China’s Major Bridges

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Summary
In response to continuous economic development over the past 30 years, China has mobilized a program of large scale bridge construction. The technology of various types of bridges, including girder bridges, arch bridges, and cable-supported bridges, has been developed rapidly. Bridge spanning capacity has been continuously improved. Girder bridges with main span of 330 m, arch bridges with main span of 550 m, cable-stayed bridges with main span of 1088 m and suspension bridges with main span of 1650 m have already been built. Moreover, two sea-crossing bridges with overall length over 30 km have also been opened to traffic. This paper briefly introduces China’s major bridges, including girder bridges with spans greater than 200 m, arch bridges with spans greater than 400 m, cable-stayed bridges with spans greater than 600 m, and suspension bridges with spans greater than 1200 m. These bridges represent technological progress in such aspects as structural system, materials, as well as construction methods and equipment.

Key words: girder bridge, arch bridge, cable-supported bridge, cable-stayed bridge, suspension bridge, steel-concrete composite bridge

1. Background
In the past thirty years, and especially during the past ten years, China has undertaken the world’s largest scale highway and bridge construction program. Rapid and significant improvements to bridge construction technology have enabled breakthroughs in the design and construction of long spans. Bridge construction activity has been concentrated in the middle and lower reaches of the Yangtze River, the middle and lower reaches of the Pearl River, as well as the deltas of the Yangtze and Pearl Rivers (Fig. 1).

This paper briefly describes the development of major bridge construction in Mainland China (excluding Hong Kong, Macao, and Taiwan) in the years before and after the turn of the 21st century.

By 1978, China had 128,210 highway bridges, with a total length of 3283 km, and 26,139 railway bridges, with a total length of 1099 km. In the past three decades from 1979 to 2008, bridge construction averaged 16,000 bridges per year. By the end of 2008, there were 594,604 highway bridges in China, with a total length of 25,240 km, and 52,355 railway bridges, with a total length of 4349 km.

Bridges in China can be divided into three types, namely girder bridges, arch bridges, and cable-supported bridges (including cable-stayed bridges and suspension bridges). Girder bridges and arch bridges make up almost 70% and 30% respectively of all bridges built in China. Cable-supported bridges occupy less than 1% of total number.

With the focus of bridge construction shifting from upper and middle reaches of rivers and lakes to lower reaches, bays, and straits, China will face challenges to apply advanced
technology in bridge construction to deal with more complicated meteorological, hydrological, navigational, and geological conditions and realize breakthroughs in longer spans.

During this period, the maximum span length of highway bridges in China increased rapidly, first exceeding 200 m in 1985, and passing 400 m in 1991, 600 m in 1993, 800 m in 1997, and 1000 m in 1999. The longest span for railway bridges exceeded 200 m in 1997, and passed 300 m in 2003 and 500m in 2008.

By the end of 2008, Mainland China’s bridge inventory includes:

- 54 completed bridges and 18 bridges under construction with main span over 400 m
- 19 completed bridges and 12 bridges under construction with main span over 600 m
- 9 completed bridges and 9 bridges under construction with main span over 800 m
- 6 completed bridges and 5 bridges under construction with main span over 1000 m

The maximum main span of completed girder bridges, arch bridges, and cable-stayed bridges has reached 330 m, 550 m, and 1088 m respectively, ranking first for each type of bridge in the world. The longest suspension bridge span in China, 1650 m, ranks second in the world.

The Yangtze River (total length of 6380 km) is the third longest river in the world. Along the 2838 km navigable channel from Shuifu in Yunnan Province to the Yantze delta, 59 bridges have been built and 21 bridges are under construction.

Bridges introduced in this paper focus on girder bridges with spans greater than 200 m, arch bridges with spans greater than 400 m, cable-stayed bridges with spans greater than 600 m, suspension bridges with spans greater than 1200 m, and sea-crossing bridges of total length greater than 30 km built in Mainland China at the beginning of the 21\textsuperscript{st} century.

### 2. China’s Highway Bridges

#### 2.1 Long sea-crossing bridges

In the beginning of this century, work began on the Donghai Bridge and the Hangzhou Bay Bridge, which marked the beginning of construction of extra-long sea-crossing bridges in China. The Donghai Bridge is 32.5 km in length and the Hangzhou Bay Bridge is 36 km long.
Both bridges are designed and constructed as 6-lane expressways with design service life of 100 years. (Fig. 2, 3)

The Donghai Bridge is located near the estuary of Hangzhou Bay, connecting Shanghai’s Port of Luchao to the Yangshan Deep-water Port. It includes 25.5 km of structure over water.

