Application of Underwater Repair Technology for Dams in China

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Abstract: There are a lot of high dams and giant hydropower stations in China. With the increase of service life, the dam would have some disease-risk conditions inevitably. Generally, emptying the reservoirs is diffcult and the cost is huge. Therefore, underwater repair technology is becoming a trend of development. With the successful application of dam underwater repair technologies in the repair of a large number of reservoir dams such as Fengman, Baiyun, and Wanyao, the underwater dam repair technology in China has greatly improved in terms of construction scale, construction mechanization level and construction technologies. This paper mainly summarizes the application cases of underwater concrete repair technology, types and effects of underwater anti-dispersant, construction methods of underwater concrete, key points for attention and safeguard measures for underwater construction, existing problems and countermeasures, etc. The results show that the underwater concrete repair technology has a remarkable significant effect on solving the dangerous problems of dams, especially in the replacement of underwater concrete, leakage plugging and crack repair.

1. General Instructions

1.1.Overview of Underwater Dam Repair Technology in China and on Abroad

According to statistics, by 2011, nine countries, including the United States, Japan, China and Iran, had built more than 600 dams with the height of more than 100m. China has more than 98000 water reservoirs[1]. There are more than 6000 dams with the height above 30m, including 216 high dams above 100 m, and 15 high dams more than 200 m.

Dam safety is one of the problems that Chinese government attaches great importance to[2]. According to the data of the first general survey of water resources in China, there are about 60200 dangerous dams in China[3], which are large in number and widely distributed. There are various problems like aging and diseases of dam, among which the seepage safety problem accounts is 25%.

Therefore, it is necessary to reinforce the dams. However, many reservoirs and dams in China and abroad need to be dry land to repair, which has the disadvantages of long construction period, high cost and slow effect. Moreover, many large reservoirs are responsible for power generation, irrigation, water supply and other functions, and the cost of venting is huge. Therefore, underwater construction technology is the current technology concerning in the field of water conservancy and hydropower engineering and the development trend of dam repair in the future.

Underwater engineering mainly includes underwater inspection and detection, underwater dredging, underwater crack and leakage treatment, underwater concrete repair and other technologies applied to underwater construction. Underwater inspection and detection technology is to use sonar and other equipment for real-time video recording, which is convenient for communication with underwater personnel, and can carry out a variety of tests at the same time, providing a basis for later repair; underwater dredging technology is to use dredgers and other equipment to extract underwater sediments; underwater crack and leakage repair technology is to use flexible treatment, rigid treatment, rigid flexible combination treatment As well as anti-seepage treatment and other ways to repair the cracks of the building under water; the underwater concrete repair technology is aimed at the phenomenon of concrete leakage, erosion, peeling and so on, through some underwater repair materials such as PBM polymer[4] , SR anti-seepage module[5], SXM underwater sealant[6], etc., using underwater planting reinforcement, underwater non dispersive concrete pouring and other ways to reinforce. At present, underwater concrete repair technology has been applied in some large and medium-sized hydropower projects in China.

1.2.Underwater Dam Repair Projects in China and on Abroad in Recent Years

With the continuous progress of underwater construction technology, many problems faced by hydropower dams at home and abroad have been solved. There are serious leakage at the water inlet of Quebec Hydropower Station Dam in Canada, the top of 5 spillways, and the two inlets downstream of the dam. Finally, the joint sealant (FMS) is selected for repair and has achieved results[7]. From the initial design to construction, the left dam abutment of the Clearwater reservoir in the United States has been seriously damaged by leakage. At the water level of 168m, the maximum leakage can reach 18.9L/s. In 2008, two companies, Bencor and Recon, jointly built anti-seepage walls, anti-seepage covers and so on. The main panel was backfilled with underwater concrete, which successfully solved the problem of leakage[8]. The underwater works and repair contents of hydropower dams in China are shown in Table 1:

Table 1: Example of underwater concrete construction of domestic dam.

