SHANGHAI COASTAL RESERVOIRS: THEIR DEVELOPMENT AND EXPERIENCE FROM THEIR DESIGN

BY JIAN ZHONG YUAN & CAI E WU

Shanghai has three coastal reservoirs used for drinking water sources in the Yangtze estuary. They are the Qingcaosha reservoir, the Dongfengxisha reservoir and the Chenhang reservoir. This article discusses why Shanghai needed to build coastal reservoirs and their evolution. The characteristics of the Shanghai drinking water sources are introduced. The key factors and the experience gained from the research and design of the Shanghai coastal reservoirs have been summarized and explained.

The evolution process of Shanghai drinking water sources

The search for drinking water sources in Shanghai goes back more than 100 years and can be divided into three stages. The first stage is the period before the 1980s when the city mainly took water directly from the lower reach of the Huangpu River and the Suzhou River. The second stage began in 1987, when the city started taking water from the upper reach of the Huangpu River. The third stage introduced the use of the Qingcaosha reservoir, the largest coastal reservoir for drinking water supply in the world. Today, more than 70% of Shanghai's drinking water comes from coastal reservoirs in the Yangtze estuary.

Why does Shanghai need to build coastal reservoirs in the Yangtze estuary?

The Huangpu River is located in the downstream part of the Taihu Basin, where water intakes are often threatened by many factors like low flow, water pollution caused by domestic and industrial wastewater, and where the fresh water sources are not protected in reservoirs, in case of an emergency such as when chemicals are accidentally discharged into the river from somewhere in the basin. The water quality of the Huangpu River is relative poor and unstable. At present, the total diverted water from the intakes in the upper reaches of the Huangpu River for the Shanghai water supply exceeds 30% of its average annual flow rate, which is close to the upper limit of the Falkenmark water stress index. If the rate of water withdrawals from the upper reach of the Huangpu River is expanded further, the river ecosystem will deteriorate, especially in the middle and lower reaches of the Huangpu River, and seawater intrusion may affect water quality at the lower intakes. Therefore, any further development or excess water withdrawals from the upper reach of the Huangpu River may cause high salinity at the intakes due to seawater intrusion.

Other rivers near Shanghai are scattered and their overall water quality is poor. Water quality in these rivers generally cannot reach the national surface fresh water standard for drinking purposes. Therefore, these rivers cannot be used as the main drinking water source for Shanghai. At the same time, the groundwater yield in the area is low. In order to effectively control land subsidence, further control and reduction in the rate of groundwater exploitation is needed in Shanghai.

With the development of Shanghai's economy and the growth of the urban population, the demand for water is rising. The population of Shanghai was 24.2 million in 2016. The water supply capacity of the city reached 11.52 Mm^3/d and the annual water supply was 3.2 Gm^3. In addition, there is a shift in the emphasis placed on the demand for water from quantity to quality. The lack of good water quality can have an impact on the sustainable development of Shanghai. Therefore, finding new water sources of adequate quality for urban water supply has become a pressing problem.

The Yangtze estuary has abundant fresh water resources of good and stable water quality that account for 98.8% of the total water resources in Shanghai. Its water quality meets the Chinese standard of fresh water for drinking purposes, and has a relatively high self-purification ability. It is better than surface water in other areas of Shanghai. The fresh water resources of the Yangtze estuary have great potential for development and utilization. Therefore, the development of the Yangtze estuary can satisfy not only the incremental fresh water needs, but also can improve the quality of the Shanghai water supply. The intermittent nature of freshwater/seawater in the Yangtze estuary may provide a feasible solution to the problem of drinking water in Shanghai.

Figure 1. Location of Shanghai Coastal Reservoirs

Shanghai authorities started in the 1980s to carry out long-term hydrological and water quality monitoring, research and analytical studies to support planning for the use of the water resources in the Yangtze estuary in order to solve the water supply problem. However, direct development in the Yangtze estuary was threatened by saltwater intrusion at the intakes. To address this problem, it was decided that a coastal reservoir with large storage capacity should be constructed to store fresh water during periods of low salinity and high quality.

