveling of rubble/cobble whose grain size is larger than 300mm, called stone in RFC. The layers of stone, called the “rockfill”, have usually 1.5-2.5m height. Then, a high ranking SCC, called high self-compacting concrete (HSCC), will be poured at the top of the rockfill. HSCC can fill the voids of the rockfill due to its high fluidity and anti-segregation. After hardening, RFC, composed of HSCC and stone, has the similar properties of mass concrete. According to the statistics of more than 50 engineering projects, HSCC in RFC is only 40%-45% in volume. Much less cements are used in RFC than traditional mass concrete.

The RFC technique is simple in construction process, it includes mainly two processes: placing of stones, production and pouring of HSCC. Both can be finished by machines. No vibration process need.

The RFC technology, since its first engineering application in 2005, has been successfully applied in more than 80 projects in China. Most of the projects constructed are medium and small-sized, with dam height of 30m-70m: wherein, the 30m-50m high RFC dam projects for about 40.3%, and the 50m-70m high RFC dam projects for about 48.6%. In all dam construction projects, the RFC gravity dam projects accounts for about 84.4% (construction of gravity dams: 71.8%, and reinforcement of gravity dams: 12.6%), and RFC arch dam projects accounts for about 15.6% (construction of arch dams: 1.6%, and reinforcement of arch dams: 14.0%).

From the statistics of engineering projects in China, Comprehensive cost of RFC construction can be reduced by 10% to 30% under the same conditions, compared with normal or roller compacted concrete. The cost reduction comes from the saving of cement, lower the requirement of construction equipment and labor.

CSG Dam Construction Technology

The cementation material dam is a new type of dam between earth & rockfill dam and concrete dam, which idea is to adjust the dam structure so as to adapt to the material properties and make full take advantage of local materials. In accordance with the particle size of raw material, it can be subdivided into cemented earth dam, cemented sand and gravel dam and cemented rockfill dam. This new type of dam can make full use of local materials, such as cement, fly ash, limestone powder, mortar and concrete, and bond soil, sand and stone together to form a kind of dam material with a certain strength, shear-bearing capacity and anti-erosion ability; and then determine the dam section according to the principle to fully play the properties of dam material, so as to achieve the purpose of safety, economy and environmental protection.

The cementation material dam remains the characteristics of gravity dam of which maintains stability by gravity; this dam can be divided into anti-seepage, anti freeze thaw and protection parts according to their functions, of which will be separated with main body of dam. The main body of dam mainly bears pressure and shall avoid being tensioned, giving full play to the compressive strength of the material; meanwhile, it shall avoid the over-strength of materials for the traditional gravity dam as possible. This kind of dam has high safety without breaking down under conditions of overtopping; moreover, it can be constructed more rapidly, economic and environment-friendly.

Generally, the trapezoidal cross section is employed for the kind of dam, which the sectional area is between concrete gravity dam and concrete faced rockfill dam, so it owns the advantages of both of them. Compared with concrete gravity dam, the section of dam body is relatively larger, the stress is distributed relatively uniform and kept at low levels; Compared with rockfill dam, its section is significantly reduced, the cemented materials are added into dam material and formed into the cemented body after rolling, so that the dam has a certain ability to resist erosion.
This technology can also be used to build water conservancy and hydropower ancillary facilities, such as dike and cofferdam.

**Intelligent Construction Technology of Concrete Dam**

The intelligent construction of concrete dam, also known as intelligent dam construction[6,10-11], is mainly based on IoT (Internet of Thing), automatic control and cloud computing technology to conduct the real-time online management and analysis on the dam structure during full life cycle, and implement the intelligent control on dam performances. Its core is the intelligent monitoring system.

**Intelligent Monitoring of Temperature Control and Cracking Prevention.** Intelligent monitoring system is similar to the artificial intelligence, including the "perception", "Internet", "analysis & decision-making" and "control". "Perception" is mainly to collect the key elements; "Internet" is to achieve multi-level online communication and realize close connection, communication and sharing among all remote and heterogeneous terminals and software & hardware resources by means of information technology; "Control" consists of the artificial intervention and intelligent control; among them, the former is mainly to form various instructions of early warning, alarm and feedback of schemes and measures on the basis of the intelligent analysis, judgment and decision; and then carry out human intervention according to the instructions; the latter is to mainly control micro-environmental indicators, such as temperature, humidity and wind speed, as well as concrete curing and cooling control by automation and intelligent means. "Analysis & decision-making" is the core of whole system, namely makes decisions through learning, memory, analysis, judgment, inversion and prediction. With "Analysis & decision-making" as the core, "Perception", "interconnection" and "control" can complement and inter-depend each other, and form an integrated intelligent monitoring.