Engineering	Depth	Position	Problem	Construction contents	Year
Sanmenxia [9]	19m	Discharge and sediment tunnel	There is a crack 3 ~ 4m away from the flip bucket in No.2 discharge and sediment discharge tunnel	Pour 12500m^3 of underwater concrete, 350m^3 of concrete tetrahedron, 150m^3 of high-strength mortar	1994
Baoquan [10]	14m	Main dam	Potential leakage	Adopt underwater concrete to cast reinforced concrete panel, with concrete quantity of 3400m^3	1994~1999
Huangshagang [11]	20m	Floor	Bending crack on invert slab	Pour 20cm underwater non dispersive concrete to seal the joint, and select HW and LW water-soluble polyurethane for grouting	1996
Fengman [12]	80m	Main dam	Leakage below elevation 226.00m	Underwater concrete pouring with floating support (1.2m-thick NDC impermeable layer, about 34800 m^2)	1999
Three Gorges [13]	139.2m	Main dam	Surface cracks on the upstream face of the dam	Carry out chemical grouting on the crack body + insert water stop material + paste rubber sheet, paste anti-seepage cover sheet on the crack and upper and lower sides, and spray cement-based permeable crystalline waterproof material on both sides of the cover sheet	2000
Zhexi [14]	60m	Main dam	Cracks appear on the upstream face of the dam	Underwater concrete cutting, underwater coating in V-shaped groove, embedding Sr, and underwater formwork pouring	2003
Danjiangkou[15]	23m	Sill for SurfaceSpillway	Overflow surface hole needs to be blocked	The underwater concrete is poured with cavity concrete stoplogs, which are combined with steel stoplogs to seal the water	2005
Wanyao[6]	12m	gate shaft	Leakage caused by underwater concrete honeycomb	Using SXM, sxpbm, LW and other underwater anti-seepage and water stop materials and underwater anti-seepage construction technology to prevent seepage and leakage	2010
Wanyao	23m	Main dam	Seepage of upstream face of dam	Pouring underwater non dispersive concrete	2017
Banqiao	34m	Spillway	The leakage of dam body and surface hole side wall is serious	Pouring of underwater non dispersive concrete 1500m^3	2019

Although there have been some exploration and practice of underwater repair engineering of hydropower station dams, there are still shortcomings of low efficiency and high cost in terms of current underwater repair technology, and there is a big gap between the application of engineering and developed countries, so it is still necessary to continue to speed up the research and development of underwater detection, design and construction technology.

With the deepening of engineering practice and research, a series of underwater construction technologies are summarized by the majority of engineering and technical personnel in the construction process. This paper will make some summary of underwater concrete construction to provide reference for similar engineering cases.

2. Underwater Concrete Repair Construction of Dam

The aging and disease of the dam concrete are generally affected by the factors such as long operation time, underwater scour, erosion and corrosion. The leakage is the focus of the outside world after the construction of the dam. For the leakage above the water surface, there are many treatment materials and processes, but for the underwater part, it has not been well solved for a long time. At present, there are two ways to repair underwater concrete of dam, chemical grouting and underwater repair materials. For small and shallow cracks, chemical grouting and underwater repair materials such as SXM, sxpbm, LW can be selected for repair[16].

The core of underwater dam repair is to solve the problem of bonding between repair materials and concrete in water. At present, most of the materials used for underwater repair of dam concrete are organic polymer materials. In the wet condition, there is attached water adsorbed on the surface under the action of residual field force on the surface. It is difficult to discharge it by general

methods, so the bonding effect is greatly reduced. In recent years, a series of materials that can be used in underwater repair, such as polymer concrete (PBM underwater concrete, HK series epoxy concrete (Zhang.2006) [16]), SXM water system fast sealant, Sr anti-seepage module and so on, have been developed in the engineering field, and achieved ideal results in the project. Figure 3 and Figure 4 are examples of underwater concrete pouring construction drawing and repair elevation respectively.

Figure 1: Construction of underwater concrete pouring in Wanyao Dam in Zhejiang.