The Hangzhou Bay Bridge, connecting Ningbo to Shanghai, shortens the driving distance between the two cities by 120 km. The Hangzhou Bay Crossing Project is located in the middle of Hangzhou Bay, one of the three strongest tidal regions in the world. The minimum water level is 4.94 m, maximum tidal range is 7.4 m, and average tidal range is 5.32 m. Annual average water current velocity is 2.39 m/s. During construction, the highest measured current velocity was 4.18 m/s at ebb tide and 5.16 m/s at flood tide, with irregular currents and complex tidal current fields. Seabed and sand movement are also complicated and variable. The site is under frequent influence of typhoons.

Both sites are overlain by quaternary deposits, and both bridges are supported on pile foundations. Prestressed high strength concrete piles and steel tubular piles were driven by pile driving barges and bored piles were cast from construction platforms. Foundation construction featured large diameter, extra-long, and extra-heavy steel tubular piles. Steel tubular piles with diameter of 1.6 m or 1.5 m and lengths of up to 90 m were driven. The weight of the longest pile reached 68 t.

Offshore approach spans, which make up over 95% of the total length of both bridges, were prefabricated in one piece, transported to site, and erected using heavy lifting equipment. Cast-in-place closures at the piers were used to transform simple spans into continuous structures. The special equipment used to erect the spans was newly developed for these projects, including a 1600 t track bridge erector used to transport and erect 50 m span box girders on the top of previously erected girders, as well as 2500 t and 3000 t barges for integrated transportation and erection 60 m and 70 m span box girders.

Cable-stayed bridges with main span greater than 400 m and 300 m were chosen for the main and secondary navigation channels for both bridges. Continuous girder bridges with main spans in excess of 100 m were used for the auxiliary navigation channels.

To improve the durability of the concrete, the low strength tension technique was adopted to eliminate cracks of mass concrete. High performance marine concrete was developed for structures under water.

These two bridges required massive construction work in the face of tough construction difficulties. It took three and a half years to complete construction of the Donghai Bridge and four and a half years for construction of the Hangzhou Bay Crossing Project.

Other major sea crossings include the recently completed Jintang Bridge (total length of 18.5 km), which is a component of the Zhoushan Linking Project, and the 29 km long Qingdao Bay Bridge currently under construction.
2.2 Girder Bridges

Prestressed concrete continuous girder bridges and prestressed concrete continuous frame bridges are widely used in China. In the 20th century, the main span of prestressed concrete continuous girder bridges reached 165 m by the year 2000 (on the north branch spans of the 2nd Nanjing Yangtze River Bridge). The main span of prestressed concrete continuous frame bridges reached 270 m by 1997 (secondary navigation channel span of the Humen Bridge across the Pearl River in Guangdong Province) (Fig. 4). Prestressed concrete continuous frame bridges are common for spans between 150 and 300 m. More than 55 bridges of this type with main span exceeding 200 m have been built. In recent years, about 10 prestressed concrete bridges with pier shafts taller than 100 m have been built for expressway projects in mountainous areas.

The bridge across the auxiliary navigational channel of the Sutong Bridge, which was open to traffic last year, is a prestressed concrete continuous frame bridge. Its main span is the second longest in China (Fig. 5). With a span arrangement of 140 m + 268 m + 140 m, it carries six lanes of highway traffic.

Several technical solutions were adopted in these new bridges to prevent common faults of prestressed concrete box girders, such as cracks in the webs and vertical deflection at midspan. These measures included providing draped tendons, enhanced vertical prestressing, and reserve prestressing force, improving the density of grout by vacuum grouting, the use of plastic duct, increased reinforcement and the provision of specific crack control reinforcement, adjusting the construction schedule to reduce the impact of early age shrinkage and creep, and improved estimates of shrinkage and creep strains. One of these bridges, a provision for 10% prestressing tendons was made. These strands could be tensioned during the service life of the bridge if necessary.
The Shibanpo Yangtze River Bridge in the city of Chonqing has a main span of 330 m in length. It was designed to meet special project requirements such as matching the layout of piers on the existing adjacent Shibanpo Bridge, visual harmony between the two structures, as well as new and more stringent clearance requirements for the main navigation channel in this region of the upper Yangtze River. The span layout of the bridge is 86.5+4×138+330+132.5 m (Fig. 6). The single box girder is 19 meters in width and carries four out-bound traffic lanes. To mitigate the stress level induced by self-weight and long-term deflection problems typically associated with long span prestressed concrete girder bridges, its 330 m main span is designed as a combination of two symmetric prestressed concrete cantilevers of 111 m length and a 108 m steel drop-in girder. The continuity between the steel drop-in girder and the two cantilever arms is established with a specially engineered steel-concrete joint segment as well as internal and external tendons. The key technology of this bridge further expands the applicability of prestressed concrete girder bridges to long spans. This bridge is the current record holder for girder bridge spans.

