The Three Gorges project on the Yangtze river in China

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Taming the mighty 6300 km long Yangtze river in south China was never going to be easy. Its history is littered with catastrophic flooding events that have destroyed lives and livelihoods and caused untold economic loss. The proposal to build what will still be the world’s largest flood-control dam at the Three Gorges site in the river’s mid-section was put forward as long ago as 1919. Wars and revolutions delayed the start until 1993 and completion is not now scheduled until 2009. This paper describes the planning and design of the £15 billion project and reports on construction progress to date. It highlights in particular the difficulties experienced in assessing the scheme’s benefits against its costs—not least the need to relocate and re-skill over one million people.

The Three Gorges dam being built on the Yangtze river in southern China (Figs 1 and 2) is being designed to alleviate flooding in the industrial and agricultural areas downstream of the dam as well as to supplement urban water supplies in northern China, including the city of Beijing.

The project includes a large hydroelectric power station, the income from which will make a substantial contribution to financing the scheme in its later stages. Initial

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Keywords

is a former member of the ICE energy board and the ICE research and innovation committee. He has worked on hydroelectric schemes in many parts of the world.
funding is through loans and a tax on energy consumption throughout the country. Another benefit of the project is improved navigation on the river from Shanghai on the coast to the inland city of Chongqing, a distance of about 3500 km.

The most expensive single part of the project is the programme to move more than one million people from the area to be flooded into new houses above the proposed reservoir level. An environmental impact study identified both positive and negative consequences of the project and the authorities say they have taken steps to solve the negative consequences.

The dam is a conventional gravity dam located on a foundation of sound and apparently impermeable granite. It is the largest hydroelectric project under construction at present and is setting new records for volumes and rates of construction. The civil engineering contracts were awarded to Chinese contractors but contracts for mechanical and electrical equipment were open to international competition and won by consortia from North America and Europe. Construction started in 1993 and impounding and first power generation is due to start in 2003. Completion is scheduled for 2009 at a final cost approaching £15 billion.

Flooding history of the Yangtze


The scale of the problem can be appreciated by the fact that, in the 1998 flood, the cost of providing emergency protection for the city of Wuhan, other downstream cities and areas of cultivated land together with the cost of clearing up flood damage was comparable with the capital cost of the proposed dam. Flooding also appears to have become more frequent in recent years as a result of cutting down trees in the upper catchment area to clear land for agriculture.

The Yangtze river (known as Chang Jiang in Chinese) rises in the plateau area of southern Qinghai province in northwest China. This is part of the eastern Tibetan plateau at an elevation of about 4000 to 5000 m with adjacent mountains rising to more than 6500 m. The river then flows 6300 km through southern China to the sea at Shanghai. About two-thirds along its length the river passes through a series of narrow limestone and sandstone gorges which extend for nearly 200 km. Near the downstream end of these gorges at the town of Sandouping, the bedrock is granite and it is this site which first attracted attention as a suitable location for a dam.
The first serious proposal to build a dam at the gorges was put forward in 1919 by Dr Sun Yat-sen, founder of modern China, but the Japanese war, the civil war and the communist revolution delayed political approval until 1992.

Benefits of the project
As part of the preliminary studies for the project, a comprehensive environmental impact study of the whole Yangtze basin was undertaken. This demonstrated that there were positive impacts in the middle and lower reaches of the river, and negative impacts in the reservoir area, but the negative impacts could be alleviated by suitable countermeasures.

As well as mitigating the downstream flood levels, the other benefits of the project are

- the capacity to transfer water from the Yangtze basin to Beijing and to other cities in northern China where there is a shortage of water
- a large hydroelectric power station (at present the largest under construction)
- improved navigation on the river
- a new source of food by the introduction of fish farming and aquaculture in the new reservoir
- a better supply of irrigation water to the farming areas downstream
- better control of the salinity of the water in the estuary region near Shanghai.

Once impounding of the reservoir starts in 2003 it will be necessary to ensure that the reservoir is not polluted by the trade and domestic wastes from adjacent cities. The city of Chongqing alone produces an estimated 1200 Mt of industrial wastewater and 300 Mt of sewage every year. At present only about a third of the industrial wastewater is treated and almost none of the sewage. The World Bank has contributed £62 million for building new sewage works and a further £136 million for treating wastewater and solid wastes.

Dam conventional in all but size
The components of the dam are straightforward and conventional—it is the size of the project that is unusual. The main structure is a concrete gravity dam 2·3 km long founded on granite and with a maximum height of 183 m. The dam crest level will be at an elevation of 185 m, the normal top water level will be 175 m and the downstream river level will be typically between 62 and 83 m.

