Discussions on the Technical Issues of the Construction of 300m High CFRD

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Abstract] With the technical progress of modern CFRD construction, more and more high CFRD were constructed. But for CFRD with the height about 300m, there are still technical challenges in the design and construction. By summarizing the experiences of previous high CFRD construction and the analysis of the main features of 300m high CFRD, it could be concluded that the stability of dam slope and seepage safety of rockfill will not be the crucial issues for determining the feasibility of building 300m high CFRD. For the construction of CFRD with the height over 300m, the main focus should be on the control of rockfill deformation and improvement of stress status of concrete face slabs. For doing this, a series engineering measures were proposed, which include optimization of rockfill zoning, selection of construction materials, improvement of rockfill compaction, arrangement of the time for concrete face slab construction, design of the thickness of concrete face slab, improvement of the face slab joint system, etc. With the application of those engineering measures, the construction of super-high CFRD with the dam height over 300m will be technically feasible.

Key words: 300m-high CFRD, deformation control of rockfill, stress of concrete face slab, rupture
1. INTRODUCTION

From the construction of the first modern CFRD in the world, the technologies for building concrete faced rockfill dam have been well developed. With continuous development and technical progresses, the technology for the design and construction of CFRD with the height below 200m is more and more matured. By investigating the general operation status of the constructed CFRD projects in the world, most of the dams present rather a good performance.

After 1960s, the interim from building CFRD with dumped rockfill to compacted rockfill had been basically completed. Cethena CFRD (110m) could be considered as the first modern CFRD in the world. It has established the foundation of modern CFRD technology. After the construction of Cethena CFRD, many CFRD with modern technologies were built in different countries. In 1980, Foz do Areia CFRD (160m) was constructed in Brazil. In 1985, Salvajina CFRD (148m) was constructed in Colombia and Segredo CFRD (145m) was constructed in Brazil. Aguambilpa CFRD (187m) in Mexico was the highest CFRD in that period.

In 21 century, several high CFRD with the height about 200m are constructed, which include Campos Novos (202m) and Barra Grande (185m) in Brazil, Kárahnjúkar (198m) in Iceland, Bakun (205m) in Malaysia. In the design and construction of the present high dams, some new technologies are applied. But during the operation, several high CFRD also present some special features, which cannot be covered by the previous engineering experiences. Those problems reflect the new features of high CFRD, which are highly concerned by the engineers in dam engineering [1][2].

The construction of modern CFRD in China started from 1985. The first constructed CFRD is Xibeikou CFRD with the dam height of 95m. According to the statistic of Chinese National Committee on Large dams (CHINCLD), up to the end of 2005, there are more than 150 CFRD constructed or under construction in China. In which, 37 CFRD have the height over 100m. TSQ-1 CFRD, which was completed in 2000, is ranked the first in the world for the same dam type in reservoir capacity, volume of rockfill, area of concrete face slab and installed capacity. Recently, China has constructed several 200m high CFRD, which include Hongjiadu CFRD (179.5m), Sanbanxi CFRD (185m) and Shuibuya CFRD (233m).

In near future, with the technical progresses of modern CFRD and the increasing demands for water resources and hydropower development, China will build series high dams in the upstream of Yangtz River and Yellow River, Nujiang River and Lanchangjiang River. As most of the dam sites of these projects are located in the area with very complicated topographical and geological conditions and very difficult for transportation, CFRD could be the most economical selection. The dam height of those projects is in the range of 250m to 300m. As there are no experiences for building such high dam, when the dam type of CFRD is selected, further studies on the properties and features of the 300m high CFRD will be
conducted.

2. TECHNICAL ISSUES OF 300M HIGH CFRD

With the increasing of dam height, the stress and deformation properties and the operation status of CFRD will present some new features. B. Cooke has pointed out: “The CFRD is an appropriate type in the future for the very highest dams. For a 300m high CFRD constructed of most rock types, acceptable performance can be predicted, based on reasonable extrapolation of measurement on existing dams."[3] As for the trend of CFRD dam height development, due to the inherent safety features and adaptability of CFRD, the first part of Cooke’s statement is definitely correct. But for CFRD with the height of 200m or even 300m, its operation features cannot be predicted by simply extrapolate of the observation data of the 100m high dams. In the engineering practices of the recently constructed 200m high CFRD in the world, both the successful experiences and frustrated lessons are accumulated. By summarizing the experiences and lessons of the previous high CFRD construction, it could be noticed that the existing design criteria and conventional construction method will be adjusted for the construction of future’s 300m high CFRD. In general, following technical issues need to be considered for building CFRD with the height of 300m.

2.1 Slope stability of high CFRD

In recent engineering practices, most of CFRD accept the upstream and downstream slope of 1:1.3 or 1:1.4. This is based on the judgment of the internal friction angle of compacted rockfill is much larger than its nature repose angle. Thus, the slope defined by the repose angle (38°) of damped rockfill (1:1.3) will have enough safety margins. For CFRD constructed by sandy gravel material, as the material has relatively low strength at low stress level, the normally accepted slope is 1:1.5∼1:1.6.

