The Three Gorges Dam of China: Technology to Bridge Two Centuries

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Some of the most sophisticated 20th-century technologies have been applied to build the largest hydroelectric dam in the world, the Three Gorges Dam Project (TGDP) of China. The author administered a study abroad course in China from May 27 to June 10, 2000, to study the massive project as it approached the halfway mark of its second and most critical stage, namely Phase II. This article sheds some light on this sizable project and summarizes information and observations gathered first-hand during this study abroad course on the construction of the Three Gorges Dam (Wahby, 2000).

As students, teachers, and other practitioners in the various technology professions read this article, it is hoped that they may get a better understanding of this substantial project, its main components, and the challenges that faced and still are facing its construction, as well as the technologies used to complete it. It is also hoped that the readers may see the tremendous effects of this massive undertaking on different aspects, on China as well as on the rest of the world. Those aspects include but are not limited to water conservancy, hydroelectric power generation, environment, ecology, geology, geography, economy, politics, transportation, society, culture, business, industry, and even technology itself.

In particular, technology is being challenged and stretched to the limit as never before to construct the Three Gorges Dam. Unprecedented production rates are becoming the norm in order to keep the sizable project on schedule, while adhering to the highest quality requirements of construction codes. After the completion of the project by 2009, the technology used in the construction of the dam will probably need to be reviewed and enhanced in light of lessons learned.

In addition to a description of the main components of the project and the phases of its construction, a historical background and a timeline of the events that culminated in China's decision to build this dam are presented in this article. The article also points out the reasons why this sizable project is being built and discusses the results that are anticipated after its completion. Some of the challenges faced in the construction of the project are analyzed, together with how they were dealt with.

Background

The TGDP is projected to become the world's largest dam—nearly four times larger than Hoover Dam, with a height of 607 ft (185 m) and a length of approximately 1.4 miles (2.3 km; Kosowatz, 1999). The TGDP is composed of the dam, two power plants, and the navigation facilities. The dam is composed of three sections: the spillway dam, the intake dam, and the non-overflow dam. The permanent navigation structures include a ship lock and a ship lift. A temporary ship lock is also a part of the project that is being used during Phase II of the TGDP.

TGDP Location

The Three Gorges is one of the world's most famous scenic sites around Qutang, Wuxian, and Xiling gorges. The TGDP is located almost 750 miles (1,200 km) south of Beijing and 650 miles (1,000 km) west of Shanghai, China. More specifically, the TGDP is being constructed in Sandouping Village, Yichang County, Hubei Province, in the Xiling Gorge, about 25 miles (40 km) upstream from the existing Gezhouba Project located at Yichang City.

TGDP Site

The site for the TGDP was selected at Sandouping, along the Yangtze River, after about 15 other sites were studied. The site has many advantages. The crystalline rock, intact granite with 100 MPa of compressive strength, forms a good foundation bed for the dam. In addition, there are no major unfavorable or injurious geologic structures in the vicinity of about 9 miles (15 km) around the dam site, while the regional seismic activities are small in intensity, low in frequency.

Interestingly, the river valley at the construction site of the TGDP is relatively open and broad, with the hills on both sides of the river fairly flat, providing for a good-size lake right at the upstream of the dam. Also, the existence of the small islet of Zhongbaodao near the right-hand side bank of the Yangtze River was favorable for the river diversion project.

TGDP Main Hydraulic Structures

1. The Dam

The 60-story high dam is a concrete gravity type that is composed of three sections: the spillway dam, the intake dam, and the non-overflow dam. The total length of the dam axis is 1.45 miles (2.31 km), with the crest elevation at 615 ft (185 m) and a maximum height of 607 ft (181 m), 650 ft thick at the base, and 50 ft at the crest. By comparison, the Hoover Dam in the United States is 0.24 mile (1,244 ft) long, 727 ft high, 660 ft thick at the base, and 45 ft thick at the crest.

The spillway dam, located in the middle of the river course, is 0.3 mile (483 m) long in total, where there are 23 bottom outlets and 22 surface sluice gates. The dimensions of the bottom outlets are 23 x 30 ft (7 x 9 m), with the elevation of the inlets at 300 ft (90 m). The net width of the surface sluice gates is 27 ft (8 m), with its sill elevation at 525 ft (158 m).

On both sides of the spillway dam section there are the intake dam and non-overflow dam sections. With a maximum discharge capacity of 102,500 m^3/s - (one m^3 = 35.32 ft^3) at the pool level 600 ft (180.4 m), the project is able to discharge the possible maximum flood (PMF) and is capable of producing 847 TW.h of electricity output annually.