Profile of Shanghai coastal reservoirs

The Shanghai municipal drinking water comes from surface water sources, which now include three coastal reservoirs in the Yangtze estuary (Figure 1): the Qingcaosha reservoir, the Dongfengxisha reservoir, and the Chenhang reservoir. These reservoirs are easily affected by saltwater intrusion because of the interaction of runoff, tide and wind, etc.

Figure 2. Map of Chenhang Reservoir

•Chenhang reservoir

The Chenhang reservoir was the first coastal reservoir used as a drinking water source in Shanghai. Its development was a milestone in the utilization of fresh water for Shanghai from the Yangtze estuary. Construction of the Chenhang reservoir started in November 1990 and was completed in June 1992. The Chenhang reservoir is located on the south bank of the South Branch of the Yangtze estuary, just downstream of the Baosteel reservoir (Figure 2). Total reservoir area is 1.336 Mm^2. Maximum high water level of the reservoir is 7.25 m (Wusong Datum). The dead storage water level is 0.5 m. The design effective capacity was 8.3 Mm^3, which has been increased to 9.5 Mm^3 after reinforcement and heightening of the reservoir dyke. The rate of water supply from the reservoir has been increased to 1.3 Mm^3/d and the maximum high water level of the reservoir is now 8.10 m. The reservoir can provide fresh water for about 7 days at the designed rate for water supply without interruption during extreme saltwater intrusion events.

•Qingcaosha reservoir

The Qingcaosha reservoir is China's largest coastal reservoir built in the Yangtze estuary. The construction of the Qingcaosha reservoir began on June 5, 2007 after nearly twenty years of research, and the reservoir started operating on June 8, 2011.

The Qingcaosha reservoir is located on the northwest side of Changxi Island between the South Channel and the North Channel of the Yangtze estuary. Figure 3 shows the general layout of the Qingcaosha reservoir. Figure 4 shows the upper water intake system and the north dyke, including the upper sluice and pump. The total length of the dyke is 48.4 km and the newly constructed dyke (IJKLMNOPQRS in Figure 3) is 22 km. The total reservoir area is 66.15 km^2. The maximum high water level of the reservoir is 7.0 m. The dead storage water level is -1.5 m. The total reservoir capacity is 0.527 Gm^3 and the design effective capacity is 0.438 Gm^3. The design daily water supply is 7.19 Mm^3/d. The capacity of the upper pumping station is 200 m^3/s. The upper gate net width is 70 m and its bottom elevation is -1.50 m. The lower gate net width is 20 m and its bottom elevation is -1.50 m too. Fresh water is conveyed by gravity out of the reservoir. The net width of each hydraulic gate is 24 m and its bottom elevation is -4 m. The design capacity of the additional pumping station was set to be initially 0.11 Mm^3/d, to enhance the intake's safety, and the pumping house's capacity now is 0.23 Mm^3/d. The reservoir's storage is large enough to ensure 68 days of water supply to Shanghai without interruption. Without this reservoir Shanghai's water supply could be at risk when the salinity at the water intake exceeds the standard during periods of continuous and severe seawater intrusion. The current water supply from the Qingcaosha reservoir benefits a population of more than 13 million in Shanghai.

Jian Zhong Yuan has served in the Shanghai Investigation Design & Research Institute Co., Ltd (SIDRI) as an engineer since 1988 and professional senior engineer since 2007. He received his Bachelor of Engineering from the Wuhan Institute of Hydraulic and Electrical Engineering in 1985, and his Master of Engineering degree from Tsinghua University in 1988. His focus has been estuarine and coastal engineering and related research, especially the development and utilization of fresh water resources in Yangtze estuary. His areas of expertise are mainly in hydrodynamic analysis, engineering impact analysis, analysis of fluvial evolution, mathematical modeling, and engineering planning.

Cai E Wu has served in the Shanghai Investigation Design & Research Institute Co., Ltd (SIDRI) as an engineer since 1984 and professional senior engineer since 2009. She received a Bachelor of Engineering from Hohai University in 1984. She mainly participated in and is responsible for the design work of the four large drinking water reservoirs in Shanghai, three of which are coastal reservoirs. Her areas of expertise are mainly in hydro-structure (dyke & sluice), pumping stations and water supply system.