The new reservoir will cover an area of 1100 km² (about twice the size of the Isle of Man) and will extend back to the city of Chongqing, 660 km upstream. The spillway section will be in the centre of the river channel with a power station on each side (Figs 3 and 4).

A ship lift and ship lock on the north side of the dam will enable ships to pass between the reservoir and the river (Fig. 5).
The Three Gorges Dam, China

The layout is similar to that of the smaller Gezhouba dam built across the Yangtze around 20 years ago at Yi Chang, 38 km downstream of the Three Gorges site (Fig. 6). This was the first dam built across the Yangtze river and it was intended that the experience gained from designing, building and operating it would be incorporated in the design of the Three Gorges project. Gezhouba dam is also a gravity dam, 2600 m long but only 70 m high.

The two power stations at Gezhouba together contain 21 Kaplan turbines with a total capacity of 2.7 GW. The annual output is 15.7 TWh, but this will increase to about 20 TWh after completion of the Three Gorges dam owing to improved river regulation. Silt is discharged through silt traps on the upstream side of each turbine and 27 sluices in the dam. There is no provision for a fish pass in the Gezhouba dam and new spawning grounds for the Chinese sturgeon, which used to pass upstream to spawn, have been developed downstream of the dam.

Resettlement—the biggest cost

The largest single undertaking in the Three Gorges project is the relocation of people and industry from the area to be flooded by the new reservoir (Fig. 7). This work is estimated to cost £2.85 billion of the initially estimated project cost of £6.43 billion. New homes above the new reservoir level are being built for 1.1 million people (Fig. 8). One third of the people to be moved from the area to be flooded are farmers and finding new land for them to farm is more difficult than allocating land for urban housing and industry.

The area of existing agricultural land to be flooded is 24 500 ha and the government has identified a sufficient alternative area for farming. But the new land is more suitable for cash crops such as tea and citrus fruit rather than the basic foods of wheat, rice and vegetables that the farmers grew at the lower level (Fig. 9). The government has recognized that it will have to import grain into the region from other...
The homes of over 1 million people will be flooded by the dam.

New housing is being built above the proposed reservoir level.

Depth marker in farmland is 40 m below final water level.

parts of China to make up for the shortfall. It is also trying to persuade up to half of the former farmers to give up farming and move into urban employment.

The agricultural benefit of the dam is that it will reduce the risk of flooding in an area of 1·5 million ha of cultivated farmland downstream of the dam. The downstream protected area is therefore about 60 times the area of the agricultural land lost by flooding upstream of the dam.

The operation of moving people out of low-lying areas upstream of the dam, which started in 1993 and will continue as the water rises, has attracted favourable comment from the World Bank. A senior water adviser has commented that the Chinese see resettlement as an opportunity to develop the area.

**Flood control**

The catchment area of the whole Yangtze river basin is 1·8 million km² and the annual mean runoff is 960 billion m³. At the Three Gorges site the catchment area is 1 million km² and the mean runoff is 451 billion m³. The flow in the unregulated river is least in the winter months of January, February and March and most in July, August and September (Fig. 10).

During the winter dry season, the river flow has in the past fallen to a minimum
22.2 billion m$^3$ will be available for flood control. This is only around 4.3% of the yearly runoff at the dam site and the reservoir therefore provides only seasonal regulation and low runoff regulation.

of about 2500 m$^3$/s but, with the new reservoir, the downstream flow will be maintained at a minimum of 5000 m$^3$/s. In the late summer the ‘average’ flood flow is approximately 35 000 m$^3$/s and in 1998 it reached an estimated 57 700 m$^3$/s.

The 100-year flood flow is estimated to be 83 700 m$^3$/s and the permanent spillway has been designed for a probable maximum flood of 102 500 m$^3$/s at the maximum top water level of 180.4 m (Fig. 11). The diversion channel and cofferdams to protect the works during construction have been designed to contain a flood discharge of 72 300 m$^3$/s (a 20-year flood).

With a normal top water level of 175 m, the total storage capacity of the reservoir will be 39.3 billion m$^3$. 22.2 billion m$^3$ will be available for flood control. This is only around 4.3% of the yearly runoff at the dam site and the reservoir therefore provides only seasonal regulation and low runoff regulation.

