Discussion on construction and type selection of China high dams

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Abstract: At the beginning of 21st century, with the rapid and steady development of China economy, a lot of large scale hydropower projects with large dams from 200 m to 300 m high are being or to be built. China dam constructions are reaching the level of 300 m high arch dam, 250 high CFRD (concrete face rockfill dam) and 200 m high RCC (roller compacted concrete) gravity dam. Due to the safety and the economy, the type selection for high dams has become the key issue during the argumentation for the hydropower projects, and further efforts are still needed in this aspect for high dams. After reviewing the high dam constructions in China and abroad, authors proposed some advices for the selection of dam types, and hope that it can provide some helpful information for the researches and the design of high dams.
Key words: construction of high dams; selection of dam types; project layout

1 Review of high dams built abroad

According to the preliminary statistics, large dams more than 200 m built abroad are listed in Table 1, there are 15 rockfill dams, 16 arch dams, 3 gravity arch dams, 5 gravity dams and 1 multiple arch dam. Most of the listed large dams were built from 1960s to 1980s, which were on behalf of the leading position in dam construction in the world during that period.

Most of the built high dams are rockfill dams and arch dams, because consumption of cement, reinforcement and flyash is less than that of gravity dam, construction time is shorter and then are more competitive. In addition, more experiences have been obtained for these two dam types, including the experiences of construction in the region with high seismicity.

From 1990s to the beginning of 21st century, due to the environmental issues and the change of energy demands, seldom achievement of large dam construction was made in both developed countries and developing countries, and there are few newly built large dams more than 200 m high. However, during this period, CFRD (concrete face rockfill dam) and RCC (roller compacted concrete) dam were developed rapidly and become more competitive.

2 Actuality of high dam construction in China

In recent 50 years, especially in the past 20 years, China has made great achievements in the construction of hydropower and water conservancy projects, dam techniques own the leading position in the world. By entering 21st century, with the continuous increasing of electric demand in China, hydropower developed more rapidly, some 200 m even 300 m high dams are under construction or to be built, the level of dam construction is reaching 300 m high arc dam, 250 m high CFRD and 200 m high RCC gravity dam.

2.1 High arch dams

Some high arch dams built or being built in China are listed in Table 2. It is obvious that, the techniques of 200 m high arch dam are successful, and China has established a sound technique foundation for construction 300 m high arch dam. However, there is no construction experience of 300 m high arch dam in the world, further efforts should be given to the following aspects, utilization of bedrock and excavation depth of abutment, control over the deformation of foundation and abutment, effects of unloading relaxed bedrock on the stresses, deformation and stability of arch dam, seismic safety of high arch dam in high seismicity region, alkaline reaction of concrete aggregates.

2.2 High gravity dams

Some high gravity dams built or being built in China are listed in Table 3, and there are not many high gravity dams about 200 m high. Longtan and Guangzhou are RCC gravity dams. Compared with conventional concrete gravity dam, RCC dams are more competitive as far as cost and construction time are concerned. After the efforts in recent 20 years, China