2.3 Arch Bridges

Modern arch bridge technologies have kept on developing in China. Several records were created in the 20th century: stone arch bridge spans (146 m for the Danhe Bridge in Shanxi Province, completed in 2000), concrete rib arch spans (312 m for the Yongning Bridge in Guangxi Province, completed in 1998), truss arch spans (330 m for the Jiangjie River Bridge in Guizhou Province, completed in 1995), concrete filled steel tube spans (360 m for the Tajisha Pearl River Bridge in Guangdong Province, completed in 2000), and box arch spans (420 m for the Wanxian Bridge in Chongqing, completed in 1997) (Fig. 7).

The beginning of the 21st century saw rapid development in steel arch bridges and composite arch bridges.
The Lupu Bridge in Shanghai is a steel box arch bridge with a world record span of 550 m. Construction of the bridge started in Oct. 2000 and was completed in June 2003 (Fig. 8).

![Lupu Bridge with 550 m span](Fig.8: Lupu Bridge with 550 m span)

The bridge was constructed with a bold idea to use a suspended basket arch system to create a unique aesthetic effect. Compared with traditional truss arch bridges, box arch bridges have a more modern style. The arch was built using the cantilever method, which involved supporting a cantilever inclined in three dimensions with a maximum weight of 480 t (Fig. 9). A half-through tied-arch bridge was chosen in response to the particularly soft soil foundation conditions in Shanghai. To balance the thrust of the main span, the structural system was transformed several times during construction to transfer tension of temporary cables to the suspenders (Fig. 10).

![Temporary cable-stayed construction system](Fig. 9: Temporary cable-stayed construction system (Travelers on arches for lifting arch rib segments))

![Horizontal cable and deck installation](Fig. 10: Horizontal cable and deck installation)
The section of the arch rib is a torsionally stiff shape. In spite of the sound aerodynamic stability of the arch rib, strong vortex shedding could still be observed during wind tunnel tests under uniform flow conditions. Based on hydromechanical calculations, a “diaphragm” aerodynamic damping measure was mitigate this condition without adverse effect on its aesthetics and a connection device was placed on the arch ribs for possible future use during installation of the diaphragm. In addition, a sightseeing platform installed on top of the arch can partially contribute to suppression of vortex shedding.

The project won the Eugene C. Figg Jr. Medal 2004 of IBC (International Bridge Conference) held in the Untied States and won the 2008 IABSE Outstanding Structure Award for being “a soaring box-arch bridge with a record span, clean impressive lines and innovative use of the side spans of the arch and the deck to resist the thrust of the main arch”.

The Chaotianmen Yangtze River Bridge in Chongqing is a half-through tied-arch bridge with the main span of 552 m. Total length of the project is 1.741 km, including 932 m for the main bridge. The span arrangement for the main bridge is 190+552+190 m (Fig. 11).

There are 8 lanes for highway and 2 tracks for railway. The bridge has double layered decks with 6 lanes on the upper level, 2 reserved highway lanes, and 2 railway tracks for dual directions on the lower level.

The bridge was erected using inclined cables and temporary towers. The project began in 2005, the main span was closed in May 2008, and the bridge will be completed in 2009.

With the completion of the first concrete filled steel tube arch bridge (The Wangcang Bridge with 115 m span) in 1990, the number bridges using this system has grown rapidly throughout the country. Presently, there are more than 300 bridges of this type in China completed or under construction and the largest main span is close to 500 m.

The 460 m-span Wushan Yangtze River Bridge in Chongqing was completed in Jan. 2005 (Fig. 12). It has the world’s longest concrete filled steel tube arch span. Deck width is 19 m. The arch has twin catenary ribs with varying cross section. Each rib consists of four main concrete filled steel tubes as the chords and small diameter tubes as the web members. The ribs are 7 m deep at midspan and 14 m deep at the arch foot. The rise to span ratio is 1/3.8, which corresponds to 121.05 m of the arch height. The span was erected using temporary cables and towers, which is now a mature technique of arch bridge construction in China. The arch ribs of this bridge were divided
into 22 sections for erection, each weighing between 71 and 118 t. Hinges at the arch foot were sealed after the arches had been closed at midspan. Concrete was pumped to the steel tube continuously through 3 steps from the foot to the top of the arch to finish the arch structure. This bridge pioneered the new technique of erection without temporary supports for long span arches (section weight: 170 t and erection height: 260 m) and of continuous pumping of concrete into large diameter pipes.