An important engineering problem is dealing with the silt in the river and with the potential sedimentation in the reservoir. These are particularly sensitive problems, especially in view of the difficulties the Chinese had in the past at the Sanmenxia reservoir on the Yellow River to the north of the Yangtze. Although the water in the Yangtze appears to be muddy in October at the end of the flood season, its average silt load at 1.2 kg/m$^3$ is an order of magnitude lower than that in the Yellow River at 37 kg/m$^3$. Any sedimentation problems on the Yangtze are not expected to be as serious as those on the Yellow River. More than half the annual silt load in the river is carried down in the three flood months July to September and it is intended that this silt load will be discharged through the outlet gates in the dam.

Even when the dam is completed, the width of the reservoir channel will be only about twice the width of the original river channel and the silt flow will be concentrated in the centre of the channel. This helps to discharge the silt through the dam sluices. The permanent gates in the spillway section consist of 23 bottom outlet gates, 7 x 9 m at an inlet level of 90 m, and 22 surface sluice gates 8 m wide with a sill level at 158 m. There are also 22 bottom outlet gates in the base of the dam which will be used during the construction phase.

**Transfer of water to the north**

There is a serious shortage of water in northern China for both domestic use and for agricultural irrigation, and this shortage has been exacerbated by the demand for more tourist hotels in the northern cities such as Beijing and Zhengzhou. In 1981 it was reported that the thermal power stations in Beijing had to close due to the shortage of cooling water, and in 1992 some sections of the Yellow River (which supplies water to Beijing) almost dried up.

Improvements are now being made to the existing local sources of supply and by raising the level of the Dan Jiang Kou dam, which is the main reservoir for transferring water from the south to the north, but even with these improvements there will still be a shortfall of the order of 17 million m$^3$ per year to supply the cities alone (and possibly twice that amount needed for agricultural use). It is intended that this water will be supplied from the Three Gorges reservoir when impounding starts in 2003.

The proposed route for the water to be diverted from the Yangtze basin into the basin of the Yellow River is from a small northern tributary of the Yangtze to the...
Dan Jiang Kou reservoir. This reservoir is about 240 km north of Yi Chang and one of those selected by the World Commission on Dams for an independent study on its ‘development effectiveness’. About six or seven other dams in the developing and the developed world will be included in the study. From Dan Jiang Kou the water is diverted into the Yellow River (and hence northern China and Beijing) by way of an existing sluice and the main channel of the south-to-north water-transfer project.

An alternative proposal is to pump water from the Daning river (another northern tributary) to an upper reservoir at an elevation of 505 m—a typical lift of 360 m when the reservoir level is 145 m. From there, two tunnels 20 km and 40 km long will be excavated through the Daba Shan mountains to a tributary of the Han river and hence into the Dan Jiang Kou reservoir.

Power stations
There will be two power stations at the Three Gorges dam. The left bank (north) power station will contain 14, 700 MW Francis turbines (Fig. 12) and in the right bank (south) power station there will be twelve 700 MW Francis turbines. The total installed capacity will be 18.2 GW and the estimated annual output will be 84.7 TWh. There is sufficient space on the south bank for a further six 700 MW turbines in an underground power station which will add a further 4.2 GW.

Electrical transmission locally is at 500 kV AC, and long-distance transmission to Beijing, some 1300 km to the north, is at 500 kV DC. International quotations from six consortia were sought for the electrical and mechanical equipment, and contracts have been placed for the 14 turbines and generators in the left bank power station, and for the associated converter and transmission equipment.

Navigation
A major part of the engineering work is the flight of five locks and the ship lift. Each lock is 280 m long, 34 m wide and has a 5 m minimum water depth. The five locks are designed to allow a 10 000 t barge to pass the dam in 3 h. Passenger ships and smaller cargo ships of 3000 t will be able to use the vertical hoist ship lift (120 × 18 × 3.5 m) and pass through in half an hour.

Despite dredging and blasting in the river bed in the 1950s to make the river more navigable, there is still a strong current in the main channel of the river, typically about 6 knots, and shoals in other reaches. This makes navigation hazardous for small vessels and difficult even for the larger boats. The designers expect that with the new reservoir the traffic on the river will increase from its present level of 10 Mt/y (mainly coal and aggregates going downstream) to 50 Mt/y, and also that the cost of water transport will be reduced by a third.

While the dam is under construction a temporary ship lock has been built on the north side of the dam to allow those ships to pass the dam which cannot pass through the current in the diversion channel.

Management
The overall decision-making body for the project is the Three Gorges Project Construction Commission, which is chaired by the Premier of the State Council and whose members include local politicians. The organisation responsible for the financing, construction and management of the project is the China Yangtze Three Gorges Project Development Corporation located at Yi Chang City. This corporation has several divisions including the engineering construction division which is responsible for the overall coordination and management of the construction. The organisation in charge of the planning, research and design is the Changjiang Water Resources Commission with access to advice from panels of international specialists.