Received 23 *February* 2009

Table 1 Large dams more than 200 m high built abroad

No.	Dam name	Country	Dam type	Dam height /m	Crest length /m	Dam volume /10^4 m^3	Seismic intensity	Storage capacity /10^8 m^3	Installed capacity /MW	Completed time
1	Rogun	Tadzhikistan	CWRD	335	660	7 550	9	133	3 600	/
2	Nurek	Tadzhikistan	CWRD	300	704	5 800	9	105	2 700	1980
3	Kambarazin Ⅰ	Kirgizstan	DBRD	275	560	11 220	8	36	1 900	/
4	Borusa	Costarica	CWRD	267	700	4 300		67		/
5	Chicoasen	Mexico	CWRD	261	485	1 537	9	16.1	2 400	1980
6	Tehri	India	CWRD	260	575	2 703	8	35.5	2 000	/
7	Jishao	India	CWRD	253	360			24		/
8	Guavio	Colombia	CWRD	247	390	1 776		10.2	1 600	1989
9	Mica	Canada	CWRD	242	792	3 211	7 ~ 8	247	2 610	1973
10	Parati	Colombia	CWRD	240	550	2 360		110		/
11	Chivor	Colombia	CWRD	237	280	1 030	9	8.2	100	1975
12	Oroville	America	CWRD	230	2 019	6 116	7 ~ 8	43.6	644	1968
13	Ketangweini	South Africa	CWRD	213.3	900					1977
14	Keban	Turkey	CWRD	207	602	1 530	8 ~ 9	306	1 240	1974
15	Karun Ⅲ	Iran	DCAD	205	388	115	8 ~ 9	27.5	2 000/3 000	2001
16	Bakun	Malaysia	CFRD	205	740		6 ~ 7	438	2 400	UC
17	Inguri	Georgia	DCAD	271.5	605	396	8	11.1	1 640	1980
18	Vaiont	Italy	DCAD	262	190	35	7 ~ 8	1.7	9	1961
19	Mauviosin	Switzerland	DCAD	237/250.0	520	203/211	8	1.75/2.05	384	1958/1991
20	El Cajon	Honduras	DCAD	234	382	160	7 ~ 8	56	60	1985
21	Chirker	Georgia	DCAD	232.5	333	136	8	27.8	1 000	1978
22	Contra	Switzerland	DCAD	220	380	66	6 ~ 7	1.05	105	1965
23	Mratinjie	Yugoslavia	DCAD	220	268	74	9	8.8	360	1976
24	Luzzone	Switzerland	DCAD	208	530	133	7	0.88	418	1963
25	Dez	Iran	DCAD	203	212	46	9	33.5	1 280	1963
26	Zimapan	Mexico	DCAD	203	130	21		14.6	29.2	1995
27	Almendra	Spain	DCAD	202	567	219	8	26.5	810	1970
28	Berke	Turkey	DCAD	201	270	73		4.27	51.45	/
29	Khudun	Georgia	DCAD	200.5	545	148	8	3.7	2 100	1991
30	Karun Ⅰ	Iran	DCAD	200	380	119		31.4	1 000/2 000	1976
31	Kolnbrein	Austria	DCAD	200	620	160 + 46		2.1	881	1977
32	Ross	America	Arch dam	164.6/201.4	380	69.5/80	8	17.4	400	/
33	Sayano–Shushenskaya	Russia	GAD	245	1 066	908	7	313	6 400	1989
34	Hoover	America	GAD	221	379	336	8 ~ 9	348	2 451	1936
35	Glen Canyon	America	GAD	216	475	375	7 ~ 8	333	900	1966
36	Grand Dixence	Switzerland	GD	285	695	600	6 ~ 7	4	864	1961
37	Bhakra	India	GD	226	518	413	9	96.2	1 050	1963
38	Dworshak	America	GD	219	1 006	493	7 ~ 8	43	1 060	1973
39	Toktogul	Kirgizstan	GD	215	292.5	335	9	195	1 200	1978
40	Lakhwar	India	GD	204	454	287	7 ~ 8	5.8	300	/
41	Manic V	Canada	MAD	214	1 314	226		1 419	1 344	1968

Note: CWRD—core wall rockfill dam; DBRD—directional blast rockfill dam; DCAD—double curvature arch dam; GAD—gravity arch dam; MAD—multiple arch dam; GD—gravity dam; UC—under construction

Table 2 Some high arch dams built or being built in China

No.	Dam name	Status	River	Dam height/m	Crest length/m	Dam volume /10^4 m^3	Storage capacity /10^8 m^3	Installed capacity/MW
1	Ertan	Completed	Yalong River	240	774.7	414	58	3 300
2	Longyangxia	Completed	Yellow River	178	1 226	174.9	276.3	1 280
3	Wujiangdu	Completed	Wu River	165	395	186.5	21.4	630
4	Dongfeng	Completed	Wu River	162	263	42.5	10.3	510
5	Lijiaxia	Completed	Yellow River	155	414.4	75	16.5	200
6	Jinping I	UC	Yalong River	305	568.6	428.4	77.6①	3 600
7	Xiaowan	UC	Lancang River	292	892.4	755	150.43	4 200
8	Xiluodu	UC	Jinsha River	278	698.1	558	126.7	12 600
9	Laxiwa	UC	Yellow River	250	459.6	258	10.79	4 200
10	Goupitan	UC	Wujiang River	232.5	552.6	245	64.55	3 000

Note: ① The storage capacity below normal water level.