Research and analysis were carried out to determine the most suitable structural system and cross section, the structural capacity of concrete filled steel tubes under special load conditions, shrinkage and creep behaviour of concrete within steel tubes, node stresses of concrete filled steel tube structures, corrosion protection of the steel structure, and construction monitoring during implementation of the project.

The Caiyuanba Yangtze River Bridge in Chongqing is a steel-concrete composite tied-arch bridge, and the main girder is double layer truss structure, with 6 highway lanes on the upper layer and two railway tracks for the lower layer. The 420 m main span consists of a 320 m steel tied-arch in the central portion of the span and two symmetrically placed 152 m “Y” shaped concrete rigid frame structures for the side spans (Fig. 13). The structural system takes advantage of two combinations: steel and concrete for the materials, and a center tied-arch and rigid frame girder for the structural system. These combinations create efficiency by taking advantage of the properties of each component material and system. The bridge was completed in 2008.

The Xinguang bridge in Guangzhou has a prestressed concrete triangular frame in conjunction with steel truss arch ribs. The span arrangement is 177+428+177 m (Fig. 14). The triangular frames are 102 m long and 35 m tall. The bridge design is unique: the weight of side spans is balanced with the mid span, the arch ribs are monolithically connected with the triangular concrete frames of the main piers. The central span structural system is a semi-floating system.

The steel arch ribs of the main bridge were erected in 5 sections. A 2850 t, 168 m span middle section of arch was prefabricated on land, transported to the bridge site, and lifted 85.6 m to allow it to be connected with the side arch sections. Arch ribs were simultaneously lifted by numerically controlled hydraulic jacks, which set a new Chinese bridge construction record in lifting size, weight, and height. The
bridge opened to traffic in January, 2007.

Since the construction of the first bridge using the rotating method in 1977, hundreds of bridges ranging from mountainous regions to plane regions have been built with this technique in China. This construction technique has been developed from balanced rotation to unbalanced rotation, vertical rotation and vertical plus horizontal rotation, and has yielded technical and economic benefits.

The Yajisha Bridge in Guangzhou is a concrete filled steel tube arch bridge with 3 spans of 76 + 360 + 76 m, constructed by the twin cantilever self-balanced rotation method. The weight of the vertical rotated structure is 2,058 t, the total weight of the horizontal rotating structure is 13,685 t and the height of tower is 63.428 m (Fig. 15).

The Beipanjiang Bridge in Guizhou Province is the first railway concrete filled steel tube bridge in China. Its main span of 236 m is also the longest span for railway arch bridges in China. This bridge was built by horizontal rotation using counterweights. The rotated weight reached 10,400 t (Fig. 16).

2.4 Cable-Stayed Bridges

The development of modern technology for the construction of cable-supported bridges in China began in 1975 in China and proceeded gradually. By now, more than 300 cable-stayed bridges and suspension bridges with main span over 100 m have been built.

The span of cable stayed bridges passed 400 m and 600 m in 1991 and 1993 respectively. (Fig 17 and Fig. 18 show the 423 m span Nanpu Bridge and the 602 m span Yangpu Bridge, both in Shanghai). At the end of last century, the main span of cable-stayed bridges reached 500 m with prestressed concrete girders (the Jingsha Yangtze River Bridge in Hubei Province, completed in 2002), 605 m with steel-concrete composite girders (the Minjiang Bridge in Fujian Province, completed in 2002) and 628 m with steel box girders (the 2nd Nanjing Yangtze River Bridge, completed in 2000) (Fig. 19). In the past 8 years, the main span of cable-stayed bridges has increased further. There are 11 cable-stayed bridges completed or under construction with main span exceeding 600 m, including one bridge with span greater than 1000 m.
The 3rd Nanjing Yangtze River Bridge is a twin pylon 5-span continuous cable-stayed bridge with the mid span of 648 m. It is the first cable-stayed bridge with steel pylons in China. The bottom part (35 m high) of the 215 m high pylon and the cross beam are of reinforced concrete. The remaining portion of the pylon (180 m high), including three short cross beams are built of steel (Fig. 20). The ‘A’ shaped pylon with a curved alignment was prefabricated in 21 segments, which also resolved the problem of geometric control of thick plate welding. It took only 90 days to erect northern pylon and 58 days to erect the southern pylon. Each pylon segment weighs between 110 and 160 t. Erection height exceeds 200 m. Segments are connected by bolting (Fig. 21). The accumulated errors are only 6 mm in elevation, 0.95 mm in twist, and 1/4000 in inclination. The accuracy has reached existing international standards, which has shown that China has made a great leap forward in the technology of large scale, complex steel structures where geometrical precision is critical.