From the experience of the construction of 200m high CFRD, when medium strength rock material (with saturated compressive strength larger than 30MPa) is used, the slope of 1:1.3 or 1:1.4 is acceptable for high CFRD. From the qualitative analysis, ordinary hard rock material normally present rather high strength and it could keep a relatively steep slope. Slope stability will not to be the determine factor for the feasibility of building 300m high CFRD. But it should also be noticed that the stress level of rockfill will be increased with the increasing of dam height. The strength of rockfill material will also be changed with the increasing of stress level. Thus, the change of rockfill strength under the condition of high stress level will be fully studied for 300m high CFRD. Based on the studies, the rational strength indices and the suitable analysis method should be employed to conduct stability analysis. Besides, further studies shall also be conducted on the standard for using non-linear strength index analysis.

2.2 Seepage safety of high CFRD

For CFRD constructed by normal rockfill material, the coarse particles of compacted rockfill are rather difficult to be washed out. Thus, in general, the
Seepage stability of rockfill material will also not be the crucial factor for high CFRD construction. For 300m high CFRD, the upstream water head will be much more increased. Under the high pressure of upstream water load, the seepage stability of zone 2A (cushion layer) and 3A (transition layer) will become one of the key issues in the design and construction. In the engineering practices of present high dams, zone 2A is designed to be semi-permeable and the normal width is 3~4m. Under the high pressure of 300m water head, the adaptability of present criteria for determining gradation of zone 2A and 3A will be carefully studied. The particle gradation of cushion zone and transition zone (include maximum size, percentage of particles with the size less than 5mm and 0.075mm) and the filter protection relation between the two zones will be designed by laboratory test and numerical analysis. Besides, it will also be emphasized that zone 2A should provide filter protection for the possible silty sand dumped from upstream when concrete face slabs have through cracks.

2.3 Deformation control of high CFRD and related engineering measures
In the design of CFRD, the deformation control of rockfill will be the most important consideration. The stress of concrete face slab and the displacement of joints are all related with the deformation of rockfill. For the construction of 300m high CFRD, the deformation control of rockfill will be the crucial factor for determining the technical feasibility of the dam with such height. With the increasing of dam height from 200m to 300m, significant increase of rockfill deformation is hard to be avoided. For conventional CFRD, a good deformation control of rockfill is to limit the maximum settlement within 1% of dam height. But for 300m high CFRD, this goal is difficult to be achieved. At present, there are no clear understandings on the deformation of rockfill and its relationship to the stress of concrete face slab. Thus, for the deformation control of 300m high CFRD, the first step is to study the quantities and distribution of rockfill deformation, characters of stress distribution of concrete face slab, quantities of stress of face slabs and the joint displacement. Based on the study, the possible factors that could have certain impacts on the stress and deformation of rockfill and concrete face slabs will be further analyzed. According to the analysis, the feasible method for improving section zoning and rockfill compaction will be studied, where the main focus will be the engineering measures for controlling rockfill deformation, reducing face slab stress and decrease joint displacement. In general, for high CFRD, the rockfill should be well compacted to achieve the highest deformation modulus. This is the most effective measure to reduce the deformation of rockfill.

The deformation of rockfill includes initial deformation and creep deformation. All these deformations are directly related with its stress status and stress level, i.e. the height of the dam. With the increasing of dam height, the creep deformation of rockfill will be more significant. Thus, the design of 300m high CFRD should be focused on the deformation of rockfill. The main consideration will include the selection of rockfill material, section zoning, staged construction sequence, criteria of rockfill compaction, pre-settlement of rockfill before face slab construction.
2.4 Design of joint system and the measures for improving stress status of face slab
Concrete face slab is the main impervious element of CFRD. The joint waterstop system is also the most important part for leakage control. From the engineering practices of the recent high dam construction, the present waterstop structure and waterstop material can successfully bearing the joint movement of 200m high dam and the high pressure of 200m water head. For future’s 300m high dams, the water pressure will be increased and the movement of joint will present some new features. Whether the present structure is suitable for the 300m high dams is still not yet proved. New waterstop materials and improved waterstop structures should be developed to meet the requirement of 300m high CFRD. The main consideration should be focused on increasing the deformation adaptability and improving the reliability of the structure and materials.

With dam height of CFRD rise from 200m to 300m, both the deformation of rockfill and upstream water pressure will be increased. Consequently, the stress of concrete face slab will subject relatively large stresses after reservoir impoundment. To improve the stress status of face slab, properly arrange the vertical and horizontal joint could be the acceptable solutions, especially, by properly filling the compressive materials in the joint. But it should also be noticed that the setting of joint may have some adverse effect and it may also reduce the general reliability of the joint waterstop system.