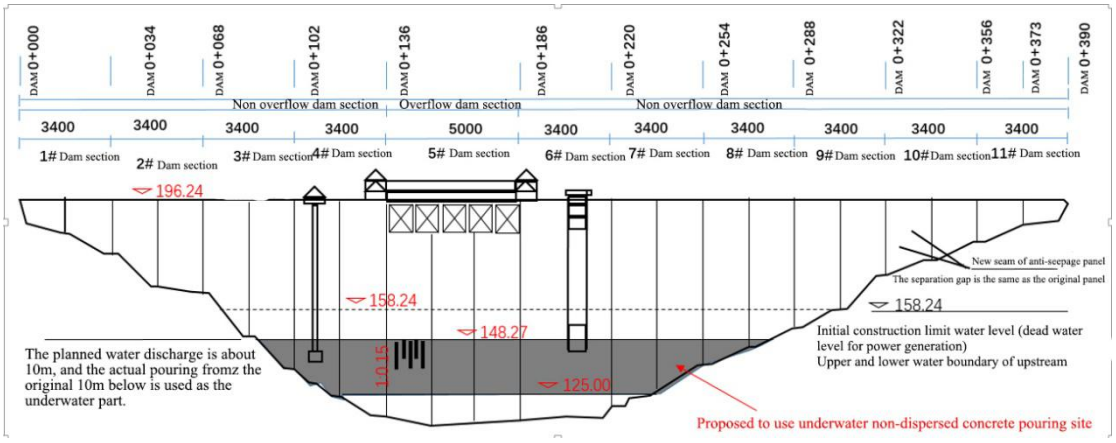

Figure 2: Vertical view of underwater concrete restoration on the upstream side of Wanyao Dam.

2.1.Difference between Underwater Concrete and Ordinary Concrete

Ordinary concrete is prepared by using water, cement, sand and aggregate under dry conditions. It can be mixed with materials such as fly ash or various admixtures to improve performance in the mixing process as required. Non dispersible underwater concrete (NDC) is a kind of ordinary concrete mixed with anti dispersing agent, which can form ion bond or covalent bond with the surface of cement particles, and play the role of compressing double electric layer to absorb cement particles and protecting cement[17]. This type of concrete can realize that the aggregate and cementitious material do not separate in layers when pouring directly in water, so as to ensure the strength of concrete.

2.2.Development of Anti-dispersant for Underwater Concrete

Since the first development of underwater non dispersible concrete by Sibo company in Germany in 1974, it has played an important role in the underwater repair of reservoir dams. Sonebi and khayat[18]19] proposed that the main components of NDC commonly used in recent years are Welan resin, cellulose and melamine resin[20]. In 1981, Japan successfully developed its own non dispersing agent. More than 800000 cubic meters of underwater non dispersing concrete were used in the Offshore Bridge and Mingshi Strait Bridge of Kansai International Airport, which were mainly used for the reinforcement of breakwater and the bottom plate of water intake of liquefied gas base [21]. NDC has been successfully used in large area underwater concrete repair of Belgian coastal defense project and West Coast Breakwater Project of Scotland.

NDC research and development has been carried out since 1980s in China. In 1983, China National Petroleum Corporation and Sibo group of Germany carried out the first technical cooperation. In 1987, UWB I NDC anti dispersant was successfully developed, and SCR cellulose series anti dispersant was developed in 1990. In 2003, UWB II type anti dispersant was developed by using polymer graft polymerization technology. So far, more than ten kinds of underwater non dispersing agent products have been developed and widely used in practical projects, with a total consumption of more than 1 million cubic meters[22], such as the heavy cargo wharf project on the right bank of the Three Gorges[23], the underwater bottom sealing of the substructure of the Huangshi Yangtze River Bridge in Hubei[24], the sea retaining project in Tianjin[25] and other underwater concrete projects.

2.3.Key Steps of Underwater Concrete Repair

2.3.1. Base Cleaning

Foundation surface cleaning includes foundation cleaning and dam surface cleaning. If the basement is in deep water area, pneumatic desilting machine can be used to achieve safe and reliable construction effect; for the dam surface, leakage points are found through underwater inspection, and high-pressure water gun and other equipment are used to clean up the surface sediment.

2.3.2. Underwater Planting Reinforcement

Underwater planting steel bar refers to a new post anchoring technology, which is to drill the concrete foundation under the condition of open water, then implant the planting steel bar glue, finally insert the anchor bar into the hole, and use the bonding effect of planting steel bar glue to anchor the steel bar into the concrete.