Table 3 Some high gravity dams built or being built in China

No.	Dam name	Status	River	Dam height/m	Crest length/m	Dam volume /10^4 m^3	Storage capacity /10^8 m^3	Installed capacity/MW
1	Three Gorges	UC	Changjiang River	181	2 309.5	2 820	393①	18 200
2	Longtan	UC	Hongshui River	192.00/216.5②	761.26/849.44②	580.00/720.00②	162.10/272.7②	4 200
3	Guangzhao	UC	Beipang River	200.50	410	271.1	32.45	1 040
4	Xiangjiaba	UC	Jinsha River	161	909.3	815	51.63	6 000
5	Jin'anqiao	UC	Jinsha River	160.0	640	480	9.13	2 400

Note: ① The storage capacity below normal water level; ② Normal water level of 400 m.

has mastered the technique system of 200 m high RCC gravity dam and owns the leading international position. As for the rural region with poor transportation conditions, gravity dam more than 200 m high is not very competitive due to the huge transportation cost.

2.3 High earth rockfill dams

Some high earth rockfill dams built or being built in China are listed in Table 4. Till now, Xiaolangdi is the highest one built in China, whose core wall material is made of loamy soil. The nature soil material near Nuozadu project has too many fine grains, so the machined gravel should be mixed with the soil material. Whereas, the nature soil material near Pubugou project has too many coarse grains, so the fine grain should be mixed with the screened soil materials. 300 m high Nurek is the highest earth rockfill dam built in the world, so the technique for building 300 m high earth rockfill dam is feasible, but China has to attach more importance to such aspects as the self-adaptable deformation between core wall and rockfill dam shell, the exploitation, maching and transportation to dam for the core wall material.

Table 4 Some high earth rockfill dams built or being built in China

No.	Dam name	Status	River	Dam height/m	Crest length/m	Dam volume /10^4 m^3	Storage capacity /10^8 m^3	Installed capacity/MW
1	Xiaolangdi	Completed	Yellow River	160	1 667	5 073	126.5	1 800
2	Nuozadu	UC	Lancang River	261.5	608.2	3 495	237	5 850
3	Pubugou	UC	Dadu River	186	573	2 400	53.9	3 300

2.4 High CFRD

China has built many CFRD since 1980s. According to the preliminary statistics, by the end of 2004, there are 150 CFRD built or being built in China, 37 of them are more than 100 m high, some high CFRD built or under construction are listed in Table 5. China has the highest CFRD and owns the leading position in CFRD construction in the world, achieved many experiences of dealing with all kinds of climate, topography, geological conditions.

Besides the design and construction experiences, China has also achieved many experiences of the operation of CFRD, the valley characteristics at the dam site, deformation and leakage of dam, crack and empty of concrete face of some 200 m high CFRD are listed in Table 6.

Table 5 Some high CFRD built or being built in China

No.	Dam name	Status	River	Dam height/m	Crest length/m	Dam volume /10^4 m^3	Storage capacity/10^8 m^3	Installed capacity/MW
1	Hongjiadu	Completed	Liuchong River	179.5	427.8	920	49.47	600
2	Tianshengqiao I	Completed	Nanpan River	178	1 104	1 800	102.6	1 200
3	Shuibuya	UC	Qing River	233	660	1 526	45.8	1 600
4	Sanbanxi	UC	Qingshui River	185.5	423.3	828.3(Main rockfill)	40.95	1 000
5	Tankeng	UC	Xiaoxi	162	507	980	41.9	60
6	Jiangpinghe	UC	Loushui	219		780	13.66	450

Table 6 Operational information of some 200 m high CFRDs

Dam name	Valley ratio of width to height	Maximal settlement/cm (measured time)	Settlement to dam height/%	Crack number of concrete face	Crack number of plinth	Leakage /(L·s^{-1})	Emptying under concrete face/mm
Tianshengqiao I	6.2	346.0(2001)	1.94	4 537	About 400	183/80	150
Hongjiadu	2.38	132.2(March, 2006)	0.74	33	117	59/20	11.9
Shuibuya	2.83	187.2(June, 2006)	0.80	255 (Stage Ⅰ)		–	40 (Stage Ⅰ)
Sanbanxi	2.28	144.96(Nov., 2005)	0.78	75	73	–	

From Table 6, it is may be concluded that, for the CFRD completed after 2000, the settlement is relatively small, less than 1 % of dam height, there are less cracks in the concrete face, leakage and emptying under concrete face are also small, and the CFRD run with high performance. The design, construction and operation experiences set up a sound basis for the construction of higher CFRD in the world.

3 Characteristics and requirements for design of extra-high dams

3.1 Extra-high dams and special requirements for design

According to the planning of hydropower development in China, a lot of high dams are planned to be built in the west region to regulate the runoff and improve the utilization of water resources, some dams about 250 m to 300 m high even more than 300 m high (named as extra-high dams) to be built are listed in Table 7.