Foundations of pylons consist of 30 bored piles of 3 m in diameter constructed in waters of maximum depth 50 m. Piles were bored and cast from a platform composed of a steel cofferdam supported by the steel casings of the piles, allowing the deep water foundations to be completed in one low flow season. This is a further example of technical progress in pile foundation construction in China since the adoption of double wall steel cofferdam.

It took only 26 months to complete the bridge, which has set up a new record of bridge construction speed in China. The project won the Gustav Lindenthal Medal of the 2007 International Bridge Conference held in the United States. It was praised as a recent outstanding achievement demonstrating harmony with the environment, aesthetic merit and successful community participation.

The Sutong Yangtze River Bridge in Jiangsu Province, which began construction in June 2003, is a cable-stayed bridge with the world’s longest main span of 1088 m. The length of the project is 7.7 km, which includes approach spans of 5.6 km. The main bridge is a twin pylon steel box girder cable-stayed bridge. The 34.0 m wide deck carries six lanes of highway traffic (Fig. 22).
The bridge is a 7 span continuous girder structure with span arrangement as 100 + 100 + 300 + 1088 + 300 + 100 + 100 m. It incorporates a semi-floating system with longitudinal elastic restraint (without vertical bearings) for the deck at the pylons (Fig. 23). Construction of the bridge involved many challenges, including adverse climate, bad hydrologic conditions, poor geological conditions, and busy river traffic (more than 2300 vessels passing the channel per day under normal conditions and up to 5000 during peak periods).

The pylon foundations were designed to resist strong tides, river-bed scour, and ship impact, and incorporate 131 bored friction piles with diameter of 2.8 m and 2.5 m. Length of piles for the north and south pylons are 117 m and 114 m respectively (Fig. 24). Pilecaps are dumbbell-shaped and are connected with cross beam between pylon shafts. It took 24 months to complete construction of the bored piles and pilecaps. The bored piles were constructed within a tolerance of less than 50 mm on location and less than 1/350 on verticality.

Grouting was used to reduce settlement of the foundations and to increase the bearing capacity of stratum. Pile tests showed that grouting increased the bearing capacity of piles by at least 20%. Scour protective measures were also taken to ensure the safety of pylon foundations.

The concrete pylons are of 300.4 m high and have an inverted ‘Y’ shape with a portal beam under the girder. Stay cables are anchored in a steel anchorage box in the upper portion of the pylon. Automatic hydraulic climbing formwork was used during construction of the pylons. The pylons were made up of 68 construction segments with a standard height of 4.5 m. It took 16 months to complete pylon construction. Deviation of the pylon tip from its required location was limited to 7 mm. Verticality was held to within 1/42000, which is much less than the specified limit of 1/3000.

Parallel wire stay cables were used. The 7 mm diameter wires were made in China with a tensile strength of 1770 MPa. Stay cables are designed to have a service life of 50 years and were tested for fatigue and water-tightness. Tolerances of the 272 stay cables fabricated satisfied the 1/20000 requirement. Fatigue tests to more than 4 million cycles showed that 13
parameters including wire strength, elastic modulus, and torsion satisfy all applicable design requirements.

**Fig.24: Construction of the Foundation and Steel Anchorage Box at the Upper Part of the Pylon**

Because the maximum cantilever length during construction of the Sutong Bridge reaches 540 m (Fig. 25), wind resistance during construction was a critical consideration. The bridge deck is a steel box girder, 41 m wide and 4 m deep, with a streamlined shape to enhance aerodynamic stability.

**Fig.25: Cantilever Erection of the Sutong Bridge**

On the side spans, the steel box girders were erected by floating crane and supported on temporary piers. The maximum box girder section erected by floating crane was 60 m long and weighed 1250 t.

By April 23, 2007, the length of the deck cantilever had reached 444.8 m, which broke the original world record of 435 m held for 8 years by the Tatara Bridge in Japan. The remaining 13 steel box girder sections with total length of 198.4 m were then erected and main span closure was completed on June 9, 2007. The bridge has a smooth and flexible geometry with even distribution of cable forces (relative deviation of cable forces is less than 5%). Elevation deviation of the two cantilever tips less than 1 mm at time of closure.