2. Power Stations

Two powerhouses will be placed at the toe of the dam, one to the left and another to the right. The total length of the powerhouse on the left is 0.4 mile (0.65 km), with 14 sets of hydro turbine generator units installed. The total length of the powerhouse on the right is 0.37 mile (0.6 km), with 12 hydro turbine generator units installed. Those 26 sets of hydro turbine generator units (Francis type, 700 MW each), totaling 18,200 MW of installed capacity, will produce 847 TW.h of electricity output annually—exceeding that of the largest dam currently in operation by almost 40%. There are 15 transmission lines, with 500 kV AC lines to central China and Chongqing City and about 500 kV DC lines to east China.

Meanwhile, enough room has been preserved on the right bank for a future underground powerhouse with an extra six hydro turbine generator units totaling 4,200 MW of installed capacity. The intakes of these units are being constructed simultaneously with the project. The hydroelectric power generated by the TGDP would replace 40 to 50 million tons of raw coal combustion each year. This reliable, cheap, and renewable energy is expected to play a very important role in the development of China's economy and the prevention of environmental pollution.

To put this in perspective, China's total power capacity in 1990 reached about 130 million kilowatts (Tillou & Honda, 1997). To keep pace with China's economic growth, with annual increases in the gross national product estimated at 6%, its power output must rise by 8% annually to reach about 580 million by the year 2015. Given that almost three quarters of China's energy comes from coal, this growing coal consumption poses a huge threat to the environment. Coal burning emits several harmful air pollutants, including carbon dioxide (CO_2)—a major contributor to the greenhouse effect and global warming. China used between 1.1 and 1.2 billion tons of coal in 1993, mostly for heating and generating electricity. Industry sources predict that China will consume as much as 3 to 4 billion tons by the year 2009. Sulfur dioxide emissions, which cause acid rain, are expected to rise from 15.5 million tons in 1991 to 2.5 billion tons by 2009.

3. Navigation Facilities

The permanent navigation structures consist of the permanent ship lock and a ship lift. The design capacity of annual one-way navigation is 50 million tons. The ship lock is designed as a double-way, five-step flight lock carved from granite on the river's left bank and lined with concrete; each lock chamber is dimensioned at 930 x 113 x 17 ft (280 x 34 x 5 m)—length x width x minimum water depth—capable of lifting 10,000 tons of barge fleet 285 ft, making it the largest such system in the world.

The ship lift is designed as a one-stage vertical hoisting type with a ship container sized 400 x 60 x 11.7 ft (120 x 18 x 3.5 m), capable of carrying one 3,000 ton passenger or cargo boat each time. In addition, one temporary ship lock is designed for use during the construction period with an effective chamber size of 800 x 80 x 13.3 ft (240 x 24 x 4 m).

TGDP Reservoir

The TGDP is the largest water conservancy project ever built in the world. The TGDP will completely block the Yangtze River course to impound a narrow, ribbon-like reservoir. This ribbon- or river-like, rather than a lake-like, reservoir will have a total length of over 400 miles (600 km)—longer than Lake Superior—and an average width of 0.7 miles (1.10 km)—less than twice the width of the natural river channel.

The total water catchment area is about one million km^2. The surface area of the reservoir will reach 1,084 km^2, and the land area to be inundated will be 632 km^2—almost twice the original water surface area. The average annual runoff is 451 billion m^3 and 526 million tons of annual sediment discharge. With the normal pool level (NPL) at 570 ft (175 m) above sea level, the total storage capacity of the reservoir is 39.3 billion m^3.

TGDP Dateline

Following is the TGDP dateline (Export-Import Bank of the United States, 1996):