Figure 3. The general layout of Qingcaosha Reservoir

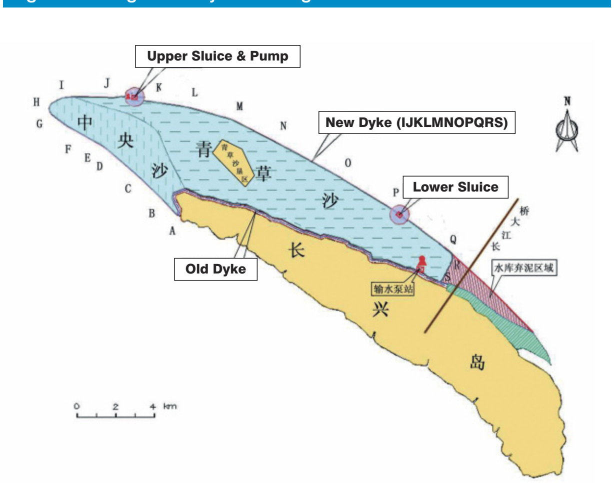

Figure 4. Aerial view of the Qingcaosha Reservoir (photo: Xinhua News UAV)

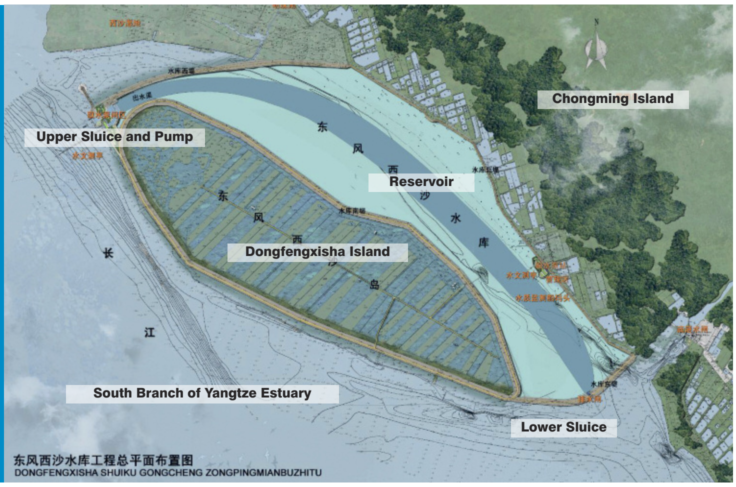

Figure 5. The Schematic Layout of Dongfengxisha Reservoir

•Dongfengxisha reservoir

The Dongfengxisha reservoir is located on the north bank of the South Branch of the Yangtze estuary, namely southwest of Chongming Island. Its construction began on November 29, 2011 and the reservoir started operating on January 17, 2014. The total length of the dyke is 12 km. In addition to this dyke there is a newly constructed dyke, which is 3572 m long. The total reservoir area is 3.74 km^2. The maximum high water level of the reservoir is 5.65 m. The dead storage water level is 1.0 m. The total reservoir capacity is 9.762 Mm^3, and its effective capacity is 8.902 Mm^3. The present design daily water supply is 0.215 Mm^3/d and it is expected to be 0.40 Mm^3/d in the future. There are upper and lower sluices and a pumping station at the entrance as shown in Figure 5. The upper pumping station capacity is 40 m^3/s. The upper sluice gate is 14 m wide and its bottom elevation is 0.0 m. The lower gate is 8.0 m wide and bottom elevation is -1.0 m. The current water supply benefits some 700,000 Chongming Island residents.

Lessons from the study and design of the coastal reservoirs of Shanghai

The main function of the Shanghai coastal reservoirs is to store fresh water during periods of low salinity and high water quality at the intakes, which means that their gates or pumps need to open and close daily based on the tidal/salinity level. In extreme cases like at very high tide, during typhoons, or oil/chemical spill accidents, the intakes close for as long as needed to avoid seawater/contaminant pollution. In any case, the hydraulic structures, intake and water supply facilities of the reservoirs must be safe and stable. The most important criteria for opening the gates/pumps is that the water quality in the reservoirs meets the requirements of the design standards at all times. Therefore, the following issues are important for any coastal reservoir design: site selection, intake operation method, arrangement of sluice and pumping house, scheduling scheme, deepwater dyke, gap closure, water quality protection and reservoir eutrophication prevention control technology, hydraulic fill dam in soft soil foundation, closure gap setting, protection and closure, permeable foundation pit maintenance and foundation treatment. In an effort to supply sufficient good quality water to Shanghai, all these aspects of the design have been proven to be correct and to have functioned properly. The experience gained from the Shanghai coastal reservoirs can serve as a useful case study for similar coastal reservoir studies, design and construction in other parts of the world. Totally different from inland reservoir designs, the coastal reservoir design needs to take account of the following issues:

Runoff and tide characteristics, fluvial processes. They play a key role in the water intake and site selection. When and how to take freshwater depends on the results of the analysis of runoff and tides. The location of the reservoir and the intake system should be selected in areas where scouring and silting is relatively small.

Saltwater intrusion and reservoir scale. Saltwater intrusion has a direct impact on coastal reservoirs. It also plays a key role in site selection, the layout of the hydraulic structures and the operation of the reservoir. A prerequisite for any coastal reservoir in an estuary is the study of seawater flow patterns and salinity profiles in the estuary. The longest continuous unfavorable time in terms of intake water quality is a decisive factor for the size of a coastal reservoir, similar to the Qingcaosha reservoir.

Site selection and arrangement of the dyke alignment. It is necessary to consider the impacts of the project implementation on the estuarine fluvial evolution, but also to take into account that regime changes may have environmental impacts on the project itself, which means that countermeasures should be proposed to minimize such impacts. The site of the reservoir and dyke alignment should be selected in areas where the riverbed/seabed is relatively stable and no serious scouring/silting occurs. There should be no obvious adverse effects on flood control and drainage, navigation channels, fluvial processes, existing engineering and other facilities.

Intake design and operation scheduling. There are three methods of reservoir intake, namely pumping, sluice, and combined pumping and sluice. The changes of water quality, saltwater intrusion and river regime evolution directly influence the reliability of the reservoir water intake. The selection of the location of water intake and its design have a direct impact on water supply safety, the scale of water intake, reservoir operation costs, and getting high-quality fresh water. For reservoirs with a large water supply capacity, it is necessary to study the tidal characteristics and saltwater intrusion in the area of the intake and pay special attention to the arrangement of the pump and gate structures. In addition, appropriate scheduling operation studies are needed in order to reduce operating costs and save energy.

Flow to a reservoir by gravity via its sluice gates is possible when the outside water level is higher than the reservoir water level, and its salinity and water quality are acceptable. The reservoirs are prone to eutrophication if water in the reservoir remains stagnant over a long time at high temperatures. Therefore, in the Yangtze reservoirs described above, there is a sluice in the lower part of the reservoir which is used to drain water from the reservoir. This arrangement can make full use of the tides by taking water into the reservoir at higher tidal level, reducing the operating energy consumption. At the same time, the operating scheme in which water taken from upstream is drained from downstream at low tide level can control the water retention time in the reservoir.

Water quality protection and reservoir eutrophication prevention and control. Coastal reservoirs are generally shallow. Flow patterns in these reservoirs also influence water

quality. After their completion, they are at great risk of eutrophication. Full consideration must be given to the reservoir shape, the layout of the pumping station and gate, scheduling operation, etc., to make the water flow smoother through the reservoir and keep water residence time as short as possible to prevent stagnation, which may facilitate eutrophication.
The way to prevent eutrophication is to optimize the shape and morphology of the reservoir; select the appropriate layout; optimize reservoir operation to increase the flow of water, supporting the establishment of a sound ecological system; and take other measures to maintain and improve water quality in the reservoir.

Through the linkage of the operation of the upstream and downstream facilities, the mobility of water in the reservoir is increased and the residence time of water in the reservoir is reduced. The ability of the reservoir to resist eutrophication is also enhanced. Dredging to make the water flow more smoothly can also reduce the risk of local algal outbreaks.