After 6 years of construction, the bridge was officially opened to traffic on June 30, 2008. The
project won the 2008 George S Richardson Medal of the International Bridge Conference, which honours a single, recent outstanding achievement.

The 25.5 km long Yangtze River Crossing Project linking Shanghai’s Pudong district to Chongming Island is currently under construction across the Yangtze River estuary. The main bridge at north part of the river is a cable-stayed bridge with twin towers and two planes of cables, with a span arrangement of 92+258+730+258+92 m (Fig. 26). The towers are 228 m high and have an inverted ‘Y’ shape with a single shaft above the deck level. The girder cross-section consists of two linked steel box girders for a total width of 51.5 m and depth of 4 m high. The project is scheduled to be completed in 2009.

Fig.26: Shanghai Yangtze River Crossing Project

In addition, the E’dong Yangtze River Bridge with main span of 926 m and the Jingyue Yangtze River Bridge with main span of 816 m are under construction in the middle reaches of the Yangtze River in Hubei Province.

Several multi tower cable-stayed bridges have been built recently, including the Yinling Bridge in Hubei Province, a three-tower bridge with two spans of 348 m (Fig. 27) and the Dongting Lake Bridge in Hunan Province, a three-tower bridge with two spans of 310 m (Fig. 28). Thanks to their applications of recent scientific research achievements, these two bridges have won several national awards.

2.5 Suspension Bridges

Although there is less than 20 years of modern suspension bridge history in China, three landmark suspension bridges were built in China in the last 10 ten years of the previous century. These projects represent a great leap forward for long-span suspension bridges.
The Shantou Gulf Bridge in Guangdong Province, completed in 1995, has a three-span prestressed concrete stiffening girder. It is the first long-span modern suspension bridge built in China (Fig. 29). It ranks first among similar bridges in the world in terms of main span length (452 m).

![The Shantou Gulf Bridge with 452 m main span](image.jpg)

The Humen Pearl River Bridge at the Pearl River estuary in Guangdong Province has a main span of 888 m. Its main girder is a flat, streamlined, fully welded steel box. At the time of its completion in 1997, it was the first modern steel box girder suspension bridge to carry six lanes of highway traffic in China (Fig. 30).

![The Humen Pearl River Bridge with 888 m main span](image.jpg)

The Jiangyin Yangtze River Bridge in Jiangsu Province, completed in 1999, was the first suspension bridge to cross lower reaches of the Yangtze River and the first bridge built in China with main span length over 1000 m (Fig. 31).
The success of the construction of these three bridges further accelerated development of suspension bridges in China. By the end of 2008, the number of suspension bridges with main span over 600 m and 1000 m completed or under construction had exceeded 20 and 10 respectively.

The Runyang Yangtze River Bridge in Jiangsu Province consists of two cable-supported bridges. A 406 m span cable-stayed bridge was built to cross the northern branch of the Yangtze, while a suspension bridge with a main span of 1490 m was used to cross the southern. At the time of its completion it was the longest span in China and the third longest in the world (Fig. 32).

The plan dimensions of the southern anchorage foundation are 70.5×52.5 m. The depth of this foundation is 29 m. Construction was carried out with the help of ground freezing, to prevent penetration of ground water and resist earth pressure by row piles and an internal supporting structure. Excavation was carried out from top to bottom with supporting structures cast section by section (7 sections altogether) (Fig. 33). After the required depth was reached, the foundation was filled with concrete. The plan dimensions of the north anchorage foundation are 69×50 m. This foundation, which sits on slightly weathered rock, has a depth of 50 m. The foundation is surrounded by a continuous underground wall, which is 1.2 m thick. This wall has an average depth of 52 m and is embedded into slightly weathered rock (Fig. 34). V shaped flexible steel plate joints were used between wall sections.
Excavation of the northern and southern anchorage foundations were subject to rigorous monitoring. Thousands of sensors were installed in walls, piles, supporting structures, and the soil inside and outside the excavations so that any change in deformation of the structure and surrounding soil would be detected to ensure the safety of excavation and structure.

Construction of the project lasted for four and half years without any defect in quality, accident, or increase of construction cost, demonstrating a new level of project management in China.

The \textit{Yangluo Yangtze River Bridge} in Hubei Province, a 1280 m span suspension bridge (Fig. 35), and the \textit{Huangpu Pearl River Bridge} in Guangzhou, a 1108 m span suspension bridge, both have circular anchorage foundations with diameter 60 m and 70 m respectively, and depth 50 m and 43 m respectively. The foundation is surrounded by an underground continuous wall structure without internal struts (Fig. 36). Both bridges have been completed and were opened to traffic in 2008.