Compared with common high dams, extra-high dams have the following characteristics:

1) Higher risk due to larger storage capacity, installed capacity and comprehensive benefits;

2) Higher safety class due to higher risk. And the design standards are also higher, for example, the flood control standards for dam, spillway, and structures for energy dissipation;

Table 7 Large dams more than 250 m high under design in China

No.	Dam name	Dam type	River	Dam height /m	Crest length/m	Storage capacity /10^8 m^3	Installed capacity/MW
1	Baihetan	Arch dam	Jinsha River	277	728	192	12 000
2	Longpan	Arch dam	Jinsha River	276	563	389	6 000
3	Gushui	Under argumentation	Lancang River	>300	≈570	≈40	2 200
4	Lianghekou	Earth rockfill dam	Yalong River	293	616	101.54①	2 760
5	Shuangjiakou	Earth rockfill dam	Dadu River	312	≈650	27.32①	2 000
6	Maji	Under argumentation	Nu River	300	940	47	4 200
7	Songta	Under argumentation	Nu River	307	962	63	4 200

Note: ① The storage capacity below normal water level.

3) Seismic design more difficulty for high dams, especially those in the region with high seismicity or those close to seismotectonic fault;

4) Higher requirements for dam shape, details and performance of construction material, due to the higher stresses in the dam and less safety margin for strength;

5) Higher requirements for the integrity, the strength and the deformation modulus of bedrock, for strengthening treatment to foundation, due to the high-

er stress in the foundation;

6) Higher requirements for quality control over concrete temperature or over moisture content of earth and rockfill material, due to the longer construction time, which makes it inevitable to suffer cold, rainy or high temperature season;

7) Higher requirements for the construction of dam and foundation below the lowest water level. It is difficulty to repair them after emptying the reservoir.

Because of the above special requirements, China active design codes specify that special researches should be conducted for dams more than 200 m high, and it is necessary to determine their special safety criteria according to the actual conditions, including structure classification, design reference period, flood control standard, seismic fortification criteria, and factor of stability and strength.

3.2 Requirements for selection of dam type

In order to regulate the runoff in the river, high dams with huge reservoir are usually built in the upper reaches of the river, where land resource is limited, transportation condition is poor. In addition, the valley is narrow and the banks are steep, the geological conditions are very complex, and flood discharge capacity is high due to large flow and high water head. So it is very necessary to conduct careful investigation, test and analysis, compare different dam sites, dam axis and then select the more rational one.

After the selection of normal water level and installed capacity, dam site, dam type and project layout greatly influence the cost and the construction time of the project, they are the key issues for global design. Besides self-adaptability, rockfill dam, gravity dam and arch dam have differences in project layout, especially flood discharge layout, construction division, natural construction material, construction layout, dam construction method, cost and construction period. Dam types and project layouts should be compared and then selected at the same dam site or at different dam sites.

Dam is the most important structures for projects with high dams for its serious secondary disaster if fail. So, safety and reliability is the first factor for selecting the dam type. In addition economy, technical reliability, convenience to construction, operation and maintenance, and environmental protection should also be accounted for.

3.3 Project layout of extra-high dams

3.3.1 Rockfill dam

Due to making use of local natural materials, more flexible to the geological condition of foundation, construction done with high mechanization, shorter construction period and lower cost, rockfill dams are developed rapidly and enjoy a prosperous future. High rockfill dam and its layout have special characteristics as follows:

1) Mass-excavation and mass-filling is the distinct feature, so the global balance between excavation and filling is very important, which makes cost low and construction rapid;

2) Achievements on dam zoning and materials, especially core wall material, harmonize the deformation between concrete face and rockfill or between core wall and rockfill dam shell, and establish a good basis for the development of extra-high one;

3) Flood is mainly discharged through open spillway, secondarily through pressure tunnel, the outlet of the open spillway is far away from the dam toe, that ensure the safety of flood discharge for the dam;

4) Due to huge filling and high construction intensity, the consistence between construction machines, planning of construction field and roads are important to ensure the safety in flood season and actualize the goal of generating power in advance.