The main construction steps are as follows:

① The underwater detection equipment is used to detect the underwater damaged parts of the building, and mark the original steel bars in the concrete; the steel bars to be embedded are pretreated, cleaned repeatedly with steel wire brush, and then cleaned with alcohol or acetone; ② the surface of the steel bars to be planted is cleaned, and the concrete surface is roughened with underwater hydraulic pick, underwater air pick and other equipment; ③ the divers use High pressure water gun or hydraulic rotary power brush shall be used to clean the debris on the roughened concrete surface to ensure there is no loose block particles; ④ divers shall drill holes with underwater hydraulic drill, underwater air drill and other equipment, and clean the holes. Ensure that the hole is vertical and free of sundries; ⑤ place the planting glue in the planting syringe, and ensure that the length of the syringe is longer than the hole depth. There are two

injection methods: one is to evenly inject it into the hole under the water until the gel overflows at the hole opening; the other is to slowly pull the trigger under the water and inject about 2/3 of the gel. After inserting the reinforcement, if there is any deficiency, inject the gel again; the other is to rotate and plant the reinforcement after the rust is removed in the same direction until it reaches the hole bottom; the other is to ensure that the reinforcement is not disturbed before the gel is cured.

2.3.3. Formwork Erection

Formwork erection refers to the preparation of formwork suitable for the underwater concrete pouring of the project according to the needs, and the formwork shall be placed at the position to be poured and fixed. The formworks are made and installed on the water, and the reinforcement mesh is used most in the underwater repair of the dam, which is welded under the water after the completion of the production on the land.

2.3.4. Construction of Underwater Non Dispersive Concrete

The construction technology of underwater non dispersive concrete includes: bag stacking method, bag opening bucket method, mold bag concrete method and conduit method.

Bagging and stacking method: add permeable fiber woven bags in the mixture, and place them in the required position underwater by staggered stacking method. Most of them are used in the temporary works of underwater leakage stoppage and emergency rescue.

Bag opening bucket method: the top of the concrete in the bucket is covered with materials with good waterproof and oil proof performance, and the end is opened along the underwater ground to ensure the normal operation of concrete pouring. It is suitable for the construction of small amount of underwater pouring concrete engineering.

Mold bag concrete method: remove the damaged concrete face slab on the water, then repair the cushion, and finally re pour the concrete slope protection technology. It is necessary to clean the deposit on the surface of underwater concrete, excavate the overburden on the riverbed, and then use the form bag concrete for pouring. The construction sequence is underwater first and then on water. The technology has been used in the repair of concrete slope protection on the right bank of Sanjiang channel of Gezhouba.

Tremie method: the tremie with good sealing shall be used for underwater concrete pouring. In the pouring stage, it is required to make the underwater non dispersive concrete flow around and spread out without contacting with the water and being scoured by the water flow when falling. Generally, it is realized by placing soft balls around the concrete in the tremie (as shown in Figure 5). After the pouring stage is completed by this method, the aggregate and inferior concrete on the surface need to be removed. The method has the advantages of high pouring efficiency, simple method, low technological requirements and good integrity. At present, the two-layer vertical pipe method and the single-layer flexible pipe method are commonly used in engineering. The technology has been successfully applied in the projects of heightening the Danjiangkou dam, sealing underwater and strengthening the outlet of Sanmenxia No.2 discharge tunnel. The repair procedure of underwater concrete is shown in Figure 3.

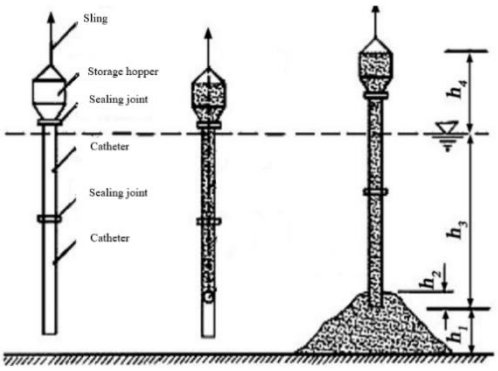

Figure 3: Pipeline casting non-dispersive concrete.