The \textit{Taizhou Yangtze River Bridge}, currently under construction, is located 66 km downstream from the Runyang Bridge and 57 km upstream from the Jiangyin Bridge. It is the first three-pylon two-span suspension bridge with both main spans longer than 1000 m. Its span layout is $390 + 1080 + 1080 + 390$ m (Fig. 37). A 95 m high steel pylon, with inverted Y shape in longitudinal elevation, was selected as the middle pylon. Concrete was used for the south and north pylons. Foundation construction (including foundations for the three bridge pylons and two anchor blocks) is now complete. Foundations for the middle pylon and the two anchor blocks are caisson structures. Experience from the successful construction of caisson foundation (plan dimension of $70 \times 50$ m with depth of 58 m) for the north anchor block of the Jiangying Yangtze River Bridge one decade ago was used to guide construction of this caisson structure.
Fig. 37: Taizhou Yangtze River Bridge (span arrangement: 390 + 1080 + 1080 + 390 m)

It is more difficult to carry out construction of the caisson foundation for the middle pylon, located in the center of the river (Fig. 38). This caisson foundation has plan dimensions of 58 × 44 m and a total height of 76 m. The lower part is a double-wall steel-shelled concrete structure and the upper part is a reinforced concrete structure, each with height of 38 m. The caisson was sunk into 19 m deep water and a 55 m thick layer of sediment. The first section of the steel-shelled caisson is prefabricated on shore, extended to a full height of 38 m in water, integrally floated and tugged to position, and placed onto the riverbed by injection of water. This is followed by casting concrete in divided chambers of the steel-shelled structure, extending by section to section concrete casting. After reaching the design elevation, a tremie seal is cast to complete the foundation. In spite of difficult tidal conditions, navigational interference, and other adverse construction conditions as loose riverbed and scour, the caisson was installed and tremie concreting completed by September 2007.

Fig. 38: Construction of caisson foundation for middle pylon of Taizhou Bridge

The Zhoushan Linking Project in Zhejiang Province between the mainland city of Ningbo and the Zhoushan Archipelago is 50 km long, half of which is connected by bridges. Three bridges have been completed (two prestressed concrete girder bridges and one 580 m span cable-stayed bridge) and two larger bridges with more technical difficulties are now under construction. One of them is the Xihoumen Bridge, a suspension bridge with a main span of 1650 m (span arrangement: 578+1650+485 m), which will become the second longest spanning bridge in the world (Fig. 39).

The site of the Xihoumen Bridge is under frequent influence of typhoons, with high wind speed and complex wind conditions. The measured maximum wind speed is 78.2 m/s. Aerodynamic stability is thus the key technical issue of the project. The selection of stiffening girder cross section is determined by its wind resistant capacity. During design stage, three alternatives were studied and compared, i.e., twin box sections separated in the middle, twin
box sections with open grid structure, and a single box section, with their respective depths of 3.5 m, 3.5 m, and 5 m. The proposal of twin box sections separated in the middle was chosen. Its critical flutter wind speed is 88 m/s (Fig. 40). It is the first separated twin box section girder structure to be used in China.

A digital simulation of wind tunnel tests was carried out to study the effect of the distance between the two box sections. The values considered were 5 m, 6 m and 6.5 m. Based on this study, a separation of 6 m was selected. The two box sections are connected by strong cross beams to ensure the integration of the girder in transverse direction. The cross beams alternate as box sections and I sections, both of which have the same 3.5 m depth as the girder. Webs of the cross beams connect to diaphragms in the longitudinal girders.

The continuous steel box girders in north side span and mid span have a total length of 2 428 m, which will a new record for the longest steel box girder in China.

To satisfy the requirements of crossing valleys in mountainous regions, 3 large span suspension bridges with light stiffening trusses construction: Sidu Bridge in the Hubei Province (with 900 m main span and 500 m deep from deck to ground level), the Baling River Bridge in Guizhou Province (1088 m main span and 330 m deep from deck to ground level) and the Aizhai Bridge in Hunan Province (1146 m main span and 350 m deep from deck to ground level).