2.5 Study of engineering properties of rockfill material and numerical analysis method
The study of engineering properties of rockfill material is the foundation for improving the design of high CFRD. Numerical analysis could also provide valuable reference for CFRD design and construction. In the past 20 years, a lot of research works were conducted on rockfill material and numerical analysis. Although fruitful results were obtained, there are still unsolved problems in the research works. In the field of engineering properties of rockfill material, the difficulties are the evaluation of the effect of reduced particle size in large scale triaxial test, determine breakage during sample preparation, measurement of dilation of the high density sample, etc. Due to the difficulties, the tested results will have certain differences to the real situation on site. Thus, the present testing method may be further improved and the relationship of the laboratory tested properties and on site properties should be established by the combination of laboratory test and on site test. In the field of numerical analysis, the present computation results can only provide the qualitative reference of the stress and deformation of rockfill and face slab. The mathematic models will still need to be further improved in simulating the change of volumetric strain under shearing, plastic yield and hardening, creep deformation and wetting deformation, especially in the condition of complicate stress status and high stress level.

2.6 Construction method and criteria of rockfill compaction
The sequence of rockfill construction and the criteria of rockfill compaction in quality control are important in the implementation of the deformation control
measures. In the construction of the recent high CFRD, the compaction density of rockfill is not strictly controlled, which has led to the large deformation of rockfill and cracks of face slabs. In the compaction of CFRD, the weight of vibratory roller, lift thickness, added water during compaction are the important factors for achieving the expected density. For high dams, heavy vibratory roller is recommended. In the practice of China’s high CFRD construction, 25t–35t vibratory roller is used. Some projects have introduced impact compaction method. For the construction of 300m high CFRD, whether it is necessary to further increase the weight of vibratory roller or what is the applicability of impact roller are need to be studied.

From the experience of the construction of 200m high CFRD, it is proven that the construction sequence of rockfill will have a significant impact on the stress and deformation status of face slab. For 300m high CFRD, the volume of rockfill is large. How to properly arrange the construction sequence of rockfill and the pre-settlement period for the construction of the staged face slab to improve the stress status of face slab will be the important subject to be studied in construction.

2.7 Rockfill zoning and face slab design
For a long time, the rockfill zoning of CFRD are all follow the pattern established by Cethana and other early stage CFRD projects. For high CFRD, its stress and deformation properties will present some new features. The zoning of rockfill may be adjusted to adapt the deformation features of the high dam. In general, the stress status of concrete face slab relies on the support of upstream rockfill. The incremental displacement of upstream rockfill is the most significant factor that has direct impacts on the stress of face slab. To improve rockfill zoning, the main consideration is to arrange good quality rockfill in the area with large incremental displacement. Besides, the deformation time history of the rockfill in different part and the breakage of the high stress level area will also be taken into consideration.

As high CFRD will subject to relatively large stresses after reservoir impoundment, the previous design of face slab will be re-evaluated. For some high CFRD constructed recently, the thickness of face slabs in riverbed sections is increased to avoid the possibility of face slab rupture after reservoir impoundment, such as Bakun, Karahnjukar and Sanbanxi. Along the direction of dam axis, permanent vertical joints are set between the face slabs. The joints in the area of abutment are tensile joints and the joints in the riverbed area are compression joints. In the construction of Alto Anchicaya CFRD, the vertical joint was filled with compressible material which leaded to the rather large opening of perimetric joints. After that, most of the CFRD projects have abolished the compressible filling material in vertical joints. In recent years, several high CFRD with the height about 200m have the problem of face slab rupture after reservoir impoundment. Therefore, it is suggested again to select several vertical joints to put compressible filling material to reduce the compression stress of the concrete face slabs in riverbed sections. For the horizontal joints of the face slabs constructed in
stages, the joint is normally treated as a construction joint, i.e. the reinforcing steel bar cross the joint and no waterstop structures and materials applied for the joints. Nowadays, with the increasing dam height of CFRD, the face slabs will bear relatively high stresses in the direction of dam slope after reservoir impoundment. For reducing the high stress of concrete face slabs, the consideration of arranging soft horizontal joints in face slabs could be acceptable. For reducing the structure cracks of concrete face slab, some recent high CFRD projects accept double layer reinforcement (reinforcement ratio unchanged). Some projects also increased the reinforcement ratio and arranged anti-spalling reinforcement in the certain area near the perimetric joints. The applicability of the measures and the further improvement of the measures for 300m high CFRD will need to be studied.

3. CONCLUSIONS

With the increasing demand for water resources and hydropower development, the construction of 300m high CFRD will be the inevitable tendency for the development of future's high CFRD. In recent years, the construction of the 200m high CFRD projects, such as Shuibuya, Bakun, Campos Novos, Kárhňukar, etc. has provided good foundation for the development of CFRD with 200m height to 300m height. By learning the experiences and lessons from previous project and conduct further research works, the construction of 300m high CFRD will be technically feasible.

Reference
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