1919 Dr. Sun Yat-sen proposes the original flood control dam.
1920 Preliminary studies and site investigations.
1954 Huge flood; all transportation stopped for 100 days.
1958 Chairman Mao proposes new plan.
1970 Compromise of the Gezhouba Dam to see whether it could be a substitute for the Three Gorges Dam.
1980 Gezhouba Dam completed and proves not to be a substitute for the TGDP.
1983 Yangtze Valley Planning Commission completes feasibility study of the Three Gorges Dam.
1985 U.S. working group formed and Canadian International Development Agency finances feasibility study.
1989 Canadian International Development Agency (CIDA) determines project is technically, environmentally, and economically feasible.
1990 Premier Li Peng revives the project in the aftermath of Tiananmen Square.
1991 U.S. Bureau of Reclamation signs contract to give technical support.
1992 End of the 40-plus-year verification phase, and the commencement of implementation phase. Chinese Congress votes on project (1,700 votes total): 1,100 for (64%), 400 against (24%), 200 abstained (12%).
1993 Former U.S. and Canadian support withdrawn. In their campaigns against the dam, International Rivers Network (IRN) and a coalition of US environment, development, and human rights groups encourage the U.S. administration to withhold financial support for the U.S. companies eager to bid for the project due to its adverse environmental and social impacts.
1993 First batch of construction teams enter into the dam site, starting the construction for the preparatory works and first-stage diversion works.
1994 (December 14) Formal start of the TGDP's construction at the dam site.
1997 (November 8) End of Phase I, Cofferdam completed, Yangtze River diverted, and ships sail through channel, start of second-stage construction.
1998 Huge flood caused by the Yangtze River, interrupting construction work of the Three Gorges Dam and affecting 300 million people, with death toll 300,000 people and US$30 billion estimated losses. This monetary loss of a single flood makes the Chinese government even more determined to complete the project, seeing that its overall cost (US$27 billion) is even less than this single loss.
2000 Phase II underway. Scheduled to be completed 2003.
2003 Scheduled end of Phase II and start of Phase III.
2009 Scheduled end of Phase III and completion of the TGDP.

TGDP Construction Phases

The total duration of construction is projected to be 17 years, divided into three phases:

- 1993-1997: First phase construction, including preparation period, dominated by massive earthmoving. Its completion was signaled by the damming of the Yangtze River on November 8 and the opening of the diversion channel.

- 1998-2003: Second phase construction, will be completed when the first generating unit in the left-bank power plant goes on line and the permanent ship lock begins operation.

- 2003-2009: Third phase (final) construction, marked by the completion of all 26 electricity-producing turbo-generators.

TGDP Quantities of Construction Work

The main work quantities to be done in the construction for principal structures and diversion works are as follows (China Yangtze Three Gorges Dam Project Development Corporation, 1999):

• Earth-and-rock excavation	102.83 million m^3
• Earth-and-rock embankment	31.98 million m^3
• Concrete placing	27. 94 million m^3
• Re-bar	463.0 x 10^3 tons
• Metal works	256.5 x 10^3 tons
• Installation of hydro turbine generator	26 sets (18,200 MW)

TGDP Cost

In 1990, the cost of the project was estimated at US$12 billion (Y90.09 billion). A more recent estimate is $27 billion (Y223 billion). Nearly half of the project's cost is being applied to the resettlement of hundreds of villages and towns along the river's edge. If the estimated cost is increased by a factor of 2.25 within 10 years, it might well be possible that the actual cost by the end of the project would reach the $50 billion mark–more than virtually any other single construction project in history.

TGDP Controversy

The construction of China's Three Gorges Dam, the largest dam in history, is already in its ninth year and is expected to be completed by 2009 with a cost currently estimated at over $27 billion. Perhaps more than any other project in the history of China, the TGDP has attracted the attention of many individuals and groups in China, as well as worldwide, and created much controversy, particularly among the experts, due to its almost equally compelling advantages and disadvantages. Supporters of the project believe that the advantages of the project far outweigh the disadvantages, and, obviously, this is the view of the decision makers in the Chinese government because the project is indeed moving forward. Following is a list of both the advantages and disadvantages for the readers to think and decide for themselves:

TGDP Advantages

1. **Flood Control:** The TGDP is projected to allow a precise control over the Yangtze River, reducing the severity of flooding by 90%, thereby saving life and property from destruction.

2. **Power Generation:** With its 26 turbines at full capacity, the TGDP is estimated to generate 18,200 MW annually, making it the biggest hydropower producer in the world. This would provide 15% of China's electricity—mostly in the Yangtze River basin area. That output is equivalent to approximately 50 million tons of coal or that of 18 nuclear power plants, producing 84 billion kilow.hrs output per year.

3. **Navigation Improvement:** The TGDP is projected to allow the passage of 10,000-ton ships to Chongqing instead of the limited 5,000-ton ships, increasing the annual one-way navigation capacity from the present 10 million tons to 50 million tons, meanwhile decreasing the navigation cost by 35% to 37%. With almost 15 million people, Chongqing will become the largest "seaport" in the world.