The initial civil engineering contracts were awarded by competitive bidding to more than ten Chinese contractors. The Harza Engineering Company of the US has been appointed to supervise the construction. The labour force is expected to reach a peak of 25 000. International bids were invited for the mechanical and electrical equipment. Of the 14 turbines and generators in the left bank (north) power station a contract for eight units has been awarded to a consortium of GEC Alsthom and ABB and a contract for six units to a consortium of GE Canada, Voith and Siemens. The total contract value for this equipment is £460 million. ABB has also won contracts for switchgear and converter stations for the HV DC link to Shanghai.

Construction programme
The construction works are being carried out in three stages. The first stage was started in 1993 and completed on time in 1997. This included building the

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**Fig. 12. Cross-section through power station showing one of 26, 700 MW Francis turbines**
access road, the first-phase cofferdam, the foundations for the third-stage upstream cofferdam, the diversion channel, the temporary ship lock, the excavations for the permanent ship locks and the foundations for the first six units in the left bank (north) power station.

The first-stage cofferdam was an earth and rockfill structure built around the temporary diversion channel on the right bank (Fig. 13). The diversion channel was excavated to a level of 45 to 50 m, while the main flow of the river continued in the main river channel which is the location for the central spillway of the completed dam. The main river channel was completely closed and diverted through the diversion channel on 8 November 1997.

In the second phase starting in 1998, the site of the central spillway and the left bank power station was enclosed within an upstream and downstream cofferdam (Fig. 14). The crest level of the upstream cofferdam is 88.5 m (Fig. 15). Construction of the cofferdams started after the flood season of 1996 by dumping crushed rock and gravel in the river bed. By October 1998 the cofferdams and their concrete cut-off walls and curtain grouting were completed and the construction area was dewatered.

By 2003 the left bank power station and dam, and the central spillway section, will be completed and the first machines will be installed in the power station. The temporary ship lock was opened for navigation in May 1998 and during the second phase work will be completed on the permanent ship lock and ship lift.

By May 2003, before the annual flood, the third-phase cofferdams in the diversion channel will be finished and impounding can start. The reservoir water level will initially be raised to an elevation of 135 m. After the 2003 flood has subsided, the first group of generators will be put into service. The permanent ship lock will also be ready for use when the water level is raised to 135 m.

In the third phase, from 2004 to 2009, the right bank power station and all other outstanding works will be completed.

The magnitude of the construction work can be indicated by the following quantities of materials:

- rock and soft excavation: 102.83 Mm$^3$;
- rock and soft filling: 31.98 Mm$^3$;
- concrete placement: 27.93 Mm$^3$;
- steel supply and erection: 256 500 t.

The seven concrete batching plants have a total capacity in excess of 2000 m$^3$/h and the peak rate of supply was in the year 2000 at a rate of 550 000 m$^3$ per month.

**Project costs and funding**

Based on 1993 prices, the ‘static’ cost of the works is quoted as £6.5 billion (¥90.09 billion). This is the sum of the project construction works estimated at £3.6 billion and the resettlement costs at £2.9 billion. These costs exclude price escalation and loan interest during the construction period. The final ‘dynamic’ cost by the time the project is completed in 2009 is estimated to be about £14.3 billion.

The main source of funding the project is by a tax on the energy supplied by the power networks throughout the country. The annual energy consumption in China is in excess of 1100 TWh (about four times the annual consumption in the UK) and the annual incremental rate of energy consumption over the next ten years is expected to be from 4% to 5%. The fund was established in 1992 and the tax was initially imposed at a rate of about 0.03 p/kWh. This was raised in 1996 to about 0.05 p/kWh but the level of the tax in each area depends on the extent to which the local network will benefit from the scheme.

Electricity used in the poorest areas is exempt as is electricity used for agricultural irrigation and drainage purposes. This tax contributes about half the costs of construction. The other half comes
By the year 2003 the Three Gorges power station will start generating electricity and the income from this electricity is expected to be the main source of income to repay the loans to complete the scheme by the year 2009.

Visitors to the Three Gorges site today will see the main spillway section of the dam and the north power station being built within the second-phase cofferdam (Fig. 16). The river is diverted through the right bank diversion channel on the site of the future south bank power station. The permanent ship locks and the ship lift are being built and a temporary ship lock is in use for ships which cannot pass upstream through the current in the diversion channel.

Discussion
If you would like to contribute to the discussion please post/fax/e-mail your comments (500 words maximum) to the editor by 1 June 2003.