Hydraulic fill dam in soft soil foundation. The dykes around coastal reservoirs are generally constructed in a seawater environment where the water depth is generally around 10 m. Therefore, conditions like deep water, fast flows and high waves are unfavorable for construction. Furthermore, the foundation soil is often unfavorable to stabilize the dyke due to its soft and weak nature and severe settlement potential. Because the long dykes for many such reservoirs may be built on water there is no land for activities supporting the construction of the dykes. In such cases specific, plastic drainage plates can be used for foundation treatment, and large and high strength geotextile bags with hydraulic filling can be placed to form a sloping dyke.
For seepage proofing of the hydraulic fill dyke, an impermeable wall of triaxial cement mixed piles has been successfully applied to the hydraulic fill dyke. For the closure section of the dykes for the coastal reservoirs of Shanghai, a new type of impermeable wall was built by assembling one row of high pressure jet grouted piles between two rows of triaxial mixed piles.

Closure gap setting, protection and closure. The coastal reservoirs in Shanghai were formed by building an encircled dyke. Therefore, the greatest concern and risk point during the construction period was on the arrangement and protection of the closure gap, as well as the closure design. Because of the effect of the reversing tide at the closure gap, the periodic tidal variation limited the continuous and available working time. Due to the shortage of stone material and land riprap, the soft and weak soil foundation can be easily washed away and it is difficult to protect. Any scouring is extremely difficult to control.
To accommodate the construction of underwater structures equipment operated from a ship whose size meets the local hydrological and water depth requirements was used. The armor face of the closure gap had a multi-layer composite protection structure. The layers of this structure were from the bottom up, large-sized high-strength geotechnical cloth bags filled with sand (sand quilt), 1,300 g/m^2 super strong geotechnical cloth soft drainage body of sand ribs, soft drainage body of chained concrete blocks, and 60 tons of string bagged stones, or 30 tons of concrete blocks. For damming the closure gap, a plain plug with steel-caged riprap was used.

Permeable foundation, pit maintenance and foundation treatment. The average tidal range in the Qingcaosha reach is 2.43 m. The foundation base elevation of the main pumping house is -12.0 m. Therefore, it was necessary to build a cofferdam in the middle of the river. Within the part surrounded by the cofferdam a deep foundation pit needed to be excavated. The soft soil layer underlying the structure was deep and thick and the load of the upper structure of the pumping station and sluice was relatively high. Because of the difference in loads, the foundation was required to be treated in consideration of the deformation that might occur between the pumping station and the sluice and both sides of the connecting embankment.

Taking the protection requirements of the cofferdam and foundation pit into consideration, a composite protection system formed by combining the cofferdam, sloped excavation and underground continuous cutoff wall was used. Consequently, the function and requirements of water retention, seepage and the construction conditions on dry land were satisfied.

The foundation reinforcement was conducted by using high pressure jet grouting piles to coordinate the deformation at the connection of dyke and gate; thus the hidden danger of leakage caused by potential uneven settlement at the connection of the structures and the dyke was avoided.

Prospects

So far the Shanghai coastal reservoirs have performed well and the water quality in the reservoirs meets the requirements of the design standards. However, some areas are still worthy of further study.

- Because the Qingcaosha reservoir forms the upstream division area between the South Channel and North Channel of the Yangtze estuary, the evolution of the channel system by sedimentation and scouring is extremely complex. The hydrodynamic processes in the reach of the Qingcaosha reservoir, especially in the waters near the west, and the upstream section at the north side of the Qingcaosha reservoir, should continue to be monitored. Beach protection measures must be carried out if necessary.
- The residence time of water in Qingcaosha reservoir was considered to be 15 ~ 20 days. The eutrophication risk in this reservoir is relatively high because nitrogen, phosphorus and other nutrient levels are high in the Yangtze estuary. A study on how to increase the reservoir water mobility to shorten the residence time to 7 ~ 10 days and further reduce the risk of a algal blooms is necessary.
- It is recommended to continue dredging and to optimize the reservoir underwater topography to enable flow conditions to meet the requirements for ecological restoration both inside and outside the reservoir embankment.
- The capacity of the Chenhang reservoir is small. It cannot meet the water demand because of the growth of the population. Research is needed on how to expand capacity and improve the water supply guarantee rate of the Chenhang reservoir.
- Water quality at the intake of the Chenhang reservoirs is easily affected by irregular drainage from the Liuhe River of Jiangsu province. Optimizing the reservoir operation scheme is still needed because the Chenhang reservoir is located downstream from the Liuhe River.
- Other potential water sources in the Yangtze estuary are still worth studying in order to meet the water demand of Shanghai in 2040, when the population is predicted to reach 25 million people. ■