4. **Other:** The project is expected to promote the development of fishery in the reservoir, as well as tourism and recreational activities. To a certain extent, it should improve the water quality of the middle and lower reaches of the river during the dry season and create favorable conditions for the south-to-north water transfer projects.

TGDP Disadvantages

1. The reservoir will flood 13 cities, 140 towns, 1,352 villages, and 657 factories—a great economical, sociological, and cultural irreversible loss—and will create a pollution problem when the infrastructure of these communities become submerged under water.

2. Construction will force the resettlement of almost two million people, cutting them from their roots and creating all kinds of social instability associated with a "river refugee new community."

3. The reservoir will flood approximately 75,000 acres of the best agricultural and cultivated farmland in the region, requiring farmers to start cultivating lesser quality lands.

4. Over 110 sites of cultural and historical importance will be forever lost.

5. It is feared that the project will alter the entire ecological system and adversely affect the environment in the area. Not only will it obstruct the river's natural course, but it will also inundate hundreds of acres of land that are the habitat for many species.

6. It is predicted that the devastating environmental damage induced by the project will also threaten the river's wildlife. In addition to massive fish species, it will also affect endangered species, including the Yangtze dolphin, the Chinese sturgeon, the Chinese tiger, the Chinese alligator, the Siberian crane, and the giant panda.

7. Chongqing and many other cities along the river will flush tremendous amounts of sewage and toxic waste into the reservoir, turning it into a "cesspool" that will threaten the health of the scores of millions who live in the Yangtze basin, while no funds have been allocated for water treatment ("China's Three Gorges Dam," 1996).

8. Pollution and slow-moving water could also threaten fish, reptiles, and other wildlife that depend on the river for their survival. Almost 80 species of fish, Yangtze dolphin, finless porpoise, Chinese sturgeon, and giant panda will be endangered ("China's Three Gorges Dam," 1996).

9. Downstream regions would be deprived of the fertile silt traditionally carried by the Yangtze River as it becomes trapped behind the dam. As silt accumulates upstream, it would affect Chongqing because the water level would rise at the reservoir's opposite end and submerge parts of it. This also could cause imbalance in the overburden pressure on soil strata, which may increase the risk of earthquakes and landslides, and eventually threaten the dam's stability.

10. Navigation benefits are exaggerated because heavy sediment buildup in the reservoir is likely to continue to hinder navigation.

11. Flood control benefits are overstated; the reservoirs could at best store only a fraction of the floodwaters entering the Yangtze during a peak-flow year.

12. Dam construction will divert funds from more beneficial, less risky projects such as constructing smaller scale dams along the Yangtze and building new canals or branches that may work as safety outlets when the Yangtze floods attack, which also brings water to new areas.

13. The dam would be a military target, creating a possible disaster area should it fall due to an attack or due to earthquakes or natural catastrophes.

14. The dam and the reservoir will destroy some of China's finest scenery and an important source of tourism revenue.

TGDP Status Highlights

The second of the three construction phases of the TGDP is already halfway completed. This critical stage presents perhaps the TGDP's biggest challenge: keeping to an aggressively ambitious schedule while constructing—according to the highest technical specifications and foreign inspection—the permanent five-story ship lock, the dam's spillway, and left intake structure, which will house 14 giant turbines. The schedule calls for the first two turbine generators to be producing power—and critical revenue—followed by the remainder of the bank in 2003. This means breaking every known record for concrete construction (Wahby, 2000).

To meet deadlines, over 25,000 workers must pour concrete at a pace of about 520,000 cubic yards (400,000 cubic meters) per month, requiring an extensive and complex system for transporting enormous quantities of concrete from the mixing plants to the dam. The equipment, from the U.S. supplier Rotec Industries, consists of about 5 miles of fast, movable, and rotating conveyors.

As the dam progresses to its eventual height of 607 ft, six tower cranes specially fitted with jacking systems will raise the conveyors. In addition to their lifting capacity, the tower cranes have swinging telescopic conveyors that are designed to pour concrete at the impressive rate of more than 600 cubic yards per hour. A mobile crane delivers concrete from a large hauler to construct the dam's left training wall. Because concrete generates a considerable amount of heat as it sets, large volumes can become exceedingly hot, damaging the material's structural strength. Hence, curing of concrete is essential to keep it at a temperature of about 45 $^{\circ}$F (7 $^{\circ}$C) as it hardens.