3. China’s Railway Bridges

The Wuhan Yangtze River Bridge, which has a main span of 128 m and which carries both highway and railway traffic, had its 50 year anniversary in 2007. A second bridge that carries both highway and railway, the Nanjing Yangtze River Bridge has a main span length of 160 m and celebrated its 40 year anniversary in 2008. These two bridges have always been the pride of Chinese bridge engineers (Fig. 41 and 42).
The **Jiujiang Yangtze River Bridge**, completed in 1993, and the **Wuhu Yangtze River Bridge**, completed in 2000, increased the span length of railway bridges to 216 m and 312 m respectively. These bridges also integrated the technology of arch-supported and cable-supported bridges with the technology of steel truss girder bridges effectively to enhance spanning capacity of bridges carrying both highway and railway (Fig. 43 and 44). The **Wuhu Yangtze River Bridge**, which has a total length of 10020 m, used 550 000 tonnes of concrete and 110 000 tonnes of structural steel. Quantity of materials for this project exceeded the total quantities of the Wuhan Yangtze River Bridge and the Nanjing Yangtze River Bridge.
The two railway bridges described below, currently under construction, will set new records:

The **Wuhan Tianxingzhou Bridge** is a double deck steel truss girder cable-stayed bridge with main span arrangement of $98 + 196 + 504 + 196 + 98$ m (Fig. 45). The bridge has been designed to carry six lanes of highway on the upper deck and four tracks of railway on the lower deck. It will be the longest and heaviest loaded combined highway/railway in the world. The structure consists of three planes of truss and three planes of stays. Construction started in September 2004, the main girder was closed in September 2008, and the bridge is expected to be completed and open to traffic in 2009.

The **Dashengguan Railway Bridge** is the first high speed railway bridge to be built in China. The main bridge has three planes of truss and a span arrangement of $109.5 + 192 + 336 + 336 + 192 + 109.5$ m (Fig. 46). The bridge is designed to accommodate high speed trains traveling at 300 km/h. It has the longest spans of any high speed railway bridge in the world. The design live loads include traffic load for two tracks of high speed railway, two tracks of grade I railway, and two tracks for the Nanjing metro. The bridge is designed to have a higher loading capacity than any other high speed railway bridge in the world. The project commenced in July 2006, steel girders at the south and north span were closed in December 2008, and main span closure is expected to be completed in August 2009. The bridge will be opened to traffic in 2010.
4. Meeting challenges

Based on knowledge learned from advanced technology outside of China and experience of domestic bridge construction practice, a complete set of technologies, including standards and specifications, computing theory, structural analysis, model testing, materials science, construction technique, instruments and equipment, construction control, and inspection technology, has been gradually been developed and adapted to China’s conditions.

According to the China Highway and Railway Network Planning Department, more than 1100 000 km of new highways will be built by 2020, of which 45 000 km will be expressway, and 57 000 km of new railways will be built, of which 16 000 km will be dedicated passenger lines (Fig. 1 and 47). To accommodate this growth, approximately 200 000 bridges of various sizes with total length over 10 000 km will be built, including over one hundred extra-large scale bridges with main span over 400 m.
It has become the guiding principle for Chinese civil engineers to adopt the concept of sustainable development with the core value of “regarding people as fundamental, saving resources, and being environmentally-friendly”. In addition to safety and durability of materials and structure, planning and design consider sustainability of social benefits as the inherent quality of bridge projects. China now attaches increasing importance to the “full life cycle cost analysis” and “effective service” of infrastructure projects.

The Hongkong-Zhuhai-Macao Bridge (HZMB), which will be built in the near future, is a major bridge and tunnel project that will connect the three cities of Hong Kong, Zhuhai, and Macao. The bridge will be constructed to carry 6 lanes of highway traffic in accordance with the Expressway Construction Standard with a design speed of 100 km per hour. A major portion of this project will be a 35 km long section consisting of both bridge and tunnel crossing a total of 6 navigable channels. Immersed tunnels of about 7 km in length will be used at the Lingding navigable channel and the Tonggu navigable channel. Bridges will be used to cross other navigable channels. Two artificial islands, each with length of 1000 m, will be constructed to connect with the bridges. Preparation for construction of the bridge is progressing well and the project is expected to be completed by 2012.

Another extremely challenging project is the Qiongzhou Strain Crossing Project linking the Leizhou Peninsula and Hainan Island. The pre-feasibility study for the project has been carried out for more than 10 years and it is expected to be constructed before 2020.

China has to face new challenges to achieve new technological breakthroughs involving the integration of structure, materials, and construction to achieve longer spans, sea-crossing bridges, deep-water foundations, and tall bridge towers.

5. Conclusions

Heading into the ‘golden age’ for bridge construction, Chinese engineers are well prepared and will cooperate with our colleagues from all over the world to meet the challenges of the largest scale bridges in the world in the new century with new structures, new materials, new techniques and new equipments as well as innovative management.

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