3.3.2 Arch dam

The site with narrow valley, symmetrical topography and geological conditions, good integrity of foundation and abutment, is propitious to arch dam. Due to powerful overload capacity, discharge from dam and low costs, arch dam becomes more competitive, sometimes the first choice. High arch dam has following special features:

1) The valley shape at the dam site and the integrity of abutment are key issues to the safety and the economy of arch dam, excavation of and treatment to foundation should make arch dam symmetry in order to improve the bearing;

2) Most of the flood flow can be discharged through top opening and middle opening of the dam, flood discharge layout is more flexible;

3) Most of arch dam projects adopt underground power plant, which is nearly independent of the dam and the spillway structures, it reduces the interference between different structures during construction and operation;

4) Innovation of dam layout makes it possible to build arch dam at wide valley, on deep river alluvium, on not symmetry foundation and on deeply weathered and unloaded foundation, with the help of special foundation treatment, or placing gravity block at abutment, special arch at the bottom, etc.

3.3.3 Gravity dam

Simple bearing mechanism, simple construction method, flexible layout of spillway structures and pow-

er plant still make gravity dam competitive. Gravity dam has many advantages as follows:

1) Owns sound capacity against flood even overtopping, openings for flood discharge, sediment flushing and emptying can be placed within the dam, and the layouts are simple and easy to solve the problem of energy dissipation;

2) According to the high stresses at heel and toe of the dam, but low stresses inside the dam, zoning for dam concrete can lower the cost;

3) With the development of flood control standard, safety criteria for stability and jointly bearing between dam and power plant at dam toe, the dam type is more reasonable and treatment to foundation is more economic;

4) Intake inside the dam and penstock on the downstream slope make plant layout more flexible, it can shorten the length of penstock and optimize the project layout.

4 Discussions about choice of dam type

During comparing and selecting dam sites, dam types and project layouts, most of the importance should be given to a. fundamental data; b. construction conditions; c. comprehensive comparison with all the related aspects. After comparison of fundamental data and construction conditions, we can select the representative schemes for further comparison. Through the comprehensive comparison, we can determine the final choice.

Selection of dam types should account for many aspects, such as rive segment for the selection of sites, topography and geology of dam site, distribution and performance of natural construction material, designing conditions for spillway structures, design and layout for diversion structures, method and measurement for dam construction, land requisition and resettlement, environmental protection, construction period and cost, convenience to construction and operation.

Nowadays techniques, experiences of design, construction and operation make it feasible to build 200 m high arch dam, gravity dam or rockfill dam at proper site, so flexibility for selection of dam types is relatively larger. However, there are few experience to construct extra-high dams, such as 300 m high or higher arch dam and earth rockfill dam, 250 m high or higher CFRD and gravity dam. So, when building an extra-high dam, more prudence and importance should be attached to at least the following aspects:

1) Gravity dam has many advantages as mentioned above, but due to the huge consumption of cement, flyash and reinforcements and expensive transportation fee, longer construction time, lack of construction experience of 250 m high or higher gravity dam in China, gravity dam usually is not the first choice of dam more than 250 m high;

2) China owns construction experience of 240 m high arch dam and design experience of 300 m high arch dam, but the safety of arch dam greatly depends on the integrity, the strength, the deformation performance of foundation and abutment, it is relatively more difficult to select a proper site for extra-high arch dam or deal with the weakened foundation. In addition, compared with rockfill dam, the transport fee of cement, flyash and reinforcement is much more expensive, the cost is relatively expensive in many cases, especially in the rural region with poor transportation conditions;

3) Except for Nurek, there is no other 300 m high earth rockfill dam built in the world. But most of built dams or high dams are earth rockfill dam, which is the most competitive one in some cases, especially the natural material meets the relative requirements and the discharge flow is relatively small. But we should pay special attention to the huge amount of excavation and filling, which may destroy more vegetation; long transportation distance for core wall material in some cases, machining of core wall material for not well-graded natural soil material, land requisition and resettlement for core wall material; diversion, especially the late diversion; the difference of deformation between core wall and rock fill dam;

4) CFRD owns the advantages of safety, economy and adaptability, so CFRD is one of the most competitive dam type at many sites. China accumulated design and construction experiences of 250 m high CFRD through the building of Shuibuya project. The experiences make it feasible to build a 300 m high CFRD after further researches, especially on the control over main deformation, secondary deformation and creep deformation at all stages.

5 Conclusions

1) Nowadays China hydropower resources are developing at an unprecedented speed, some 200 m even 300 m high dams are under construction or to be built, the level of China dam construction is reaching 300 m high arch dam, 250 m high CFRD and 200 m high RCC gravity dam.

2) At the early half of the 21st century, there are still many extra-high dams to be built in Jinsha River, Lancang River, Nu River, Yalong River, Dadu River and the upper reaches of Yellow River, the selection of

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