"Intelligent monitoring system" contains two links of "monitor" and "control", and "monitor" is to fully detect, monitor and learn about the information of each construction link on temperature control and cracking prevention through perception and interconnection functions; "Control" is to carry out the intelligent control or manual intervention against factors to influence the temperature during process. Fig. 2 is an intelligent monitoring system of dam site. The sensors are arranged at all links of concrete construction, including mixing building, casting bin surface, cooling water chamber and concrete surface; the sub-control stations need to set up in the dam area as necessary to collect and manage the information and sends out the control commands, and intelligently control the variables of each link where appropriate. Each sub-control station can exchange information between and main control room through wireless transmission, so as to constitute an integrated monitoring system.

Figure 2. Schematic diagram of intelligent monitoring system in site.
Since 2009, some functions of intelligent monitoring system have been successfully applied in Jinping 1st stage, Xiluodu, Ludila, and Zhangmu Projects. At present, this system is being applied in other engineering, which the construction safety and quality of projects have been improved since the system has been implemented. For example, since the intelligent control system was introduced during the construction of Jinping 1st stage arch dam, no temperature cracks have been identified.

**Intelligent Monitoring Technology for Construction Quality of RCC Dam.** It is shown from the engineering practices that dam seepage is the most common quality issues of RCC dam after the reservoir is filled with water. Due to construction process and material characteristics of roller compacted concrete, the insufficient rolling compaction will cause poor impermeability of concrete; the insufficient interlayer rolling frequency and vibration strength may cause poor concrete floating and bad interlayer bonding; as one of upstream anti-seepage layer, the upstream distorted concrete layer may have poor impermeability when the grouting amount or artificial vibration is not sufficient. Three factors above are main reasons for leakage of RCC dam. In order to overcome the above problems, the intelligent roller compaction equipment and technology and distorted concrete additive vibration equipment and technology have been developed.

Intelligent rolling equipment is to install GPS and vibrometer in the conventional vibration roller to track and record the travel track and vibration state of vibration roller, set the rolling parameters according to the rolling process as required, including free-vibration rolling times and vibration rolling times, which can effectively avoid the missed rolling, as shown in Fig. 3.

Intelligent slurry dispensing is to install an automatic cement slurry dispensing device on the vibrating machine, so as to quantitatively grout cement slurry into the spreading RCC concrete according to the setting parameters, and ensure the content of cement slurry in concrete to meet the design requirements. Intelligent vibration is to input the vibration parameters from the test into the vibrator, so as to automatically adjust vibration strength and time of each part, and record such data to ensure concrete vibration meet design requirements without over vibration or missed vibration. See Fig. 3.

It is shown from the practices that the construction quality can be guaranteed for RCC dam since two technologies above have been employed.

**Intelligent Earth-Rockfill Dam Construction Technology**

China is building and will build a number of world-class super high earth rockfill dam, such as Nuozhadu core wall rockfill dam (261.5m) on Lancang River and Lianghekou core wall rockfill dam (293 m) on Yalong River, both of them are facing new technical problems during the construction quality control. The super high earth rockfill dam is featured as huge work quantity, complicated division of stage and zone, and high requirements for dam filling and rolling quality. Due to more human disturbance and extensive management, the routine QC means is difficult to ensure the quality of filling and rolling process, which may cause security risks.

The technological progress has been promoted with the concept of "digital dam" put forward [7-9] and the application in Nuozhadu engineering. Based on the GPS, GPRS, PDA and information technology, the real-time monitoring and information feedback can be conducted for dam material transportation and dam construction parameters, test results and monitoring data, so an information application and technology analysis platform can be provided for quality control and safety diagnosis of dam during construction process. With vehicle-mounted GPS positioning device, the entire-process monitoring can be realized for transport vehicles on dam from stock yard to the filling site on dam surface, so as to provide the basis to ensure the accurate material unloading on the dam and optimization scheduling of transport vehicles, and further realize the whole process, meticulous, online real-time monitoring for almost all rolling parameters, and provides a new way of quality control for the HCRFD (high core-wall rockfill dam) construction, and can be promoted into RCC dam.
In the engineering application of Nuozhadu HCRFD dam, the real-time monitoring has been realized for all 15 sets of rolling machine and nearly 200 dam transport vehicle during the construction of dam, which not only effectively controlled discharging accuracy and rolling parameters, such as the rolling times, driving speed, vibration force and compaction thickness, ensure each rolling parameter in line with the control requirements, but also lowered reworks, optimized the allocation of resources, improved the construction efficiency; and established the construction quality control system of "monitoring→analysis→feedback→settle" on the basis of digital dam system, and incorporated monitor result into unit quality acceptance link, which has achieved remarkable effect.

Conclusions

The construction of reservoir dam in China has played an important role in the development of economy and society as well as energy security and ecological security. The dam technology innovation is promised due to development of information, digital and intelligent technologies. For all aspects of dam construction and management, the digital, internet and automatic control technologies with perception, simulation, analysis, early warning and decision focused, have been utilized to improve the accuracy of construction management, and enhance the dam construction and management level. As future dam project in China is featured as large scale and complex geological conditions, and will face difficult technical and construction issues, it is more necessary for the support of technological innovation.

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