The construction pit for erecting the main dam was dug to a depth of 260 ft, allowing the foundation work to begin. Numerous holes (with a total length of more than 60 miles) are currently being drilled into the ground and filled with pressurized grout. This "grout curtain" will help protect the main dam from uplift by preventing water from seeping underneath the structure. (For the same purpose, 870,000 sq ft of concrete walls were sunk below the transverse cofferdams.)

To facilitate transporting thousands of workers to the construction site, the government built a four-lane highway from Yichang, the nearest city of significant size. By any standard, the $110-million road, which cuts through the mountains that frame Xiling, was itself a considerable undertaking: 40% of its total length of 17 miles consists of bridges and tunnels, including a twin bore that is more than 2 miles long. Additionally, a 2,950 ft suspension bridge, the longest in Mainland China, outside of Hong Kong, was built at Sandouping for access to the project's right bank.

The double-way, five-step flight ship lock was carved from granite on the river's left bank and lined with concrete. To carve space for the multiple chambers of the lock, workers had to blast with precision more than 75 million cubic yards of hard rock.

The construction progress can be described as follows:

- **Land requisition in dam site:** The total construction area of dam site is 3,700 acres (15. 28 km^2). The land requisition and relocation of 12 thousand residents have been finished and an enclosed management in-site area carried out.

- **Internal and outside transportation:** The expressway from Yichang city to the dam site and Xiling Bridge across the Yangtze River have been in operation since October 1996. Main docks and an internal road system at the site area have been finished.

- **Aggregate processing and concrete batching plant system:** Two aggregate excavating and processing systems have been constructed and are able to supply coarse- and fine-size aggregates for concrete mixing. With the addition of two other concrete batching plant systems, the concrete production rate could reach 2,380 m^3 per hour, which can satisfy the capability of 550 thousand m^3 per month concrete placing. Each batching plant has its own cooling system that guarantees a 7 $^{\circ}$C temperature for cooling concrete in the summer.

- **Diversion works:** Completed; diversion channel opened for navigation on schedule.

- **Temporary ship lock project:** Completed; put into operation on schedule.

- **Ship lift:** Excavation work and concrete placement completed on schedule.

- **Permanent ship lock:** The following were completed on schedule: Surface and underground excavation, excavation work for the lock chambers, concrete placement, underground excavation of the water feed and empty system including inclined shafts and gate shafts, concrete lining.

- **Non-overflow dam sections:** The concrete placement of the left and right bank non-overflow dam sections was started in 1996 and 1997, respectively. Currently, several segments have reached an elevation of 120 m with the left abutment dam sections having reached to the crest elevation of 185 m.

- **Left bank intake dam sections and powerhouse:** Concrete placement of No. 1 to 6 intake dam sections of left bank was started at the end of 1997. No. 1 to 6 units of the left bank powerhouse are planned to be the first batch of generators put into operation. Because of its convenient construction condition, the excavation of the powerhouse for No. 1 to 6 was arranged in the first construction stage and was finished at the end of 1997. The concrete placement was started in January 1998. At the end of 1998, the No. 1 to 5 powerhouse concrete placement of the basement and the tailrace tube were basically finished. The excavation for No. 7 to 14 units was finished by the end of 1998. Concrete placement is in progress.

Conclusions

When completed, the TGDP of China will be the largest water conservancy project as well as the largest hydropower station and dam in the world. Technology is being challenged and stretched to the limit as never before to face a variety of engineering challenges in the construction of the TGDP. This includes many aspects such as site preparation, the dam's foundations, the details of the project's main structures, some of which are carved in very hard rocks, not to mention having to work under ever-changing weather. Production rates never before attained are becoming the norm in order to keep the sizable project on schedule. After the completion of the project by 2009, the technology used in the construction of the dam will probably need to be enhanced in light of lessons learned.

After the completion of the TGDP, precise flood control can be achieved and enormous hydroelectric energy will be produced annually, replacing coal consumption and saving the environment. However, this will not be without cost considering the negative effects such as submerging numerous cities, towns, and villages and inundating some of the best farmland, besides threatening wildlife, not to mention the resettlement of almost 2 million people.

The TGDP is a massive effort in technology transfer. The author asked the chair of the Association of Retired Engineers in Chongqing whether Chinese people are proud of the Great Wall more than they are with the TGDP. After a moment of deep thinking, he stated with a smile that "the Great Wall was built by the Chinese people, and it is indeed their pride, but the Three Gorges Dam is being built by the whole world, so it should be the pride of the whole world!"

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