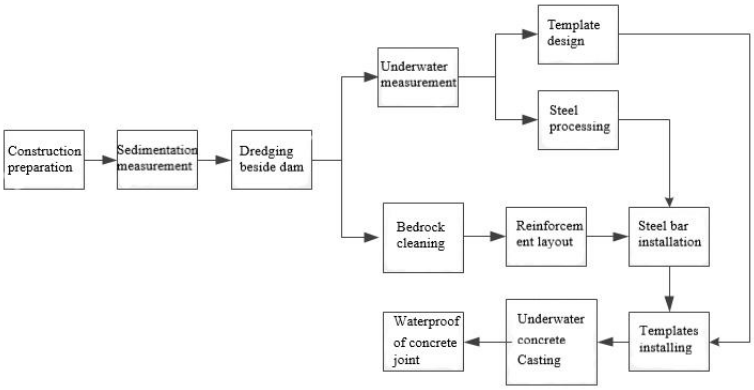

Figure 4: Key steps in the construction of an underwater concrete anti-seepage layer for a project.

2.4.Key Points of Underwater Concrete Construction

During the construction of underwater non dispersive concrete, attention shall be paid to:

(1) If it is necessary to clean up the mud in the bedrock, it is recommended to use a high-pressure water gun to disperse the mud around the bedrock, and use a desilting pipe to clean up and transport it to the outside of the construction area;

(2) The gap between bedrock and formwork needs to be well treated. The dry cement mortar in long bags can be laid along the formwork and bedrock to reduce the amount of slurry. During the pouring, the diver monitors the joint between the formwork and the bedrock, and blocks the slurry flowing area;

(3) The formwork can be removed in two ways: first, the diver goes deep into the water and uses the underwater cutting technology to cut the screw rod, and starts the floating crane to lift it slowly after the formwork completely falls off; first, the material that can reduce the adhesion between the formwork and the concrete, such as kraft paper, should be pasted in the formwork first, and then the diver uses the crowbar and other tools to remove it underwater;

(4) In case of slurry leakage during underwater concrete pouring, it is necessary to seal it with cotton yarn and other materials in time. When pouring by tremie method, continuous and slow pouring technology shall be ensured to avoid that the air in the tremie can not be discharged in time to form high-pressure air bag;

(5) During the preparation of underwater concrete, it is necessary to ensure that the water consumption is moderate. After the preparation, it is necessary to visually check whether the workability meets the requirements, and arrive at the construction pouring site in time according to

the transportation distance and temperature.

3. Problems in Underwater Concrete Repair

The research of underwater construction technology in China is relatively late in developed countries, and there are still a series of problems to be further discussed and studied.

(1) For underwater repair, especially for concrete scour pit, new damage will still appear after repair. In underwater treatment, the new and old concrete contact surface can not achieve the ideal clean state, which affects the bonding effect;

(2) The insufficient depth of the surface water stop joint leads to the connection between the reservoir water and the original dam foundation to form leakage;

(3) When cracks appear in the lower face of the auxiliary impervious blanket in front of the face slab dam and rockfill dam, it is very difficult to reinforce it because of the thick overburden; the face slab of Zhushuqiao reservoir dam and Baiyun hydropower station dam are damaged in the lower part of the auxiliary impervious blanket, so it is worth studying whether the existence of the auxiliary impervious blanket is necessary;

(4) Most of the leakage of concrete face rockfill dam is caused by the damage of water stop structure of peripheral joints, which leads to the damage of cushion and serious leakage. It is suggested to further repair the water stop;

(5) The performance of underwater repair materials used in underwater repair can not be fully developed in the actual project. Many materials can not be painted, embedded and pasted quickly and easily in the underwater.

4. Countermeasures and Prospects

(1) The underwater concrete repair of the dam shall be arranged on the fresh bedrock surface without sundries.

(2) The surface water stop joint shall be embedded 0.5-1.5m into the bedrock as much as possible to prevent the water flow around the bottom of the water stop joint, causing the connection between the reservoir water and the original dam foundation to form leakage;

(3) Consider whether it is possible to cancel the auxiliary impervious blanket in front of the dam, or make targeted research on the repair of the lower panel of the impervious blanket, so as to reduce the difficulty of reinforcement due to the thick overburden;

(4) Strengthen the sealing structure of the joints around the dam. It is found that the quality of concrete under the middle waterstop of the dam such as Baiyun reservoir and Zhushuqiao is poor, so it is considered to cancel the middle waterstop, strengthen the top waterstop that can be checked and repaired in time, and adopt the combination of flexible waterstop material and closed metal waterstop to prevent seepage.

(5) It is necessary to develop more underwater repair materials with good construction performance, such as planting reinforcement glue, so as to give full play to the performance and efficacy of the materials.

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